# Piezoelectric Acousto-Optical Modulation in Aluminum Nitride for Integrated RF-Photonics

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## Abstract

Over the past several years, rapid advances in the field of integrated photonics coupled with nanofabrication capabilities have enabled studies of the interaction of light with the mechanics of a variety of physical structures. Concurrently, mechanical resonators have been extensively studied in the MEMS community due to their high quality factors, and have been implemented in a variety of RF filters and oscillators. The combination of MEMS with integrated optomechanical structures can generate a variety of novel devices that can be used for applications in RF-Photonics, timing and optical switching. While there are several demonstrations of electrostatic devices integrated with optomechanical structures, fewer examples exist in the piezoelectric domain. In particular, photonic integration in a piezoelectric material can benefit from some of the traditional strengths associated with this type of actuation, such as the ability to easily scale to higher frequencies of operation by patterning lateral features, the ability to interface with  $50\Omega$  electronics and strong electromechanical coupling. In addition, it enables a platform to produce new architectures for photonic-based electronic frequency reference oscillators that incorporate multiple degrees of freedom.

This thesis presents the development of a piezoelectrically-actuated acousto-optic modulator in the aluminum nitride (AlN) material system. The process of implementing this device is carried out in five principal stages. First, light coupling from optical fibers to the AlN thin film is demonstrated with the use of on-chip grating couplers, exhibiting a peak insertion loss of -6.6 dB and a high 1 dB bandwidth of 60 nm for operation in the telecommunications *C*- and *L*-bands. This is followed by characterization of photonic whispering gallery mode microdisk and microring resonators with optical quality factors on the order of  $10^4$ . Next, a robust fabrication method combining optical and electron-beam lithography is developed to produce a fullyintegrated device preserving the critical features for acoustic and photonic resonators to be colocalized in the same platform. Acousto-optic modulation is demonstrated with the use of a contour mode resonator which drives displacements in the photonic resonator at 653 MHz, corresponding to the mechanical resonance of the composite structure. The modulator is then implemented in an opto-acoustic oscillator loop, for which an initial phase noise of -72 dBc/Hz at 10 kHz offset from the carrier is recorded with a large contribution from thermal noise at the photodetector. Finally, some possibilities to improve the modulator efficiency and oscillator phase noise are provided along with prospects for future work in this area.

*Key words*: Optical microelectromechanical devices, modulators, microstructure fabrication, resonators, piezoelectric actuators, AlN

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## **Chapter 1 Introduction**

The use of photonic technologies for the processing and control of radio frequency (RF) signals has been envisioned since the demonstration of the first laser in 1960. Since then, fiber optic communication systems have been employed worldwide and played a major role in the advent of the Information Age. This is in large part due to the inherently high carrier frequency of optical signals (on the order of 200 - 1000 THz), which ensures bandwidths and thus information capacity far in excess of electrical transmission or microwave systems. Optical fiber links also provide a number of advantages over conventional electrical transmission systems including reduced size, weight and cost, a high degree of physical flexibility, as well as low and constant attenuation losses over the entire RF modulation frequency range. For example, optical fiber typically weighs 1.7 kg/km versus 567 kg/km for coaxial cable [1], and exhibits attenuation losses on the order of 0.2 dB/km. The combination of these features makes it ideal for use in signal distribution and application in environments such as aircraft, satellites and cell-phone towers. Simultaneously, consumer demands on information rates and broadband services are constantly increasing. The proliferation of handheld devices for example, will require a more extensive wireless infrastructure. In addition, the deployment of fiber to the premises (FTTP) networks (e.g. Google Fiber) is expected to grow steadily in the near future. From an environmental perspective, widespread adaptation of pico- [2] or femtocell networks can also produce a much greener carbon footprint than current macrocell networks, which require high-power base stations [3]. These trends will require the additional development of photonic technologies to perform analog frontend processing for RF signals.

The basic requirement for any RF Photonic link is to produce RF modulation of an optical carrier, which can be recovered through photodetection. The link thus requires a modulation device capable of performing the electrical to optical (E/O) conversion, while the photodetector performs the optical to electrical (O/E) conversion. Theoretically, a lightwave can be

modulated with respect to amplitude, frequency or phase. The first stage of the photodetector however contains a photodiode, which produces a photocurrent directly proportional to the intensity (W/m<sup>2</sup>) of the transmitted signal. Therefore the photodiode can only detect intensity modulation. This modulation can be produced either directly (by applying a time-varying current to the laser source) or externally. One of the disadvantages to direct modulation is the generation of chirp, in which the optical frequency is inadvertently modulated [4]. For most demanding RF Photonics applications, researchers have focused on the use of external modulation. The advantage of this approach is that the system can make use of continuous wave (CW) sources operating at high powers with low relative intensity noise [5]. A representation of this externally modulated scheme is shown in Figure 1.1.



Figure 1.1: RF signal processing through external modulation on an optical carrier

Several factors have prevented the RF Photonic concept from being widely implemented beyond the laboratory, including performance, reliability and cost. Most systems are composed of discrete components (e.g. lasers, modulators and detectors) connected by fiber pigtails, which produces a number of problems. The use of discrete components naturally occupies larger size, while the use of fiber pigtails reduces system sturdiness and reliability. In addition, the use of discrete components produces high system cost as a result of packaging for each element [6]. These difficulties can be addressed in large part by pursuing integration of RF and photonic components. To this end, the implementation of large-scale photonic integrated circuit (PIC) technology can simplify optical system design, improve reliability and reduce overall footprint, inter-element coupling losses and power consumption. In order to maximize these benefits, monolithic integration is typically the preferred approach. The implementation of an integrated RF-Photonic front-end thus requires a suitable approach for modulating RF signals, which can be compatible with other functions on chip.

#### **1.1 MEMS for Integrated RF-Photonics**

A technological solution uniquely positioned to perform RF signal processing integrated on chip is to make use of microelectromechanical systems (MEMS). The use of MEMS for RF applications has largely been driven by the potential to utilize the high mechanical quality factors (Qs) of resonant microstructures to replace elements of wireless transceivers that require the use of high-Q passives. The reason for this stems from the fact that the legacy technologies (such as quartz crystals and surface acoustic wave (SAW) resonators) currently implemented to perform the frequency referencing and filtering functions required in an RF front-end are typically all offchip components that cannot be directly integrated with CMOS circuitry. This has led wireless designers to opt for the use of direct-conversion or low-IF receiver architectures at the expense of increased transistor circuit complexity and reduced multiband reconfigurability [7]. In contrast MEMS resonators offer access to high-Q, dense integration (which enables new possibilities for RF channel-selecting filter banks and reconfigurable oscillators) as well as the possibility of CMOS integration [8].

MEMS based resonators can broadly be classified by their transduction mechanism – namely electrostatic or piezoelectric excitation. Electrostatic transduction has been shown to produce very high mechanical  $Q_{\rm S}$  (>10,000). They typically suffer from poor electromechanical coupling, especially at high frequencies of operation. Piezoelectric resonators on the other hand may have lower  $Q_{\rm S}$  (~1,000-4,000) on account of additional loss mechanisms such as the metal electrodes

patterned on the resonator body. However they exhibit much higher electromechanical coupling, which can be orders of magnitude higher than in the electrostatic case. In addition they show low motional impedances which allows direct matching to  $50\Omega$  electronics – an important feature for RF applications.

Among piezoelectric MEMS devices, the contour mode resonator (CMR) [9] is a technology that combines many of the features desired for implementation in future RF front-ends. One of the main advantages for this class of resonators is that they have a fundamental frequency which can be defined by in-plane lateral dimensions. This is in contrast to the film bulk acoustic resonator (FBAR) [10], which has enjoyed commercial success, but is limited in frequency setting to the thickness of the piezoelectric film used. In enabling frequency setting at the layout level, the CMR can be applied where multiple frequencies are produced on the same chip. This is a desirable feature to address the multiband requirements of evolving wireless standards.

By leveraging the strengths of MEMS and CMR devices in particular, we can identify an approach that efficiently performs RF functionalities on chip for RF Photonic applications as well. In order to interface this capability with PIC technology, optomechanical devices which combine the attributes of MEMS resonators with integrated photonic structures will be considered. Specifically, we will consider devices that generate RF modulation of an optical carrier. This combined approach can thus be used as a building block for integrated RF Photonic front-ends.

#### **1.2 Aluminum Nitride material properties**

As discussed, the CMR is a device that combines the compact filtering and frequency reference capabilities of MEMS devices, while providing the ability to span multiple frequencies on a single chip with strong electromechanical coupling. A number of piezoelectric materials (e.g. ZnO, PZT) have been proposed for producing this type of resonator. However, the one that has

emerged as a dominant choice for commercial and research applications alike [11], is aluminum nitride (AlN). This can be attributed to excellent acoustic and thermal [12] properties, as well as its CMOS compatibility and the ability to easily deposit thin films on silicon with the use of physical vapor deposition (PVD). While its use as a material for manufacturing PICs has not been widely pursued, its potential for optoelectronic applications has long been explored as with the other wide bandgap III-V nitrides [13]. With appropriate doping, AlN is also a suitable material for the integration of active sources on the same substrate.

	Si	SiO <sub>2</sub>	Si <sub>3</sub> N <sub>4</sub>	GaAs	GaN	LiNbO <sub>3</sub>	AIN
Index (1550 nm, ordinary)	3.47	1.45	2.0	3.37	2.31	2.21	2.04
Bandgap	1.12 eV	8.9 eV	5.1 eV	1.43 eV	3.4 eV	4.0 eV	6.2 eV
Optical losses (α)	0.3 dB/cm	0.007 dB/cm	0.055 dB/cm	0.5 dB/cm	0.65 dB/cm	2.03 dB/cm	0.6 dB/cm
Integrated structure	Waveguide [14]	Microtoroid resonator [15]	Ring resonator [16]	Waveguide [17]	Waveguide [18]	Disk resonator [19]	Ring resonator [20]
Piezoelectric	N/A	N/A	N/A	$d_{31} = 0$ $d_{33} = 0$ $d_{14} = -2.7$ pC/N	$d_{31} = -1.9$ pC/N $d_{33} = 3.7$ pC/N	$d_{31} = -1 \text{ pC/N}$ $d_{33} = 6 \text{ pC/N}$ (Z-cut)	d <sub>31</sub> = -1.98 pC/N d <sub>33</sub> = 4.98 pC/N
Elasto-Optic	N/A	N/A	N/A	p <sub>11</sub> = -0.026	p <sub>11</sub> = -0.086* (*estimated, [21])	p <sub>11</sub> = -0.026	p <sub>11</sub> = -0.10* (*estimated, [21])

Table 1.1: Properties for commonly used optical and piezoelectric materials.

In order to benefit from the RF Photonic platform that integrates piezoelectric MEMS and PIC functionalities, the material should exhibit characteristics required for both classes of device. As a means of comparison, some popular integrated photonic and piezoelectric materials are shown in Table 1.1. For example, a great deal of interest has been placed on the development of silicon photonics as a result of its vast microelectronics infrastructure. Due to its centrosymmetric crystal structure silicon does not exhibit piezoelectricity, which limits MEMS-based implementations to electrostatic devices. It also lacks electrooptic effects (the basis of traditional

LiNbO<sub>3</sub> modulators), while its narrow bandgap makes it susceptible to two-photon absorption and limits its range of operation. With the exception of LiNbO<sub>3</sub>, AlN exhibits higher piezoelectric coefficients than any of the other materials compared. In addition, it has demonstrated proven RF filtering capabilities [22], [23] and been implemented in the demonstration of reconfigurable CMOS oscillators [24]. As an optical material it also exhibits low losses. For all of these reasons as well as its relative ease of processing, we select the use of AlN.

#### 1.2.1 Piezoelectric effect

AlN has a wurtzite crystal structure, which lacks inversion symmetry. In the presence of mechanical stress, the crystal supports an internal electric polarization, which means it is piezoelectric. The converse effect also exists, in which the piezoelectric crystal becomes strained when an electric field is applied to it, making it a reversible process. The effect is a linear interaction between the electrical and mechanical variables of a crystalline material. There are several different formulations for the piezoelectric equations, but a common form in which the electric field (*E*) (3 x 1 matrix) and the stress ( $\sigma$ ) (6 x 1 matrix) are the dependent variables is as follows,

$$S = s\sigma + d^{T}E$$

$$D = d\sigma + \varepsilon E$$
(1.1)

where *S* is the strain (6 x 1 matrix), *s* is the compliance (6 x 6 matrix), *d* are the piezoelectric coefficients (3 x 6 matrix), *D* is the electric displacement field (3 x 1 matrix) and  $\varepsilon$  is the dielectric permittivity (3 x 3 matrix). By sandwiching a material with electrodes to apply an alternating electric field across it, the converse effect can be used to drive the body into motion. As it vibrates, the deformations produce piezoelectric charge on the surface of the electrodes through the direct effect. In order to generate the in-plane lateral vibrations used in CMRs, the  $d_{31}$  coefficient is typically used for c-axis oriented thin films such as those of AlN.

#### 1.2.2 Optical characteristics

As a result of its wide bandgap, AlN exhibits a transparency window extending into the deep ultraviolet range. This has been utilized to produce LEDs [25] for example, and can also be exploited for various applications such as solid-state lighting and chemical/biological sensing. With regard to guided optical wave applications, the piezoelectric properties have been utilized to generate acousto-optic diffraction with the use of surface acoustic waves [26]. This work also highlights the existence of appreciable elasto-optic coefficients in the material, which have been estimated theoretically in the literature [21]. A combination of all these features in AlN enables direct electrical control amenable to RF modulation over a broad range of optical wavelengths. Therefore, this could form the basis for a new class of electro-optomechanical devices.

#### **1.3 Review of Cavity Optomechanical Devices**

Cavity optomechanical systems offer an efficient platform coupling optical and mechanical degrees of freedom, which have enabled the demonstration of numerous physical principles and the possibility of engineering novel nanoscale devices for a variety of applications. Numerous types of optomechanical devices have been demonstrated in the literature, in which light can be used to excite mechanical vibrations or where mechanical motion is excited electrically and sensed optically. Light-driven resonators and oscillators include the use of radiation pressure [27], gradient forces [28], or electrostriction [29]. In the case of electrically excited, optically sensed mechanical resonators, there are several examples of electrostatic devices [30]–[32], and some recent examples of piezoelectric devices [33]–[35]. This section highlights some of the relevant designs which are used as motivation for the devices that will be demonstrated in this thesis. While some of these systems have been driven by applications in the quantum domain, we will consider those operating in the classical regime. Future investigations may however consider existing proposals for enabling interactions of phonons and photons that will specifically benefit from integration in a piezoelectric material [36].

#### 1.3.1 Radiation pressure actuation

Radiation pressure was one of the first actuation forces to be considered in cavity optomechanical systems. Its effect has been noted in whispering gallery mode (WGM) optical resonators in a variety of materials. The original demonstration was made in silica microtoroids exhibiting ultrahigh (>10<sup>6</sup>) optical Qs, which could also be driven into self-oscillation without the use of an external feedback system [27]. Optical power circulating in the WGM exerts a radial force on the resonator body, which causes the cavity structure to expand. As a result, the optical resonance frequency decreases (resonant wavelength increases) and the radiation pressure in the resonator decreases. The relaxation of this force reverses the initial mechanical deformation, and the process resumes. Periodic motion occurs at a mechanical eigenfrequency of the resonator structure. Evanescent coupling of the optical wave to the microresonator is often accomplished with the use of a tapered fiber assembly. However, fully-integrated solutions consisting of monolithically defined resonators and waveguides have also been demonstrated, with high optical Os, notably in silicon nitride [37]. Since silicon nitride exhibits similar optical properties to aluminum nitride, this demonstration serves as a good model for an aluminum nitride optomechanical resonator driven into self-oscillations, without the use of external excitation. The key differences in AlN compared to silicon nitride however, are the piezoelectric and elasto-optic effects (neither of which are present in silicon nitride), which can be used for enhanced device performance. These unique characteristics of AlN will be considered in more detail in subsequent sections.

#### 1.3.2 Electrostatic actuation

Electrically actuated, optically sensed mechanical motion has been demonstrated electrostatically in silicon, with the use of coupled disk resonators [30]. In this case, a mechanical disk resonator is driven through the use of an electrostatic capacitive gap, to excite vibrations that get coupled to the optomechanical disk resonator. The radial vibrations of the structure affect the

optical resonance condition of the WGM (just as in the case of the radiation pressure driven oscillator), and allow the mechanical vibration to be detected as an intensity modulation of the output light thus enabling its function as an acousto-optic modulator. This device serves as a good model for what can be reproduced in the piezoelectric domain with the use of contour mode resonators coupled to optically resonant structures. As we shall see, there are distinct advantages to a piezoelectric implementation (as in AlN) versus electrostatic actuation, particularly with regards to transduction capability and frequency scaling. While transduction capability in electrostatic resonators may be boosted via sub-100nm resonator-electrode gaps, frequency scaling beyond 1 GHz is extremely complicated [32]. On the other hand, piezoelectric actuation has been shown to enable much higher actuation frequencies in the SHF range [23]. In addition, the elasto-optic effect in AlN may be utilized to enhance the efficacy of high modulation frequency scaling, and this presents an opportunity which has not been widely explored to date.

Another type of optical modulation (not relying on the WGM) has been shown in the direct control of end-coupled waveguides through electrostatic forces in indium phosphide [31]. In this case, transmission through a gap in the waveguide itself is modulated through the use of a combdrive actuator. This allows the device to behave as an optical switch, or a resonant sensor at low (~1MHz) frequencies.

#### 1.3.3 Piezoelectric actuation

Recent work has also demonstrated the interaction of piezoelectric transduction with optical cavities to explore the possibility of quantum state transfer in optomechanical crystals [33] and enhanced interactions with microwave signals through the use of suspended RF probes [34] and microstrip resonators defined on a separate chip [35]. Towards the aim of producing mixed RF-Photonic systems however, it would be advantageous to employ a fabrication method in which electrodes may be directly patterned on the resonator body, in order to improve the electromechanical coupling, provide seamless integration with filters, oscillators and other

devices commonly produced in the RF MEMS community and potentially operate with multiple frequencies on a single chip. This approach would both benefit from the strengths associated with using piezoelectric transduction as well as the large body of work that has already been generated for resonant MEMS devices [11]. This thesis will demonstrate these concepts, and develop a platform which may also later be extended to study higher operation frequencies and elasto-optic interactions through the use of demonstrated capabilities in AlN CMR technology.

#### 1.4 Thesis organization



Figure 1.2: Piezoelectrically-actuated AlN acousto-optic modulator with chapter references to development stages

This thesis presents the development of a fully integrated monolithic piezoelectricallyactuated acousto-optic modulator in the AlN material system. Optical modulation is generated in whispering gallery mode photonic resonators with the use of laterally-vibrating contour mode acoustic resonators. The constituent microphotonic components enabling this demonstration, including grating couplers and photonic resonators have been studied and analyzed. A unique fabrication process has also been implemented in order to effectively co-localize acoustic and photonic resonators, while preserving critical features required for their effective operation. The modulator has then been implemented in an opto-acoustic oscillator loop as an initial application. The progression of this work is shown pictorially with the associated section describing its development in Figure 1.2.

This dissertation is organized in the following chapters:

Chapter 2 provides an overview of various light coupling techniques to integrated dielectric waveguides, and describes the theory and simulation of optical grating couplers in AlN thin films. A brief description of visible spectrum gratings is provided, followed by a discussion of the fiber array setup utilized in the remainder of the thesis as well as the AlN gratings designed for *C*-band operation.

Chapter 3 discusses the background and theory for photonic whispering gallery mode resonators, including the simulation of axisymmetric mode profiles. An overview of the waveguide to resonator coupling behavior is provided, followed by results from the experimental characterization of AlN microdisk resonators. The chapter concludes with a description of the optomechanical modulation model used for the released devices.

Chapter 4 summarizes the evolution of the fabrication process that ultimately led to the colocalization of acoustic and photonic resonators. An overview of the three generations of process development is provided along with a description of some representative cases that motivated the design changes required to ultimately produce a functional modulator device.

Chapter 5 introduces the fundamentals of piezoelectric contour mode resonator and discusses its role in the demonstration of the AlN acousto-optic modulator. Simulations of the mechanical and optical modes are provided along with experimental characterization of the device. The electro-optomechanical response of the device is measured and modulated with respect to input RF and optical power levels in order to extract the piezoelectric optomechanical coupling factor  $\eta_{om}$ .

Chapter 6 demonstrates the application of the modulator in an opto-acoustic oscillator loop with the use of SMA components. A phase noise model is developed, in which thermal noise at the photodetector output is identified as the dominant contributor. Some perspectives on improvements to the phase noise are also provided.

Chapter 7 provides a summary of the primary thesis contributions and concludes with some proposals for future research ideas that extend and build upon concepts developed in this thesis.

# Chapter 2 Optical grating couplers for guiding light in AlN thin films

The realization of any photonic integrated circuit requires efficient coupling of the light source to a dielectric waveguide. A variety of different approaches have been proposed to address this problem since the use of thin films in integrated optics became widely adopted in the 1970s [38]. These have included the use of edge or surface coupling techniques. With the rapid growth of silicon photonics in the past decade, there has been renewed interest in developing surface couplers that can be placed anywhere on a chip and not only at the edges to facilitate wafer level testing. To this end, the grating coupler has been identified as a suitable interface element that enables optical connectivity to a die and can be designed and laid out similarly to electronic chips. This feature has enabled its recent integration in a CMOS platform for producing optoelectronic systems on chip [39]. While these characteristics are beneficial for the integrated photonic devices we will consider, an additional advantage of the grating coupler is its compatibility with the release processes that are required for producing MEMS structures. This chapter therefore outlines the development of grating couplers in AlN thin films, and describes the setup used to characterize their performance, which is also applied in the subsequent chapters.

### 2.1 Light coupling techniques

There are several difficulties associated with efficiently coupling light from a source to an integrated photonic waveguide including alignment, material and dimensional differences. The latter is often a problem when considering the optical mode that would be supported in the two structures. A single mode optical fiber has a core diameter of 8-9 microns, while a dielectric thin film waveguide will have a typical cross-section that is 1-2 orders of magnitude smaller. The mismatches can thus be addressed by a number of approaches, which correct for the modal discrepancy. These are shown in Figure 2.1.



Figure 2.1: Guiding light in thin films via: (i) butt-coupling, (ii) lensed focusing, (iii) inverted taper, (iv) prism coupling and (v) grating coupling

The most basic approach to the coupling problem would be to simply move the source as close as possible to the edge of the waveguide in a method called butt coupling. Due to the mismatch of refractive indices and the dimensions involved, this results in a very low coupling efficiency, and is not a viable option [40]. The efficiency can be improved by using a lens that focuses the light into the edge of the waveguide, which reduces the mode guided in a fiber before it reaches the chip. In theory, excellent coupling efficiency can be achieved if the beam diameter is carefully matched to the waveguide thickness. This however becomes a challenge for alignment purposes when considering the sub-micron dimensions of integrated waveguides. To avoid the use of lensed fibers, some devices utilize a mode converter. An example structure of this process is the inverted lateral taper. As the waveguide becomes smaller towards its edge, the carried mode becomes less well confined within the material and begins to grow in size, becoming decoupled from the core. At some point the size of the mode matches that of the fiber mode, and strong coupling can be achieved [41]. A drawback of this technique is that the chip must be diced accurately near the tip of the taper to prevent optical coupling in the substrate.

Among surface coupling methods, the most direct approach is to end-fire couple, where a beam is focused on the end of a waveguide. This approach only works if a clean edge of the waveguide is accessible and the external beam can be tightly focused and positioned, which is often not the case [40].



Figure 2.2: Oblique coupling of light into a waveguide

In addition, there is a fundamental problem if we consider simply focusing the light on a waveguide at an oblique angle of incidence as shown in Figure 2.2. We will consider the coordinate system shown, where we assume monochromatic light of frequency  $\omega$  and free-space wavelength  $\lambda$  should propagate in the *z* direction. In order for the wave to propagate inside the waveguide (where it is totally reflected at the film boundaries), it must satisfy the conditions [42],

$$kn_c < \beta_z < kn_f$$

$$kn_s < \beta_z < kn_f$$
(2.1)

where  $\beta_z$  represents the propagation constant in the film and  $n_c$ ,  $n_f$  and  $n_s$  are the refractive indices of the cover, film and substrate materials, respectively. In addition, the absolute value of the wavevector, denoted by k is given by

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c} \tag{2.2}$$

where *c* is the velocity of light in vacuum. For coupling to occur, the phase velocities of the waves in the *z*-direction must be the same in both the waveguide and the incident beam. This would suggest the satisfaction of the expression  $\beta_z = kn_c \sin \theta$ . It is however apparent from (2.1) that this cannot be achieved with a real angle of incidence  $\theta$ . In order to generate this phase matching condition, one reliable method that has often been used to couple light to thin films is to use a prism coupler. Here,  $n_p$  is selected which is greater than  $n_o$  and  $n_s$  and the beam is totally internally reflected at the interface with the air (where  $\theta_p$  exceeds the critical angle determined by Snell's Law). This establishes a mode which is stationary in the x-direction, but moves in the *z*-direction with the phase constant  $\beta_p$ . If the spacing between the prism and the film is small enough, there is evanescent coupling to the waveguide mode and the  $\beta$  terms can be matched by the condition  $\beta_z = \beta_p = \frac{2\pi n_p}{\lambda} \sin \theta_m$ , thereby launching the light in the waveguide. While this is a useful method for characterizing large thin film structures, the use of prism couplers requires precise location of a relatively large bulk object over a waveguide and is not the most convenient approach for interfacing with integrated photonic devices.

Another approach to satisfying the phase matching condition is to use corrugations in the waveguide itself, which forms a grating coupler. As the incident wave strikes the grating, it is broken into several other beams, including a reflected wave, a transmitted wave and several diffracted waves - in which the direction of the beam is altered from what would be expected with reflection or refraction. This is dictated by the period  $\Lambda$  of the grating, which perturbs the waveguide modes in the film and generates a matching condition to the propagation constant. Under the correct conditions, a portion of the incident wave can couple into the guided mode of the waveguide (as discussed in the following section). Although they are relatively narrowband in comparison to edge coupling, grating couplers offer several advantages over the other techniques. These include simplicity of fabrication, flexibility in placing the optical interface anywhere on the

chip, increasing the density of on-chip devices and the ability to eliminate polishing or other surface preparation steps. As a result, we have chosen to focus our efforts on developing this device.

#### k<sub>x</sub> m=0 θ m=1 kn *k*n<sub>c</sub> k, n<sub>c</sub> δ ≎ Ît n<sub>f</sub> 2π а < $\rightarrow$

#### 2.2 Grating coupler operation and numerical methods

Figure 2.3 Grating geometry and k-space diagram for phase matching of first diffractive order

For periodic structures the most fundamental formula describing their behavior is the Bragg condition, which describes the relationship between the wavevectors of the incident and diffracted waves. As shown in Figure 2.3, for a grating with a uniaxial periodicity along the z-axis, the expression is,

$$\beta_z = k_{in.z} + mK \tag{2.3}$$

where  $\beta_z$  is the propagation constant of the guided mode in the waveguide,  $k_{in}$  is the incident wavevector, m is the diffraction order, and  $K = \frac{2\pi}{\Lambda}$  in which  $\Lambda$  is the period of the grating. In order to achieve phase matching as indicated in (2.2) we should consider the projection of the incident wavevector in the z-direction, such that  $k_{in,z} = \frac{2\pi n_c}{\lambda} \sin \theta$ , where  $\lambda$  is the wavelength of the light,  $n_c$  is the effective index of the cover layer and  $\theta$  is the angle of incidence. The propagation of the guided mode may also be expressed in terms of  $n_{eff}$  (the effective index in the grating) as  $\beta_z = \frac{2\pi}{\lambda} n_{eff}$ . This results in the expression

$$\frac{2\pi n_{eff}}{\lambda} = \frac{2\pi n_c}{\lambda} \sin \theta + m \frac{2\pi}{\Lambda}$$
(2.4)

For the case of vertical coupling (such as to an optical fiber) we consider the first order diffraction, where m = 1 (as shown by the matching of phase fronts in the *k*-space diagram of Figure 2.3). Thus a simplified expression to select a grating period that can be used for input and output light coupling is

$$\frac{1}{\Lambda} = \frac{n_{eff}}{\lambda} - \frac{n_c}{\lambda} \sin\theta$$
(2.5)

We should note that the Bragg condition is exact for infinite structures (*i.e.* where there are infinite periods). In a finite structure, there is not one discrete wavevector for which diffraction occurs, but a range of them, surrounding the one predicted by the Bragg condition [43]. For modeling purposes, we select a center wavelength upon which to base the design, and the extent of the range – or the bandwidth of the device – can be determined from simulation of the coupling efficiency.



Figure 2.4: (Left) One-dimensional dielectric slab with asymmetric claddings, (Center) Dispersion relationship of normalized parameters, and (Right) Effective index method

#### 2.2.1 Mode confinement

In order to make a reasonable estimate for the grating period, we need to consider the "effective refractive index" for the guided mode in the waveguide. The  $n_{eff}$  value considered in the Bragg condition is actually an average of this effective refractive index for the waveguide and the index of the grating etch regions (or amount of etched region, where the index matches that of the cover layer). This average is determined by the duty cycle of the gratings. One way to analyze the modes in a dielectric waveguide is to use the effective index method, which considers each dimension of the two-dimensional waveguide separately as a one-dimensional slab. In the 1D slab we can use the film stack previously considered shown in Figure 2.4, which is a generic case for different cover and substrate layers. For the guided mode, effective refractive index describes the free-space velocity divided by the waveguide phase velocity. It can also be expressed as the ratio of the guided propagation constant to the free space wavevector as

$$n_{eff} = \frac{c}{v_p} = \frac{\beta}{k}$$
(2.6)

To simplify the process of determining the modes of propagation in the structure, we can use the following normalized parameters

$$V = kt \sqrt{n_f^2 - n_s^2}$$
 Normalized waveguide thickness  

$$a = \frac{n_s^2 - n_c^2}{n_f^2 - n_s^2}$$
 Assymetry parameter (2.7)  

$$b = \frac{n_{eff}^2 - n_s^2}{n_f^2 - n_s^2}$$
 Normalized guide index

These expressions can be substituted into the dispersion relation given for the transverse electric (TE) mode [42] to yield the characteristic equation

$$V\sqrt{1-b} = \upsilon\pi + \tan^{-1}\sqrt{\frac{b}{1-b}} + \tan^{-1}\sqrt{\frac{a+b}{1-b}}$$
(2.8)

where v indicates the mode number. The relationship is plotted in Figure 2.4 for the fundamental and first order modes, which can be used to extract the effective refractive index for a slab, where the thickness t is known. Once this is done for one dimension the process can be repeated in the other, using the " $n_{eff,1}$ " value determined and the bounding indices of the materials along the second axis as indicated in Figure 2.4. Throughout the remainder of the thesis, we will always consider the TE mode for the analysis of guided modes in waveguides as the gratings are optimized for this polarization state, where the electric field is directed parallel to the grating lines.

While the effective index method and other analytical methods provide useful tools for assessing the effective index in integrated waveguides, a complete description of a 2D waveguide cross-section involves the contribution of all six electric and magnetic field components. The normal modes for a waveguide structure (in which we assume the waveguide is unchanging in the z direction) can be analyzed through a vectorial electromagnetic simulation. In this method, the field components are expressed in differential terms derived from Maxwell's Equations, and then discretized to finite difference terms [44]. An eigenmode solver can be used to find the solutions to these equations, which allows each of the field components to be determined in addition to the propagation constant  $\beta$  (which is used to find  $n_{eff}$ ). In order to evaluate the modes in integrated waveguides, we use the mode solver in COMSOL. As an example, we can consider an integrated AlN waveguide with a thickness of 400 nm and width of  $1.3 \,\mu$ m, encapsulated by silicon dioxide cladding layers at a free space  $\lambda$  of 1.55 µm. The highest refractive index TE mode (corresponding to the fundamental guided mode) is shown in Figure 2.5. The effective index of this mode is simulated to be 1.67. The same problem can be solved using the effective index method, where a = v = 0, and the dispersion relationship in Figure 2.4 is used to produce a similar value of 1.68.


Figure 2.5: TE polarized mode for integrated AlN waveguide with  $n_{\text{eff}} = 1.67$ 

### 2.2.2 FDTD simulation and material model

Similar to the eigenmode solver, the finite difference time domain (FDTD) method uses a discretization of Maxwell's equations in a uniform grid to produce solutions to electric and magnetic field propagation in two-dimensional and three-dimensional structures. It is often difficult to produce analytical solutions in these cases, and the FDTD method can in theory handle any structural geometry, at the expense of computation time and memory. For the grating coupler however, FDTD is a very useful tool in evaluating the transmission characteristics as a function of the numerous parameters involved, including grating period, duty cycle, input source pitch angle and cladding thicknesses. As the transmission response can be determined with respect to input wavelength, it is also possible to evaluate the bandwidth of a coupler design. In this thesis, we have made use of commercial software Lumerical FDTD Solutions, in all the simulations for grating coupler transmission.

Grating couplers are simulated with a two-dimensional geometry along the cross-section of the grating and connecting waveguide, which reduces computation time but still appropriately models the behavior of the device. The simulation region is defined with a perfectly matched layer (PML) boundary, which confines the computational area and the fields inside. Sources and detectors can be defined anywhere inside the simulation region, in which the source type and time or frequency domain monitor can be specified. All simulations in this thesis assume a Gaussian source. These collect the information for electric and magnetic field propagation, which is used to measure the transmission response (as a ratio of power) and plot the spatial profile of the structure. The grating structure itself is typically meshed with a finer dimension grid (of cell size 30 nm) to provide a higher accuracy for the field propagation in the grating region specifically (and not requiring a fine resolution mesh for the entire structure). A setup for this is shown in Figure 2.6.



Figure 2.6: FDTD simulation setup and spectroscopic ellipsometry extraction of Cauchy coefficients for sputter 400 nm AlN thin film on 4" silicon wafer

Finally, we must define a material model for our waveguide. Throughout this thesis we will consider polycrystalline AlN thin films deposited with a Tegal Advanced Modular Sputtering (AMS) plasma vapor deposition tool. In order to characterize the optical properties of this AlN, 400 nm thin films were sputtered on silicon wafers. Spectroscopic ellipsometry measurements were then collected over a wavelength range of 400 nm – 1700 nm (Woollam M2000). The measurements were fit to Cauchy's dispersion equation [45]

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$$
(2.9)

where  $n(\lambda)$  is the refractive index as a function of wavelength, and A, B and C are the coefficients for the material. The extracted Cauchy coefficients are  $A=2.0353\pm8.03\times10^{-4}$ ,  $B=0.0124\pm2.39\times10^{-4}$ , and  $C=0.0006\pm3.28\times10^{-5}$  for the AlN thin films. These parameters were then used to define an AlN material model in Lumerical. The data with coefficients mapped as a function of wafer location are also shown in Figure 2.6.

# 2.3 Free space coupled visible spectrum AIN gratings

As a result of the wide bandgap in AlN, the transparency window extends well into the ultraviolet range. Therefore, it is possible to produce integrated waveguides and couplers that operate in the visible spectrum. To test this experimentally, a simple structure was considered in which gratings were defined in a 150 nm thick AlN thin film sputtered directly on silicon. In order to produce waveguiding in the AlN, a cladding layer is typically required of lower refractive index, as described in the preceding sections. To simplify the fabrication involved, the waveguides and integrated grating structure were intended to be fully released from the substrate through XeF<sub>2</sub> etching, with air serving as the surrounding material. Additionally the gratings were designed to be fully etched, such that the pattern definition could be done in a single lithography step. The structure was simulated in Lumerical, in which a variety of dimensions for grating period ( $\Lambda$ ) with 50% duty cycle were considered that would produce transmission in the wavelength range of the tunable laser source. The input light is coupled through free space, where numerical aperture (NA) of the source is 0.25. Simulated transmission for a single grating as well as scanning electron microscope (SEM) images of the fabricated devices are shown in Figure 2.7.



Figure 2.7: FDTD simulation for transmission through fully suspended (XeF<sub>2</sub> released) AlN visible wavelength gratings and SEM images of the structure. Bottom right: 100 nm coupling gap in waveguide also demonstrated in selected devices.

To test these structures, the free space optical setup shown in Figure 2.8 was used. A tunable Ti:Sapphire laser with a harmonic generator is used to generate the input light in the range of 350 – 500 nm. After it is guided through free space and focused on the input grating, the output is collected at a charged coupled device (CCD). Photon counts for the transmission intensity (in arbitrary units) can be made by focusing the output light on a lensed optical fiber which feeds into the CCD detector. Visible spectrum images for the transmission are also shown in Figure 2.8, in which the output coupling light intensity is maximized for the 440 nm wavelength. Although the transmission efficiencies were not sufficient to measure the modulation of end-coupled optical waveguides separated by a gap, this experiment provides a good example of optical waveguiding in AlN thin films. The setup however is somewhat complicated, and not readily amenable to configuration for RF probing. Thus we consider the fiber-array based approach described in the following section, which is used for all subsequent experiments.



Figure 2.8: Experimental setup and optical images collected from testing of visible wavelength gratings

# 2.4 Fiber array based setup

Standard single mode fiber (SMF) is designed for operation at 1.55  $\mu$ m and 1.3  $\mu$ m – corresponding to the minimum losses exhibited in silica. Most optical communication systems are thus designed to operate in the conventional or "C" band of 1530 – 1570 nm [46]. In order to facilitate wafer scale device testing, the V-groove array is a commonly used assembly which holds any number of optical fibers at a fixed separation. This allows convenient alignment capability to the input and output ports of a device, namely our integrated grating couplers. The SMFs are laid in the grooves of the base (in channels that resemble a "V" from the end face) and

covered with a Pyrex glass lid. While this may obscure a large portion of the surface for the device under test, the use of the V-groove assembly is very convenient, particularly when considering its compatibility to be mounted on a standard RF probe station. The selection of the fiber array based setup thus motivates the design choices for the AlN gratings we develop.



#### 2.4.1 Design and simulation

Figure 2.9: C-band grating geometry and TE mode (obtained via COMSOL FEM) in AlN slab waveguide (at location of gratings)

Aluminum nitride has a refractive index of approximately 2.0 at wavelengths in the telecommunications C-band. A silicon-dioxide cladding (refractive index = 1.45) was used on the top and bottom surfaces of the AlN layer to provide index matching with a standard SMF and low leakage into the underlying silicon substrate. The moderate index of the AlN (as compared to semiconductors such as silicon and indium phosphide) is advantageous for producing gratings with larger period that do not require partial etching. The grating geometry is shown in Figure 2.9, where the duty cycle of the grating period ( $\Lambda$ ) is fixed at 50%. Using Eq. (2.4), where the cover layer is now silicon dioxide, an approximate value for  $\Lambda$  may be determined. We fix the thickness of the AlN layer to 400 nm and the input angle of the fiber to 8°. Experimental

considerations were used in the setting of these parameters. The 400 nm thick AlN layer is selected based upon the optimized geometry of the silicon nitride grating coupler [47]. This thickness is also compatible with available microfabrication processing techniques, making it ideal for the production of optical and micromechanical structures which shall later be synthesized using the same process. Likewise, 8° is a polish angle that is commonly available in glass V-groove fiber arrays for testing silicon-on-insulator photonic structures, and may also be applied to this context. Testing was carried out at telecom wavelengths, *i.e.*  $\lambda = 1550$  nm. Using a mode solver, the effective index of the AlN waveguide is 1.74 as also shown in Figure 2.9. Here, the effective index was calculated with COMSOL for the waveguide at the location of the grating, where the width of the AlN slab is 17.5 µm and its height 400 nm. When averaged with the oxide, which accounts for 50% of the grating, this yields a n<sub>eff</sub> of approximately 1.6. As a result, a grating period of 1.2 µm is used. Given the duty cycle, each grating tooth and fully etched spacing is 600 nm wide.

A 2-D FDTD simulation was run for the grating geometry shown in Figure 2.9 with Lumerical. A bottom cladding layer of 2.15  $\mu$ m and a top of 2.0  $\mu$ m were used in the analysis. The exact thickness of these layers has a direct impact on the value of the center wavelength of the coupler because of reflection from the silicon substrate. For this reason, these thickness values were confirmed by direct measurement of the films after fabrication. In the simulation, a 9- $\mu$ m fiber core (also SiO<sub>2</sub>, with refractive index = 1.45) is butt-coupled to the surface of the top cladding at 8° incidence angle and centered over the ~4th grating tooth from the waveguide. The source injected through the core is a transverse-electric (TE) polarized Gaussian beam with 11  $\mu$ m mode width between 1/e<sup>2</sup> points. Since the fiber core is surrounded by a cladding, and encapsulated in a glass V-groove array in the experiment, the refractive index of the surrounding region on the top surface is also set to 1.45. The grating itself consists of 13 periods, and the entire structure rests upon a polished silicon substrate. In the simulation, the grid size was set to

30 nm, and the source wavelength was swept between 1.50  $\mu$ m and 1.65  $\mu$ m. A 1-D transmission monitor placed in the AlN layer (4  $\mu$ m away from the gratings) was used to record the power transmission in the waveguide relative to the source. Results of the FDTD simulation are shown in Figure 2.10. Transmission monitor data is plotted in dB to provide the transmissivity of a single grating with respect to wavelength. The peak transmissivity simulated is -4.8 dB, and the 1-dB bandwidth of the grating is 60 nm. In this demonstration, the selected geometry peaks at 1613 nm, but this value can be controlled by changing the grating period and/or fiber angle.



Figure 2.10: Electric field profile and transmissivity of a single grating from FDTD simulation

### 2.4.2 Fabrication

Grating structures were designed to require a single lithography step and such that testing could be carried out with a standard glass V-groove assembly holding single mode fibers polished at 8 degrees. Fibers in the V-groove are separated by 250  $\mu$ m, and therefore the gratings are also laid out on the chip to have the same spacing to align to the input and output fibers. The two gratings are connected by a U-shaped waveguide, which is tapered from 17.5  $\mu$ m at the gratings to 1.3  $\mu$ m through the curved section. In order to provide a gradual confinement of the guided mode in the waveguide, a tapered section is used to reduce the waveguide width from the gratings

to the curved portion. The length of this taper is 900  $\mu$ m. An optical image of the device and the process steps are shown in Figure 2.11.



Figure 2.11: Fabrication process and optical image of gratings with connecting U-shaped AlN waveguide

To fabricate the structures, PECVD oxide is first deposited on a bare silicon wafer to serve as the bottom 2.15  $\mu$ m cladding. The aluminum nitride layer (400 nm) is then sputter deposited on the cladding. X-ray diffraction measurements on the AlN film confirmed that it is multigrained with c-axis orientation, as the (0002) symmetric diffraction index peaks at 36° on the rocking curve with a full width at half maximum (FWHM) value of 6°. Although the measured FWHM should have a minimal impact on the piezoelectricity of the AlN films [48], further optimization to the AlN on oxide recipe is provided in later sections to improve the orientation of the c-axis film, and optimize device performance. Another thin layer of PECVD oxide (200 nm) is deposited on the AlN to serve as an etching hard-mask layer. After this, ZEP520A resist is spun and patterning is done with an Elionix 7500EX electron beam lithography system. The structural outline is defined with the ZEP520A (a positive tone e-beam resist), and 7  $\mu$ m of isolation is defined on all edges of the waveguide. The hard-mask is first etched with CHF<sub>3</sub> chemistry, and finally the aluminum nitride layer is etched with a  $Cl_2$  and  $BCl_3$  based inductively coupled plasma reactive ion etch. After the etching is complete, a top layer of cladding (2.0 µm) of PECVD oxide for better index matching is deposited on top of the structures. Images of the cladded gratings with the waveguide and scanning electron microscope images of the gratings (unclad for clarity) are shown in Figure 2.12.



Figure 2.12: SEM images of fabricated AlN gratings

# **2.5 Experimental measurements**

The C-band gratings were tested with the use of the V-groove fiber array mounted on a manipulator arm and a semi-automatic probe station (Cascade Alessi REL-6100) to collect insertion loss measurements. The manipulator was also fitted with a goniometer in order to provide control of the pitch angle. A tunable laser source with a tuning range of 1500–1630 nm (Santec TSL-510) provided the input to the single-mode fiber. The fiber is fed through polarization paddles to select the TE mode injection into the gratings. The output fiber was connected to a power meter (Exfo PM-1103). Input power was kept fixed at 0 dBm, such that any power measured at the output in dBm describes the loss of the structure. The wavelength was swept between 1530 and 1630 nm in discrete steps of 0.1 nm, and the power meter output was

collected to determine the insertion loss of the entire structure (two gratings and the waveguide). This approach is used to characterize individual gratings, as well as coupled photonic structures (such as the resonators presented in Chapter 3). The test setup is shown in Figure 2.13.



Figure 2.13: Test setup for insertion loss measurements and optical image of sample substrate with V-groove array

### 2.5.1 Transmissivity characterization

The transmissivity of a single grating coupler is one-half of the total insertion loss measured. Reciprocity of the grating and waveguide structure was tested by reversing the input and output gratings in successive insertion loss measurements. Though slight variations occur in the transfer characteristic likely due to inevitable perturbations in the fiber coupler setup, the differences are negligible for characterizing the transmissivity of a single AlN coupler. Two sets of transmissivity data that demonstrate peak coupling and maximum bandwidth for a single grating coupler are shown in Figure 2.14. For the initial positioning of the fiber, the higher plot (blue) was produced, in which the peak transmissivity is -6.6 dB. This peak transmissivity value is only 1.8 dB lower than the simulated value. Due to the limitation of the tunable laser sweep, it was not possible to collect insertion loss measurements beyond 1630 nm. In order to demonstrate the full wide-bandwidth capability of the grating, the input pitch angle was increased, such that the peak would shift lower in wavelength. Hence, the lower plot (red) of Figure 2.14 was produced, which demonstrates a 1 dB bandwidth of 60 nm, making it one of the largest reported for a grating coupler butt-coupled to standard single-mode fiber [47]. Our measurement setup did not have fine angle controls. Coarse adjustment of the pitch and roll angles (around the nominal values of 8° and 0°, respectively), were used to produce the plots of Figure 2.14 that demonstrate the best performance.



Figure 2.14: Experimental measurements of grating transmissivity separately demonstrating peak transmission response (blue curve) and full 60 nm 1 dB bandwidth (red curve)

#### 2.5.2 Pitch angle variations

In order to demonstrate the experimental dependence of the transmissivity on the pitch angle, the V-groove was manually adjusted, and a side-mounted microscope was used to determine the approximate angle of incidence for the fibers. Data from the angle variance is presented in Figure 2.15. Pitch angle was varied in increments of approximately 1 degree, and the value of the pitch angle closest to each plotted line is shown in Figure 2.15. As the data shows, an increase in the pitch angle corresponds to a shift in the peak value of the transmission, such that at lower wavelengths, higher transmissivities are consistently measured for higher pitch angles. The V-groove array is itself beveled at 8 degrees, somewhat complicating the process of positioning the fibers to align accurately over the couplers. Measured transmissivity depends largely on the exact location and pitch angle of the fiber. A better response should be possible if accurate positioning with multiple degrees of freedom and sub-micron translational ability is available. In addition the use of an index matching oil may help further improve the demonstrated coupling efficiency as shown in [47].



Figure 2.15: Measurements of grating transmissivity as a function of pitch angle variation

# **Chapter 3 Photonic whispering gallery mode resonators**

The optical resonator is one of the fundamental structures used to capture and manipulate the flow of light. Much like its electronic and acoustic counterparts, the resonator is characterized by the ratio of the amount of energy it stores to the power it dissipates. In particular, optical microresonators provide spatial and temporal storage of this electromagnetic energy at a particular wavelength (or optical frequency) for a long period of time compared to the cavity's photon lifetime. This principle has allowed it to be employed towards a number of applications including stimulated emission [49]-[50], filtering [51]-[52] and sensing [53]. In general, an optical resonator may be classified in one of two categories, based on the mechanism by which light energy is confined. These include standing wave resonators, such as photonic crystal cavities or Fabry-Perot etalons, and traveling wave resonators such as rings or disks. Thanks to steady progress in microfabrication capabilities, both classes of resonator have been successfully implemented in integrated photonic devices with very high temporal confinement, as described by optical quality factors (O) on the order of  $10^4$  -  $10^8$  [54]-[55]. In this thesis, we consider structures that support a whispering gallery mode - a traveling wave mode which was first described by Lord Rayleigh for sound waves in St. Paul's Cathedral as early as 1910 [56]. Relevant parameters needed to describe the coupling of optical modes to the resonator are described in this chapter and extracted from experimental data. This will form the basis of our optomechanical resonator and consequently determines its optical modulation capacity.

# 3.1 Electromagnetic mode analysis

Propagation of electromagnetic energy in all media is fundamentally described by Maxwell's equations. If one introduces into Maxwell's equations the phasor terms  $E(r)e^{j\omega t}$  and  $H(r)e^{j\omega t}$  for the electric and magnetic fields respectively, the time dependence  $(e^{j\omega t})$  may be factored out and

separation of variables is accomplished (thereby isolating the spatially-varying fields of interest). The curl equations (Faraday's Law and Ampere's Law) may thus be expressed as follows:

$$\nabla \times E = -j\omega\mu_o H , \qquad (3.1)$$

$$\nabla \times H = j\omega\varepsilon_o n^2 E \,, \tag{3.2}$$

where  $\mu_o$  and  $\varepsilon_o$  represent the permeability and permittivity of vacuum respectively, and *n* is the complex refractive index in the media. Upon substituting one of the curl equations into the other, the two equations may be combined to yield the Helmholtz equation in terms of *E* or *H* as,

$$\nabla \times \nabla \times E = \left(\frac{\omega}{c}\right)^2 n^2 E, \text{ or}$$

$$\nabla \times \left(\frac{1}{n^2} \nabla \times H\right) = \left(\frac{\omega}{c}\right)^2 H$$
(3.3)

in which  $c = \sqrt{\frac{1}{\mu_o \varepsilon_o}}$  represents the speed of light in vacuum. By solving the Helmholtz equation

in the resonator structure with the appropriate boundary conditions, one can determine the resonance frequency and mode profile for the resonator. In practice, the photon lifetime in a dielectric resonator is finite as a result of intrinsic leakage of energy from the optical mode as well as fabrication or material imperfections. As the total electromagnetic energy of the  $n^{\text{th}}$  mode  $U_n$  decays over time, the resonator is said to be lossy, and  $U_n$  has the approximate form [57]

$$U_{n}(t) = U_{n,0} e^{-\omega_{n} t/Q_{n}}$$
(3.4)

Here,  $\omega_n$  is the resonant frequency of the  $n^{\text{th}}$  mode, and we define a dimensionless quantity known as the quality factor  $Q_n$  to describe how well the resonator stores energy. The quality factor is different for each mode, and larger Q-values are associated with higher quality resonances with lower losses. In the absence of loss, the Q becomes infinite. An expression for the quality factor can also be obtained by expressing the power lost  $(P_n)$  for the  $n^{th}$  mode, averaged over one cycle. This results in

$$P_n = -\frac{dU_n}{dt} = \frac{\omega_n U_n}{Q_n}$$
(3.5)

Re-arranging terms produces a general definition for Q,

$$Q_n = \omega_n \frac{U_n}{P_n} = \frac{\text{Resonator stored energy}}{\text{Average energy lost per cycle}} \text{ (for the nth mode)}$$
(3.6)

Up to this point we have assumed  $\omega_n$  is a real frequency. In the presence of losses, the resonant frequency  $\omega_n$  must be represented as a complex frequency. This is commonly expressed as  $s_n$ , where

$$s_n = j\omega_n - 1/\tau_o \tag{3.7}$$

and  $\tau_o$  represents the cavity's photon lifetime. Thus we can see that in the absence of losses, the photon lifetime is infinite, and  $e^{s_n t}$  simply reduces to  $e^{j\omega_n t}$ . The time-dependent electric and magnetic fields may then be expressed as

$$E_n(r,t) = \operatorname{Re}\left\{E_n(r)e^{s_n t}\right\} = e^{-t/\tau_o} \operatorname{Re}\left\{E_n(r)e^{j\omega_n t}\right\}$$

$$H_n(r,t) = \operatorname{Re}\left\{H_n(r)e^{s_n t}\right\} = e^{-t/\tau_o} \operatorname{Re}\left\{H_n(r)e^{j\omega_n t}\right\}$$
(3.8)

As the average electric and magnetic field energies are proportional to the field intensities  $|E_n(r,t)|^2$  and  $|H_n(r,t)|^2$ , both are in fact proportional to  $e^{-2t/\tau_o}$  and the total resonator energy may be expressed as

$$U_n(t) = U_{n,o} e^{-2t/\tau_o}$$
(3.9)

As a result, combining (3.6) and (3.9), we can express the photon lifetime in terms of Q as follows,

$$Q_n = \frac{\omega_n \tau_o}{2}.$$
(3.10)

The spatial profile of the electric field distribution in a dielectric microdisk resonator surrounded by vacuum is shown in Figure 3.1 for an example guided mode. The energy is primarily localized at the perimeter of the microdisk, and will be of interest in considering the order of the guided mode. Any such mode in which the electromagnetic wave is confined and guided along the circumference of the resonator is also called a whispering gallery mode (WGM).



Figure 3.1: Resonator geometry in cylindrical coordinates and electric field profile of whispering gallery mode in  $r\phi$  plane

#### 3.1.1 Optical resonance condition

The most common geometries to implement a traveling wave resonator are a disk or ring/annulus geometry. This type of resonator has axial symmetry about its central axis – which is defined as the center of the circle in the plane of the resonator. In the cylindrical coordinate system, the unit vectors (r,  $\phi$  and z) correspond to the radial, azimuthal and vertical directions, respectively. As a result of its circular symmetry, one can expect the modes to exhibit a periodic behavior as a function of the azimuthal angle ( $\phi$ ). The field distributions can thus be written as

$$E = E_r(r, z), E_{\phi}(r, z), E_z(r, z)e^{j\omega t - jm\phi}$$
  

$$H = H_r(r, z), H_{\phi}(r, z), H_z(r, z)e^{j\omega t - jm\phi}$$
(3.11)

The integer m indicates the azimuthal order of the mode. A particular mode may also exhibit a radial mode order (denoted by p), which indicates the number of lobes in the spatial distribution normal to the plane of the resonator. This is indicated in Figure 3.2. A mode with p = 1 is called the fundamental mode, and produces the greatest confinement among the radial modes.



Figure 3.2: Increasing radial mode order of WGM resonances

For consecutive modes of an optical cavity (in which the radial order p is the same), the amount of frequency spacing is called the free-spectral range (FSR). In general, the FSR is indirectly related to the physical size of the resonator. That is, the FSR increases as the cavity path length is reduced (this is similar to the case of a Fabry-Perot etalon). The roundtrip travel of the wave at the resonator's perimeter can be explained through total internal reflection (TIR) occurring at the sidewalls. After a complete roundtrip, the resonance condition is met when the phase change in the roundtrip is a multiple of  $2\pi$  (*i.e.* the wave is in phase with one at the start of the trip, generating a constructive interference). If the propagation constant of the traveling wave inside the resonator is represented by  $\beta$ , a resonance can occur for a certain mode order *m*, where the condition

$$\beta L = 2\pi m \tag{3.12}$$

1

is satisfied. Here, *L* is the effective length or circumference of the resonator. The propagation constant may also be expressed in terms of the effective index of the traveling mode ( $n_{eff}$ ) and the wavenumber in vacuum ( $k_o$ ) as,

$$\beta = n_{eff} k_o = n_{eff} \frac{2\pi}{\lambda_o} = n_{eff} \frac{\omega_o}{c}$$
(3.13)

where  $\lambda_o$  and  $\omega_o$  represent the resonant wavelength and frequency, respectively. In the disk or ring geometries of interest, the path length is  $L = 2\pi R$ , where *R* is the outer radius. Thus, the optical resonance condition for such a structure may be written as,

$$n_{eff} 2\pi R = m\lambda_o$$
, or  
 $n_{eff} R = m \frac{c}{\omega_o}$ 
(3.14)

in terms of wavelength or frequency, respectively.

#### 3.1.2 Axisymmetric mode simulation

While there exist some analytical solutions for the Helmholtz equations in microdisk and microring resonators, it is very difficult to estimate accurate resonance frequency and electromagnetic mode properties. For practical structures, finite element modeling (FEM) analysis provides a good approach to extract information about the field components in the resonator, while reducing required computational resources [58]. By making use of the axial symmetry of the problem, it is possible to reduce the 3D geometry to a 2D geometry with variables r and z. In order to simulate the modes of the WGM resonator, we follow the method outlined in references [59], [60] applied to COMSOL. The basic approach is briefly outlined here – although the complete method and example modeling may be found in the references. Since the magnetic field strength H is continuous across interfaces (assuming negligible magnetic susceptibility in the dielectrics), it is generally easier to solve for H as opposed to the electric

field strength E. In the axisymmetric case, the time-independent part of the magnetic field strength takes the form,

$$H(r) = e^{jm\phi} \left\{ H^{r}(r,z), jH^{\phi}(r,z), H^{z}(r,z) \right\}$$
(3.15)

where the *j* term is inserted in the field's azimuthal component to allow all three component amplitudes  $\{H^r, H^{\phi}, H^z\}$  to be represented as a real amplitude multiplied by a common phase factor in the subsequent solutions. By substituting this expression into a modified version of the vector Helmholtz equation, it is possible to solve for the individual components of the magnetic and electric fields, by applying the appropriate boundary conditions. Namely, this includes the satisfaction of Gauss' and Faraday's Laws at the walls of the resonator in cylindrical coordinates, which requires  $\mathbf{H} \cdot \hat{\mathbf{n}} = 0$  and  $\mathbf{E} \times \hat{\mathbf{n}} = 0$  (where  $\hat{\mathbf{n}}$  indicates the wall's surface normal unit vector) for continuity.



Figure 3.3: Transverse electric mode solution ( $TE_{p=1,m=132}$ ) and false color intensity plots of field components for 20 µm radius AlN microdisk

The setup and field components for a typical WGM resonator simulated in COMSOL are shown in Figure 3.3. For this case, we consider a 400 nm thick, 20 µm radius AlN microdisk

resonator encapsulated in silicon dioxide. In the setup to the problem, we specify the materials based on the relative permittivities of the dielectrics and select a mode number (m) for the simulation based on an expectation for the resonance frequency (or wavelength). This sets the corresponding effective index, which then allows us to identify a family of modes with the same transverse profile but different azimuthal mode order (m) by comparing the FSR for consecutive resonances from the experimental data. In general, optimum coupling from a waveguide to the resonator is generated when there is phase matching between the waveguide mode and the resonator mode [61]. The fact that different mode families exhibit different FSRs is equivalent to assigning a different effective refractive index to each mode family. In this example, we consider one of the fundamental modes for the microdisk for m = 132, corresponding to a frequency of 190.1 THz (or 1577 nm). The magnetic and electric field components are shown in Fig. 3.3, in addition to the quasi transverse electric (TE) (or TE-like). This term originates from the fact that the electric field is primarily projected on the in-plane components ( $E^r$  and  $E^{\phi}$ ), while the out of plane component  $(E^{z})$  is very small. We will primarily modes with TE polarization in the WGM resonators as the grating couplers and bus waveguides with which the coupling occurs are also designed for TE operation. In addition to matching with the experimental resonator data, simulating the WGM resonance also allows us to understand how the field components will interact with the micromechanical structures that will be considered.

# 3.2 Waveguide to Resonator Coupling

One of the critical requirements for all resonator applications is controlling the coupling of energy into and out of the resonator structure. For integrated applications, we consider the use of the waveguides presented in Chapter 2. By making use of the evanescent electromagnetic wave carried in the waveguide, it is possible to engineer proper coupling to a resonator structure by laterally side-coupling the waveguide [51], or vertically positioning it above or below the resonator [62]. While the vertical coupling approach relaxes requirements for stringent control of

the waveguide-resonator coupling gap lithography, it presents additional complexities in terms of additional fabrication layers and planarization steps. As a result, it is possible to fabricate sidecoupled resonators in a single lithography step along with the waveguides, and it is the approach we follow here.

In order to analyze the coupling of modes, we can follow the general formalism developed by Haus through perturbation analysis [63]. The temporal response for an isolated resonator can be written as

$$\frac{da}{dt} = \left(j\omega_o - \frac{1}{\tau_o}\right)a \tag{3.16}$$

where *a* is normalized such that its squared magnitude is equal to the resonator energy and  $\tau_o$  is the cavity lifetime. Since  $|a|^2$  decays as  $exp(-2t/\tau_o)$  (as noted for Equation 3.9), and the time rate of energy decrease goes into the dissipation power  $P_d$ , we can write,

$$\frac{d|a|^2}{dt} = -\frac{2}{\tau_a}|a|^2 = -P_d$$
(3.17)

In the case where the resonator is coupled to an external waveguide, the decay rate of the mode and the time rate of energy change are modified to:

$$\frac{da}{dt} = j\omega_o a - \left(\frac{1}{\tau_o} - \frac{1}{\tau_e}\right) a, \text{ and}$$

$$\frac{d|a|^2}{dt} = -2\left(\frac{1}{\tau_o} - \frac{1}{\tau_e}\right) |a|^2$$
(3.18)

respectively, where  $1/\tau_e$  represents the additional rate of decay due to escaping power (extrinsic to the resonator). Now, considering the waveguide carries a wave traveling toward the resonator of amplitude  $S_{in}$ , where the impinging wave serves as a drive for *a*, the resonator's time response is further modified to

$$\frac{da}{dt} = j\omega_o a - \left(\frac{1}{\tau_o} - \frac{1}{\tau_e}\right) a + KS_{in}$$
(3.19)

where *K* represents the degree of coupling (coupling coefficient) between the resonator and the wave  $S_{in}$ . The term  $S_{in}$  is normalized such that  $|S_{in}|^2$  is equivalent to the power carried by the incident wave. This is shown for the case of a microdisk in Figure 3.4.



Figure 3.4: Side coupling of an input wave Sin to a microdisk cavity

The resonator can support traveling waves in both the clockwise (CW) and counterclockwise (CCW) directions. The CW and CCW modes are orthogonal to one another and do not exchange energy unless there is considerable perturbation in the resonator (such as sidewall roughness). Assuming no CW-CCW coupling and no reflected power ( $S_{ref} = 0$ ), the forward mode of the waveguide will couple energy to the CW mode of the resonator. If the source is at frequency  $\omega$  we find from (3.19),

$$a_{cw} = \frac{KS_{in}}{j(\omega - \omega_o) + \frac{1}{\tau_o} + \frac{1}{\tau_e}}$$
(3.20)

In addition, we can express the following relationships between the coupling coefficient *K*, the extrinsic time constant  $\tau_e$ , and the waveguide-mode amplitude in the forward direction after interaction with the resonator (*S*<sub>out</sub>):

$$S_{out} = S_{in} - K^* a_{cw}$$

$$|K| = \sqrt{\frac{2}{\tau_e}}$$
(3.21)

Thus, by combining (3.20) and (3.21), we can find an expression for the waveguide transmission as a ratio of the input and output amplitudes:

$$\frac{S_{out}(\omega)}{S_{in}(\omega)} = \frac{j(\omega - \omega_o) + \frac{1}{\tau_o} - \frac{1}{\tau_e}}{j(\omega - \omega_o) + \frac{1}{\tau_o} + \frac{1}{\tau_e}}$$
(3.22)

As noted in (3.10) for the definition of a quality factor corresponding to a particular mode n, we can assign an intrinsic quality factor  $(Q_o)$  corresponding to the photon lifetime  $(\tau_o)$  and an extrinsic, or coupling quality factor  $(Q_c)$  corresponding to the extrinsic time constant  $(\tau_e)$  as follows,

$$Q_o = \frac{\omega_o \tau_o}{2} \& Q_c = \frac{\omega_o \tau_e}{2}$$
(3.23)

Therefore the transmission expression can be re-formulated in terms of the Q-factors as

$$\frac{S_{out}(\omega)}{S_{in}(\omega)} = \frac{\frac{j2(\omega - \omega_o)}{\omega_o} + \frac{1}{Q_o} - \frac{1}{Q_c}}{\frac{j2(\omega - \omega_o)}{\omega_o} + \frac{1}{Q_o} + \frac{1}{Q_c}}$$
(3.24)

The intrinsic and coupling quality factors may thus be extracted from experimental data by fitting the transmission function to a given resonance. The full width at half maximum (FWHM) of the transmission about its resonance frequency  $\omega_o$  is given by

$$\Delta \omega_{FWHM} = \frac{\omega_o}{Q_L} \tag{3.25}$$

where  $Q_L$  is defined as the loaded quality factor of the waveguide-resonator coupling structure. By applying the conversion factor  $\Delta \omega = \frac{c}{\lambda^2} \Delta \lambda$ , we can also express the loaded quality factor in terms of wavelength as

$$Q_L = \frac{\lambda_o}{\Delta \lambda_{FWHM}}$$
(3.26)

which is useful for extracting quality factors from transmission measurements where the wavelength is swept. The loaded quality factor can also be expressed in terms of the intrinsic and coupling quality factors as

$$\frac{1}{Q_L} = \frac{1}{Q_o} + \frac{1}{Q_c}$$
(3.27)

Using these factors to characterize resonances, we can identify three regimes of operation for a given waveguide-resonator structure. The first is the critical coupling regime, in which  $Q_o = Q_c$ . In this case  $Q_L = Q_o/2$ , and the transmission magnitude would drop to zero at the resonance frequency – exhibiting a maximal possible extinction. As a result, this is also the regime of operation most desirable for generating a maximum amount of optical modulation through perturbations, as we shall consider in the subsequent sections. The second regime is under-critical coupling, in which  $Q_o < Q_c$  and the coupling is weak. Finally, there is over-critical coupling, in which  $Q_o > Q_c$  and the coupling strength is high. While there are multiple parameters that can be considered in properly engineering the coupling coefficient K (and correspondingly the  $Q_c$ ) [64]–[66], one of the critical dimensions is the gap between the waveguide and the resonator. In the case where all other parameters (such as waveguide width, interaction length, etc.) are fixed, the coupling strength is directly related to the waveguide-resonator gap. Thus by varying the gap size for identical resonators, it is possible to identify the various regimes of operation. This approach will be considered in the following section.

### **3.3 AlN microdisk resonators**

The microdisk is one of the traveling wave resonator geometries most commonly studied in the literature [49], [64]–[66]. As a platform toward further optomechanical device integration, we developed microdisk resonators in AlN to study their coupling, losses and power handling capabilities. These concepts are also applied in the analysis of the acousto-optic modulator.

#### 3.3.1 Design and fabrication

As noted previously, AlN exhibits similar optical features to silicon nitride. The refractive index of the material at 1550 nm is roughly 2.0. In order to provide confinement of the optical modes in the resonator, we make use of silicon dioxide cladding layers (refractive index = 1.45) and apply the same material stack we employed to demonstrate the gratings. Evanescent modes guided in wire waveguides can thus couple into the disk structure placed sufficiently close to them. The use of cladding layers also confines the electromagnetic energy less tightly, which relaxes the lithography requirements (which will be noted in the released devices). In this work, the AlN waveguides are 400 nm thick and 850 nm in width. Silicon dioxide layers 2.25  $\mu$ m and 1.0  $\mu$ m thick are used for the bottom and top cladding layers, respectively. In order to study the coupling conditions, we fabricated microdisks of 20  $\mu$ m radius with gap (disk to waveguide distance) sizes varying from 50-700 nm in increments of 50 nm.



Figure 3.5: AlN microdisks with various waveguide-resonator gap spacings and fabrication process

Using the grating couplers presented in Chapter 2, light is coupled into AlN wire waveguides (and thus evanescently coupled into the microdisks). As the gratings do not require partial etching, patterning may be performed in a single step in conjunction with the resonator, resulting in a simple fabrication process. In order to simplify the lithography of the gratings, waveguides and microdisks, and define them all in a single  $(300 \ \mu m)^2$  writing field (consequently improving the feature resolution, which is required for the definition of small gap dimensions), the waveguide taper length is reduced. The gratings are separated by the 250  $\mu m$  pitch required for the fiber V-groove array, and connected by the U-shaped waveguide, tapered from 17.5  $\mu m$  at the gratings to 850 nm in the straight section. 850 nm is selected as a width for the bus waveguide to provide single mode confinement, similarly to what has been demonstrated in silicon nitride [52]. Disks are placed adjacent to the straight waveguide for coupling of evanescent modes. An optical microscope image of the waveguide/disk structures with gratings may be seen in Figure 3.5.



Figure 3.6: Unclad SEM images of the fabricated AlN microdisk, 200 nm waveguide-resonator gap and etch sidewall angle (clockwise from top left)

Fabrication of these structures is done by first depositing the bottom oxide cladding layer on a bare silicon wafer. 2.25  $\mu$ m of Plasma Enhanced Chemical Vapor Deposition (PECVD) oxide was deposited. Next, 400 nm of AlN is sputter coated on the oxide. A rocking curve measurement confirmed the AlN film is c-axis oriented with a full width at half maximum (FWHM) value of 6° at the (0002) peak. The low orientation in the AlN film is partially on account of using a lower quality PECVD oxide for the bottom cladding (which itself has a measured roughness of 7.3 nm), and a non-optimized AlN on oxide recipe. Development of an improved recipe is discussed in Chapter 4. Another 200 nm layer of PECVD oxide is then deposited on top of the AlN to serve as the etching hard mask. Electron-beam lithography is used to define all the structures. A positive e-beam resist, ZEP-520A is spun on the AlN on insulator wafer, and then patterned with the use of an Elionix 7500EX system. Since ZEP-520A is a positive resist, the waveguide and resonator structures are defined by etching away the AlN in the region surrounding the edges of the desired geometries. In order to isolate the waveguide and disk from the AlN surface, a minimum of 5  $\mu$ m

isolation is maintained around the edges of the structures, as seen in Fig. 3.5. Following the resist development, the oxide hard mask is etched in a parallel-plate reactive ion etcher with CHF<sub>3</sub> based chemistry. Once the hard mask is patterned and e-beam resist residues are removed, the AlN layer is patterned in a  $Cl_2$  and  $BCl_3$  based inductively-coupled plasma etch step. Finally, an additional 1.0 µm of PECVD oxide is deposited on top of the AlN layer to serve as the top layer cladding for the structures. These steps are pictorially depicted in Figure 3.5. Scanning electron microscope (SEM) images of the disk, waveguide and grating structures may be seen in Figure 3.6. The sidewall angle for the etch process was determined from SEM images to be approximately 7°.

3.3.2 Experimental characterization



Figure 3.7: Transmission spectrum and loaded Q for 300 nm microdisk-waveguide gap

Testing of the microdisks is carried out with the V-groove array mounted on a Cascade Alessi REL-6100 probe station to allow micrometer scale alignment to input and output grating couplers. Light is launched into the device with a tunable laser source (Santec TSL-510) that has a tuning range of 1500-1630 nm. Polarization paddles are used with the input fiber to select transverse electric (TE) mode injection into the gratings. The output fiber is then connected to a power meter (Exfo PM-1103) to make insertion loss measurements for the entire structure. An

un-normalized transmission spectrum of the 20 µm radius microdisk with a 300 nm diskwaveguide gap is shown in Fig. 3.7a. In this sweep of 1520-1620 nm in 200 pm steps, the laser output is kept fixed at 0 dBm. The insertion loss of the device varies as a function of wavelength, based on the transfer characteristic of the grating couplers. As it is visible in the plot, the coupling efficiency of a single coupler varies between -11 to -7.1 dB. A finer resolution sweep (1 pm steps) for one of these modes is reported in Fig. 3.7b. This data is normalized, and then leastsquare fit to a Lorentzian function, which allows a value for the full-width at half-maximum (FWHM) to be determined. The FWHM of the transmission dip ( $\Delta\lambda$ ) is thus used to determine the loaded quality factor ( $Q_L$ ) for the resonator using Eq. (3.26), where  $\lambda_o$  is the wavelength corresponding to the center of the resonance dip. In addition, as the power transmission measurement monitors changes in the square of the  $S_{out}/S_{in}$  expression shown in (3.24), we can express the resonator's response as:

$$T(\omega) = \frac{P_{out}}{P_{in}} = \frac{|S_{out}|^2}{|S_{in}|^2} = \left| \frac{\frac{j2(\omega - \omega_o)}{\omega_o} + \frac{1}{Q_o} - \frac{1}{Q_c}}{\frac{j2(\omega - \omega_o)}{\omega_o} + \frac{1}{Q_o} + \frac{1}{Q_c}} \right|^2$$
(3.28)

Thus, by using the value for  $Q_L$  and expressions (3.26) and (3.28), a least square fit of the data to the transmission function of Eq. (3.28) allows  $Q_o$  and  $Q_c$  to be extracted for the resonator as well. In the particular data shown in Fig. 3.7(b), a maximum extinction ratio (defined as the difference between the transmission level at resonance vs. off-resonance) of 19.2 dB is observed, indicating that the resonator is critically coupled. In the ideal critical-coupling condition,  $Q_o = Q_c$ , and thus the loaded Q is approximately one-half the intrinsic value. Given the  $\Delta\lambda = 56$  pm observation in Fig. 3.7(b)  $Q_L = 28,350$ , and thus we estimate  $Q_o = 56,700$  for the AlN microdisk.



Figure 3.8: Loaded quality factor and maximum rejection ratio for various microdisk-waveguide gaps

Critical coupling was therefore observed in resonators with a 300 nm waveguide-disk gap. Measurements for loaded optical quality factors from two separate substrates with the same fabrication process as a function of gap size are shown in Fig. 3.8. Fitting of the resonance data to Equations (3.24) and (3.28) confirms that disks with a separation of 50-250 nm are overcoupled, while disks with 350-700 nm separation operate largely in the undercoupled regime. This can also be observed by monitoring the change in the extinction ratio (or rejection at resonance) for the different gap spacings. The rejection ratios are plotted in Fig. 3.8 as well, which also allows the data to be separated into the overcoupled and undercoupled regimes for gap sizes less than or greater than 300 nm, respectively.

As seen in Fig. 3.7, the measured free spectral range (FSR) for the resonator is approximately 9.82 nm. The group index  $n_g$ , can be determined from the FSR and the resonator path length (L) as  $n_g \approx \lambda_o^2/(FSR)(L)$ . In the critical coupling condition, another expression for  $Q_L$  is,

$$Q_L = \frac{1}{2} Q_O = \frac{\pi n_g}{\lambda_o \alpha_{disk}}$$
(3.29)

where  $\alpha_{disk}$  is the total propagation loss per unit length in the disk [67]. The group index is 2.02 near  $\lambda_o = 1577$  nm. From equation (3.29), we estimate  $\alpha_{disk} = 6.15$  dB/cm. This figure is an upper bound of the propagation losses. The characterization of the film surface roughness by atomic force microscopy (AFM) yielded a root mean square (rms) roughness of 8.8 nm. Therefore it is very likely that the majority of losses are caused by grain boundary scattering and scattering due to sidewall roughness.



Figure 3.9: AFM measurement of microdisk AlN film on PECVD oxide surface roughness

### 3.3.3 Power sweeping

It is interesting to note that the high extinction ratio observed in the critically coupled resonator also remains relatively constant across coupled powers and the device behaves linearly even at high power levels. Laser input power was initially set to 0 dBm, but was also varied up to a maximum of +14 dBm. As seen in Fig. 3.10(a), a red shift of transmission dip center wavelength ( $\lambda_o$ ) occurs with increasing optical input power ( $P_i$ ). In this case, the gratings' loss is subtracted out. The red shift likely occurs because of heating of the disk and change in refractive index. The contribution to the red shift from the Kerr effect was excluded as, according to [68], the non-linear optical coefficient for sputtered AlN films would result in a negligible shift in the resonance wavelength. The dropped power ( $P_d$ ) is related to the normalized resonant transmission minimum ( $T_{min}$ ) through  $P_d = (1 - T_{min})P_i$  [69]. The relatively constant extinction ratio across coupled powers indicates that there is no nonlinear absorption changing the quality factor of the

disk. Peak shift is plotted as a function of  $P_d$  in Fig. 3.10(b). As the plot shows, the shift is mostly linear and, to a first order, can be fit by a straight line with a slope  $S = \Delta \lambda (P_d)/P_d = 0.0495$ pm/µW. This value in AlN is also comparable to the shift reported in silicon nitride ring resonators as a function of dropped power [16]. This experimental data showing a small thermooptic coefficient in AlN confirms that it makes for an interesting material for integrated photonics in addition to optomechanics.



Figure 3.10: (a) Shift in microdisk transmission spectra with increasing input power  $(P_i)$ . (b) Shift of disk resonance plotted for different coupled powers.

# 3.4 Optomechanical modulation

In cavity optomechanical systems, the optical and mechanical modes are simultaneously supported in the same structure. The microdisk resonator we have considered thus far can be turned into an optomechanical resonator by releasing the structure from the substrate and allowing a mechanical mode to co-exist. While there are detailed models for describing the physics of optomechanical interactions that can generate amplification or cooling based on coupled-mode theory [70] and quantum mechanical derivations [71], fewer lumped parameter models exist for predicting device performance when considering its application as an optical modulator. This is however, what we are ultimately interested in quantifying in order to implement these devices at a systems level. To estimate the output power modulation in an RF-

Photonic link, we will consider a generalized model that utilizes the transfer function of the WGM resonator as its resonance condition is modified with respect to wavelength (or optical frequency).

# 3.4.1 Generalized model



Figure 3.11: Optomechanical modulation model based on displacement-based (i & ii) or refractive index-based (iii) changes

In an optomechanical system, we can consider two primary sources for producing optical modulation. The first is through displacement-based changes that generate physical deformation of an optical cavity. The second can be through refractive-index based changes which, in the context of a piezoelectric material, can be produced through the strain-based elasto-optic effect for example. These effects can be illustrated through a number of example devices, shown in Figure 3.11. In the case of displacement-based changes, we can consider piezoelectric actuation modulating the resonance condition of a WGM photonic resonator through dilation of the optical path length or directly modulating transmission between two end-coupled waveguides by

inducing axial offsets. Likewise, refractive-index based changes can also modulate the resonance condition of a WGM resonator configured as a racetrack by inducing stress in one of the straight sections, for example. At the output of the cavity, the modulated optical signal is then fed to a photodetector, which has a conversion gain G and produces an output voltage that can be read out by an electrical measurement tool, such as a spectrum analyzer. The portion of the transmission affected by linear displacements is termed the responsivity ( $R = \partial T/\partial x$  or  $\partial T/\partial z$ ). In the WGM resonator (which will be our main focus), *R* is based upon the conditions of the WGM. In order to account for the effect of modulating the WGM resonance condition, the responsivity term should be expanded to consider the effects on wavelength as follows:

$$\Delta T(x,n) = \frac{\partial T}{\partial x} \Delta x + \frac{\partial T}{\partial n} \Delta n = \frac{\partial T}{\partial \lambda} \frac{\partial \lambda}{\partial x} \Delta x + \frac{\partial T}{\partial \lambda} \frac{\partial \lambda}{\partial n} \Delta n$$
(3.30)

In the WGM resonator, the  $\partial T/\partial \lambda$  term describes the slope of the optical transmission function. The measured transmission at the output of the waveguide will decrease at the resonant wavelength ( $\lambda_o$ ), and this transmission dip is represented by a Lorentzian function. Another way to model the expression for this transmission as a function of wavelength is therefore given by

$$T(\lambda) = P_{trans} \left( 1 - \frac{\Gamma^2}{4(\lambda - \lambda_o)^2 + \Gamma^2} \right)$$
(3.31)

where  $P_{trans}$  represents the off-resonance optical power measured at the output of the waveguide, and  $\Gamma$  is the FHWM of the Lorentzian function. As described in Eq. (3.26) FWHM of the transmission dip is used to directly determine the loaded Q of the resonator. Therefore, the change in transmission as a function of wavelength in the WGM resonator is given by

$$\frac{dT}{d\lambda} = \frac{P_{trans} 8\Gamma^2 (\lambda - \lambda_o)}{\left[4 \left(\lambda - \lambda_o\right)^2 + \Gamma^2\right]^2}$$
(3.32)

It should be noted that the  $\partial T/\partial \lambda$  term is maximized at the half-maximum point of the optical resonance, and is a function of the  $\Gamma$  (or optical Q). For modeling purposes, we generally assume a maximum for the  $\partial T/\partial \lambda$  term, which corresponds to a detuning of the optical source to a wavelength where the transmission is roughly -3dB relative to the off-resonance transmission. Plots showing the relationship between the transmission and its derivative when biased for any wavelength detuning, corresponding to Eq. (3.31) and Eq. (3.32) are shown in Figure 5.12. As we shall see in later sections however, the actual peak modulation point may differ based on non-linearity in the WGM transmission response.



Figure 3.12: Transmission function and its corresponding derivative with respect to wavelength for sample case of -20 dBm off-resonance power level and optical *Q* of 20,000

To describe the  $\partial \lambda / \partial x$  term, we can expand the optical resonance condition given in Eq. (3.14). When a mechanical deformation in the resonator causes the body to dilate, the condition is modified. We consider acoustically generated radial vibrations to create a small displacement  $\Delta r$  (equivalent to  $\Delta x$  of Eq. (3.30)), which changes the resonance condition to  $n_{eff} \cdot 2\pi (R + \Delta r) = m \cdot (\lambda_o + \Delta \lambda)$ . This simplifies to
$$\frac{\Delta \mathbf{r}}{\mathbf{R}} = \frac{\Delta \lambda}{\lambda_o} \quad \text{or,}$$

$$\frac{d\lambda}{d\mathbf{r}} = \frac{\lambda_o}{\mathbf{R}} = \mathbf{g}_{\text{om}\lambda}$$
(3.33)

where  $g_{om\lambda}$  is defined as the optomechanical coupling coefficient with respect to  $\lambda$ . An analogous argument may also be made to describe the coupling of refractive index based changes to output power modulation through  $\partial \lambda / \partial n$ . This model thus allows us to describe all optical output power modulation originating from the WGM resonator.

### 3.4.2 Cavity transfer function

In the preceding section, the responsivity term was differentiated with respect to wavelength. The term may also be differentiated with respect to optical frequency. The transfer function can then be expressed as

$$\Delta T(x,n) = \frac{\partial T}{\partial x} \Delta x + \frac{\partial T}{\partial n} \Delta n = \frac{\partial T}{\partial \omega} \frac{\partial \omega}{\partial x} \Delta x + \frac{\partial T}{\partial \omega} \frac{\partial \omega}{\partial n} \Delta n$$
(3.34)

Similar to Eq. (3.31), the transmission as a function of the frequency can be described by

$$T(\omega) = P_{trans} \left( 1 - \frac{\kappa_{ext} \kappa_{int}}{\Delta_o^2 + (\kappa/2)^2} \right)$$
(3.35)

Here  $\Delta_o = \omega_o - \omega_p$ , which represents the detuning of the optical cavity as a function of the laser's pump frequency  $\omega_p$ . Likewise the extrinsic, intrinsic and total loss rates ( $\kappa$ ) can be extracted from the coupling, intrinsic and loaded quality factors (Q) through the relationship

$$Q = \frac{\omega}{\kappa} \tag{3.36}$$

By determining the loss rates from the fitted quality factors, we can have a better description of the transmission behavior of any resonator, versus the transmission given in Eq. (3.31) which is

ideal for critically coupled resonators. The change in transmission as a function of the frequency is then:

$$\frac{dT}{d\omega} = P_{trans} \frac{2\kappa_{ext}\kappa_{int}\Delta_o}{\left[\Delta_o^2 + \left(\frac{\kappa_{tot}}{2}\right)^2\right]^2} = P_{trans}H_{opt}$$
(3.37)

where  $H_{opt}$  is the cavity transfer function, as described in the literature where optomechanical coupling is described [72].

Thus we can utilize the framework presented in this section to model optical modulation capability. By estimating the key factors  $P_{trans}$  (insertion losses, mostly produced by gratings) and loaded optical quality factors we can utilize the wavelength-differentiated transmission function of Section 3.4.1, or describe transfer characteristics by considering the coupling behavior from experimental data with the use of the cavity transfer function.

# Chapter 4 Fabrication processes for co-localized acoustic and photonic resonators

The devices presented thus far have all been integrated photonic components encapsulated in oxide cladding layers to allow efficient coupling to optical fibers and support guided modes on chip. In order to co-localize these structures with piezoelectric acoustic contour mode resonators (CMRs), a number of requirements need to be satisfied for producing each type of device. This presents challenges in the development of a fabrication process that can enable an integrated platform. Specifically, attention needs to be given to the release of the mechanical resonators and the corresponding anchoring for the device, the effect of including metals and tethers on the optical resonators, incorporating a wide range of lithographic dimensions in a single process and the suspension of integrated waveguides. In the development of a final process, a number of revisions were made based on experimental observations and the original design was modified accordingly. The experimental results and the associated process modifications are summarized in this chapter.

## 4.1 Finalized process

The process flow ultimately implemented to demonstrate acousto-optic modulation with cofabricated CMRs and WGM resonators is summarized in Figure 4.1. This design features partial etching of AIN to simultaneously provide optical confinement in rib waveguides, and also serve as a release mask to suspend the resonators. In addition, feature dimensions and anchoring points have been selected to enable a short release while mitigating any stress-related effects to keep waveguides and resonators in the same plane. Metals used for the piezoelectric excitation have been decoupled from the optical resonator, but are still fully integrated with the composite structure. In addition, a sub-100 nm coupling gap is defined between a curved waveguide (which avoids problems of buckling) and the photonic ring resonator. The rationale for selecting these features and dimensions is largely driven by fabrication considerations. Specifically, we will consider each step of this process and justify the choices for the oxide thickness and etching approach, the AlN deposition, patterning of the electrodes and AlN etching with the use of partial thicknesses.





## 4.2 Oxide thickness and release

All our demonstrations of integrated photonic resonators have required a  $SiO_2$  undercladding to ensure optical confinement in waveguides, so we fixed this thickness to  $1.1\mu m$  of thermally grown oxide. The under-cladding layer was reduced in thickness from the previously used  $2.25\mu$ m in order to reduce the amount of reactive ion etch (RIE) required to expose the underlying silicon and enable XeF<sub>2</sub> release. The process of modifying the release step ultimately implemented is discussed in this section.

The selection of 1.1µm for the oxide thickness was based on the fact that the grating transmission demonstrates a periodic dependency on the under-cladding thickness based on the reflections generated from the silicon substrate. The effect of the bottom cladding on transmissivity is shown for the grating geometry of Chapters 2 and 3 in Figure 4.2. While there is theoretically another local maximum occurring at 600nm, structures fabricated with this under-cladding thickness (tested with the use of a PECVD oxide on silicon) did not exhibit measurable transmission through the gratings.



Figure 4.2: Lumerical simulation of AlN grating transmissivity as a function of bottom cladding thickness (varied in 100 nm increments from 0.1 µm to 2.5 µm)

#### 4.2.1 Released microdisk resonators

As a first step towards the subsequent integration with acoustic resonators, the release process was tested for the photonic microdisks previously described. Allowing the microdisks to vibrate freely would also enable the possibility of measuring thermomechanical noise through the buildup of radiation pressure in the cavity with sufficient optical  $Q_s$  [73]. Thus the radial contour

modes of the disk could be detected. In order to suspend the disks, a release window was defined with the use of a photoresist mask. Wet release with buffered oxide etchant (BOE) was then used to simultaneously etch the top cladding layer and undercut the disk – up to a point where a PECVD oxide pedestal would remain in the center. However, it is not possible to undercut more than a few microns and ensure the survival of the photoresist. This also dampens the ability of the structure to freely vibrate. A limited release of 20  $\mu$ m diameter microdisks was successfully performed in this way. As a result of higher bending losses, the optical quality factors were typically lower than those measured in the 40  $\mu$ m diameter disks, but it became more difficult to produce a sufficient undercut while keeping the waveguide suspended in the plane of the resonator. An example of this is shown in Figure 4.3. In addition, the BOE was also found to aggressively attack the PECVD oxide in several samples (top and bottom claddings), generating significant amounts of debris on the surface of the sample. As a result of these issues, a dryetching approach and the use of thermally-grown oxide for the bottom substrate was favored in subsequent trials.



Figure 4.3: (Clockwise from top left) Release of 40 µm diameter AlN microdisk with photoresistdefined release window, Microdisk with photoresist removed, SEMs of waveguide buckling



Figure 4.4: (a) 20  $\mu$ m diameter disk with BOE undercut, (b) 40  $\mu$ m diameter disk with top and bottom claddings undercut with XeF<sub>2</sub>, (c) 40  $\mu$ m diameter disk with bottom cladding undercut with XeF<sub>2</sub>

In order to repeat the release process with dry etching tools, we applied  $XeF_2$  gas to etch silicon, which is commonly used to release MEMS resonators. To expose the silicon, the release windows were patterned, and a RIE step was applied first to etch through the oxide layer(s) (this was performed for substrates with and without a top oxide cladding). Some representative examples of released microdisks with corresponding optical resonances are shown in Figure 4.4. While the optical quality factors in all of the successfully released microdisks were not large enough to enable the measurement of thermomechanical noise, it is not a limitation in the case of a resonator driven by piezoelectric excitation. Therefore, the process modifications (use of dry etching and thermal oxide) were noted and applied to the development of piezoelectricallyactuated devices – which is the primary motivation for enabling the integrated RF-Photonics platform.



Figure 4.5: Optical transmission for 40 µm diameter AlN disk (100 nm gap) with and without thermal oxide etched release window

The first observation from the completed process with piezoelectric resonators was a degradation of the response for the photonic resonators as a result of etching the oxide undercladding. This issue was identified from comparison with grating test structures that did not have the release etch. From the same processed die, in which certain devices had a release window definition, and by comparing to free-standing grating/waveguide test structures, it was surmised that the 1 µm RIE etch could be the source of the losses. To verify this hypothesis, identical sets of resonators were prepared, with and without the RIE etch step, and the insertion loss measurements were compared. This is shown in Figure 4.5. As shown in the plot, the presence of the release window and the associated effects of the etching step, generated significant losses for device with otherwise identical processing (AIN etch & gap + grating definitions). In all cases, presence of the oxide etch window produced significant insertion losses, where it became hard to distinguish the output from generic noise in the optical setup (generally around -70 dBm). The comparison in Figure 4.5 was captured with the use of extended optical fibers (not encapsulated in the fiber array), which allowed the positioning to the gratings to be verified visually, and a degraded response (with evidence of optical coupling) to be observed.

Since the degraded optical transmission presented a significant problem for characterizing released devices, the addition of PECVD oxide cladding as a post-processing step was considered. In this case it was found that adding 1 µm of PECVD oxide cladding produced a restorative effect on the device responses, significantly reducing insertion losses by 18-24 dB and shifting the peak transmission wavelength higher. Additionally, the addition of PECVD oxide to the release window etched devices allowed an output to be measured from the devices, where there was high degradation/none before. Optical resonances were also measured with quality factors comparable to their non-etched counterparts. However, insertion losses were still consistently higher in the release window devices (on the order of 15-25 dB) compared to the non-etched counterparts. These effects are shown in Figure 4.6. Hence, the post-processed PECVD addition was required for subsequent device testing. As discussed in the section on electrode patterning however, this posed a problem for measuring electrical device responses.



Figure 4.6: Effects of adding 1 µm PECVD oxide on non-etched (left) and release window-etched (right) photonic resonators

In addition to these issues with measuring optical transmission, another problem associated with the RIE-based release followed by  $XeF_2$  was the inability to control stress in the oxide layer. A common problem that was observed for example was the breaking of anchoring and tether points due to stress as seen in Figure 4.7. This also motivated the final decision to optimize the process of releasing with an etch of the bottom oxide, instead of leaving it under the device.



Figure 4.7: Examples of broken connection points following XeF<sub>2</sub> release

## 4.2.3 HF-based release

The finalized process uses a vapor HF based release. This is made possible by utilizing partially etched AlN as a natural etch mask. Many of the problems experienced with RIE/XeF<sub>2</sub> etching were solved by using HF to remove the bottom oxide. The main problem encountered with this process previously was the ability to perform long (10-15  $\mu$ m) undercuts, as in the case of the microdisks. This had also been attempted for 10  $\mu$ m width rings (requiring a 5  $\mu$ m undercut) with BOE, with similar difficulties. Therefore, release would be limited by primarily focusing on rings with a smaller width dimension (undercut requirement would be limited to 3  $\mu$ m). Additionally, since photoresist was deemed to be an unreliable masking material for relatively long HF-based release processes, a partial etching of the AlN layer would be considered in order to use AlN as a natural masking material. Ultimately, the etch quality improved significantly in a vapor environment.



Figure 4.8: (a) 49% HF-based release, (b) VHF release (note pockmarks are due to EBL alignment window scan development of PMMA development and not from process) with corresponding optical resonance, (c) Top metal delamination in 49% HF (left) vs. survival in VHF (right)

Targeted AlN partial etch thicknesses of 75-100 nm were tested for their ability to serve as a release mask. AlN ring structures were prepared with the width limitation previously mentioned, and released with the use of 49% HF. In this process, the partially etched AlN was initially attacked and prominent pockmarks would appear throughout the substrate (shown in Figure 4.8). This issue was largely alleviated by eliminating the water-based rinse following the etch step. However, delamination of the top gold electrodes continued to be a problem in the aqueous release process. As a result, a vapor HF (VHF) release process was implemented, which resolved the delamination issue and also produced a much cleaner etch profile. Optical quality factors could thus be measured in the photonic resonators, in addition to successful electrical probing for the test structures.

## 4.3 AlN deposition

The deposition of highly c-axis oriented AlN on oxide had been a consistent problem in past rounds of process development. All depositions make use of AC reactive sputtering from an Al target with the Tegal Advanced Modular Sputtering (AMS) tool which uses a dual cathode S-Gun magnetron source [74]. Several attempts had been made to modify the recipes (for both the wafer plasma etching and deposition stages) used for silicon substrates. Baseline stress and rocking curve FWHM values are shown in Table 4.1 for 300 nm deposition on silicon and thermally oxidized substrates. To improve the orientation, the deposition recipe was modified to operate with higher N<sub>2</sub> flow in "deep poison" mode. With the modified recipe, a shorter pre-etch time was found to improve the orientation significantly, as indicated in Table 4.1. Argon flow was also later adjusted to reduce the film stress, and determine the final recipe (noted in the Appendix A process flow). The optimized process was found to be quite repeatable during the characterization, with all wafers (4) deposited showing FWHM values on the order of 2°. This is contrasted with 27 depositions under the other process conditions generating FWHM values ranging from  $3.97^{\circ}$  to  $7.19^{\circ}$ .

Substrate/Mode	Pre-etch	Deposition	Stress	FWHM at 36° peak
Silicon/Baseline	180sec, 150W, 15sccm Ar	23sccm Ar, 32sccm N <sub>2</sub>	+48 MPa	1.87°
Oxide/Baseline	180sec, 150W, 15sccm Ar	23sccm Ar, 32sccm N <sub>2</sub>	+7 MPa	5.57°
Oxide/Deep Poison	180sec, 150W, 15sccm Ar	23sccm Ar, 45sccm N <sub>2</sub>	-68 MPa	5.45°
Oxide/Deep Poison	240sec, 150W, 15sccm Ar	23sccm Ar, 45sccm N <sub>2</sub>	-64 MPa	6.36°
Oxide/Deep Poison	90sec, 150W, 15sccm Ar	23sccm Ar, 45sccm N <sub>2</sub>	+164 MPa	2.08°

Table 4.1: Selected variations used to determine high-orientation AlN on thermal oxide recipe

## 4.4 Electrode patterning

The basic approach sought to fabricate monolithic acousto-optic modulators was to extend the standard process used in the making of AlN CMRs [9], and include the requisite components for producing photonic resonators and optical gratings. To begin, platinum bottom electrodes (50-100nm thick) are first patterned, and followed by the deposition of 400nm AlN. Vias are then patterned, and followed by a lift-off of aluminum (100-200nm thick) for the top electrodes. In the initial process, all features in AlN were defined at the same time (using a single mask) with the use of a 5x g-line stepper and fully etched. Finally the resonator release windows were patterned, followed by a RIE etch of the thermal oxide (ThOx), and the devices could be released in  $XeF_2$ . This process flow is shown pictorially in Figure 4.9. Some of the challenges associated with the use of metals include isolating them from the optical resonators, and ensuring hard mask layers in the processing would not interfere with device response.



Figure 4.9: Basic optical (stepper) lithography process flow for acoustic and photonic resonators

## 4.4.1 Metals on photonic resonators and device anchoring

A study was carried out to determine the effects of metals and anchors on the photonic resonator response by preparing identical devices with and without these features. The most efficient way to apply piezoelectric excitation would be for the CMR and WGM resonator to be located in the same structure. Identical microdisks were thus prepared in which metal electrodes are located at the periphery of the WGM resonator and also without (this type of structure would also be able to generate electro-optic modulation in AlN). In the case of patterned metal electrodes, the inclusion of metals at the edges very likely scatters the confined wave, and as a result the resonances found in non-metalized devices are absent in the electroded counterparts. An example of this is shown in Figure 4.10.



Figure 4.10: (a) Comparison of optical transmission response in identical photonic resonators with and without metals (Pt and Al), Effect of 5 µm anchor on 1 µm PECVD (b) unclad and (c) cladded 40 µm diameter microdisks

Likewise, the presence of an anchor (required for release as well as routing of electrodes to piezoelectric resonator) also reduces the confinement of the circulating wave in the structure, and lower optical quality factors (consistently ~300-500) are recorded in 40  $\mu$ m diameter microdisks. A direct comparison for anchored vs. non-anchored structures generated from the same mask set is unavailable. However, the oxide cladded structure with anchoring (from which an optical resonance is plotted in Figure 4.9(c)) can be compared to the microdisks demonstrated in Chapter 3 (in which critically coupled  $Q_L$  ~28,350 was measured). The only notable difference between the two devices is the thickness of the bottom oxide cladding (which should more directly affect the transmissivity of the gratings and less so to the optical quality factor of the resonator). This highlights the importance of reduced anchor widths – which are ultimately used in the final process.

## 4.4.2 Measurement of XeF<sub>2</sub> released structures with full processing



Figure 4.11: (a) Double ring and (b) LFE device types selected for characterization. Optical coupling in (c) 100 nm waveguide-resonator gap (unclad SEM) and (d) connected structures (cladded SEM)

Based on the conclusions of the metal study, we implemented the full process with the use of structures in which the WGM resonator was free of metals along most of its periphery. Specifically, these included coupled ring devices (with a ring width of 10-20  $\mu$ m and diameter of 200-220  $\mu$ m) and lateral field excitation (LFE) type disks (with a diameter of 200  $\mu$ m) as shown in Figure 4.11. All released structures were post-processed with the addition of 1  $\mu$ m PECVD oxide cladding to enable optical transmission. In doing so, it was possible to characterize optical resonances in devices with integrated electrodes. Devices had been prepared with the gap dimensions of 300 nm, 100 nm and a full connection at the stepper lithography level between the WGM resonator and the waveguide. While characterizing the transmissions, it was found that 100 nm gaps could produce weak coupling, but critical coupling was only recorded for the connected structures (as shown in Figure 4.11). Therefore, only this dimension was selected in subsequent characterization of optical resonances that could be used in conjunction with piezoelectric

excitation. Some prominent optical quality factors extracted for each device type are shown in Figure 4.12.



Figure 4.12: Notable examples of optical quality factors measured in modulator devices for double rings (top row) and LFE type devices (bottom row)

Optical transmission could be measured with the addition of the PECVD oxide (albeit with some unresolved questions regarding the nature of the release window etch degradation, and its possible partial etching of the gap region). This however produced a problem in RF probing from the acoustic end of the device. The response of the acoustic resonators was likely masked in parasitic capacitance, making it difficult to take electrical admittance measurements to characterize the device independently. Some efforts were made to make the optomechanical measurement by supplying electrical excitation to the RF pads from a vector network analyzer (VNA) and monitoring the photodetector coupled output while biasing the laser along the optical resonances shown in Figure 4.12. This was carried out with and without the use of an electrical amplifier from the source end. However no response could be recorded for these measurements. As a result, these experiments also confirmed the need for a process which does not rely on post-

processing with oxide to enable optical transmissions. This is achieved with the use of the partially etched AlN.

# 4.5 AlN etching

The key motivations for implementing the partial etching of AlN were to provide a robust natural release mask and to eliminate oxide hard mask etching steps wherever possible. In the case of the latter, this is also enabled by reducing the thickness of the AlN layer. Prior to implementing the partial etch process, the AlN lithography steps also needed to be optimized in order to enable simultaneous definition of large and small feature sizes in the finalized device in a repeatable manner.

## 4.5.1 Lithography process development



Figure 4.13: (Top) Optical and SEM images of photoresist-mask defined AlN features. (Bottom) AlN sidewall angles with and without the use of a PECVD hard mask

As shown in Figure 4.9, lithography for the AlN etch layer was initially carried out with the use of a photoresist mask, followed by a  $Cl_2/BCl_3$  based etch step. Several exposure times and development conditions were varied for the use of 1µm thick photoresist (AZ 4110). Although

the pattern definition appeared acceptable in several cases with reasonable accuracy on the lithographic dimensions, the etched gratings did not demonstrate a clean profile. An example of this can be seen in Figure 4.13. In addition, the photoresist-defined etch produced a relatively shallow sidewall angle ( $\sim$ 42°). As a result, the use of a 200 nm PECVD hard mask was considered in order to improve the sidewall definition, and utilize a shorter etch in the initial pattern transfer for the "small" features in the AlN layer (namely, to define gratings and gaps). This improved the sidewall angle to  $\sim$ 68° (also shown in Figure 4.13), and the hard mask was incorporated into subsequent processing steps.



Figure 4.14: (Clockwise from top left) PECVD hard mask and AlN layer viewed from end of waveguide; Viewed from side of gratings; AZ 4110 resist imaged with incomplete definition; Overdeveloped resist

Using the PECVD oxide the lithography was repeated, and a  $CHF_3/O_2$  based RIE etch was performed first to define the features in the hard mask. Following the transfer of the pattern to the AlN, the small feature resolution was still not sufficient to generate photonic integration. Upon imaging the etched features, there appeared to be evidence of mask erosion, but the source of the inaccuracies could be resolved by imaging the developed photoresist. In doing so, it became apparent that the photoresist removal was not complete, despite appearing to have residues in the trenches when viewed from the top as shown in Figure 4.14. To resolve this problem, several more aggressive development recipes and times were attempted (an example of which is shown in Figure 4.14), but this led to unsuccessful pattern transfer into the hard mask layer.



Figure 4.15: (Left) FIB-cut gratings, (Right) S1805-defined gratings with variable repeatability

As the feature definition & pattern transfer in the photoresist appeared to be the problem, the use of a thinner resist (Shipley S1805) was also attempted to improve the resolution. This improved the pattern definition somewhat, but consistent repeatability continued to be a problem. As was observed with the use of the AZ4110 resist as well, small features (< 1  $\mu$ m) could be well-defined in some parts of a wafer, but not in others. In addition, there was also variation that could appear among the same features in a single die. An example of gratings produced with S1805 is shown in Figure 4.15, in which this variability is shown. Another approach which was briefly attempted to circumvent the problem of small feature definition was to use a focused ion beam (FIB) to manually mill the AlN (also shown in Figure 4.15). To test this idea, a second set of gratings was defined in the waveguides, which could be used to couple in and out of separately from an original pair. However, this method did not yield consistent dimensions (as discussed in

Chapter 2, grating geometry uses  $1.2 \ \mu m$  period with 50% duty cycle), and the measured structures did not produce any measurable transmission.

These examples provide a sampling of the main efforts applied towards adapting the process shown in Figure 4.9 to enable light coupling and measurement of photonic resonators in a process flow primarily designed to generate CMRs. The main problem encountered throughout these trials was the inability to define large and small features simultaneously with the use of stepper lithography. Although selected features could sometimes show the correct dimensions after etching was complete, it was not possible to identify a process that would yield consistent dimensions. As a result, a new approach was sought in which e-beam lithography (EBL) could be integrated with the stepper process to separately define the small features with consistent repeatability.

Prior to incorporating the use of EBL into the flow, a number of process modifications needed to be considered. EBL was implemented on an FEI Sirion SEM with the use of the Nanometer Pattern Generation System (NPGS). The resist used for processing is PMMA – which, in its A7 dilution, can be spun up to a thickness of  $\sim 1 \,\mu$ m (at the potential loss of high-resolution). An initial test was done to verify the selectivity of the PMMA to the required 400 nm AlN etch. It was determined that the PMMA would not survive the etch, and therefore a hard mask layer is required. In addition, PMMA etches relatively quickly in the O<sub>2</sub>-rich RIE recipe used to etch the PECVD oxide, so an additional hard mask bilayer would be required. Aluminum was selected as the bilayer material, since a relatively low thickness would be required to mask the oxide, and it would be automatically etched away in the subsequent AlN etch step. An additional benefit is that it serves as a layer to dissipate excess charge buildup due to the use of the insulating substrate (PECVD SiO<sub>2</sub>, AlN and Thermal SiO<sub>2</sub>). The PECVD oxide hard mask thickness was adjusted to 175 nm (based on a more accurate selectivity measurement for the oxide:AlN etch), and the Al thickness was fixed to 75 nm (in excess of the selectivity required of





Al:oxide etching). In addition, a number of markers are incorporated into the AlN stepper mask layer in order to enable EBL alignment with coarse (used for the gratings) and fine (used for the gaps) accuracy. Since EBL could be used for higher feature resolution, gaps were also modified with dimensions between 0-300nm (while previously a minimum gap size of 600nm had been specified in the stepper mask. The process amendments are shown in the modified flow of Figure 4.16. This approach resolved the issues concerning lithographic dimensions. However (as also discussed in the preceding sections), the need to etch the PECVD hard mask prior to releasing the device in XeF<sub>2</sub> generated problems for the grating transmission.

4.5.2 Hard mask removal effect on grating transmission



Figure 4.17: Grating transmission response prior to and following removal of PECVD oxide hard mask

Another oxide etching effect observed was a degradation of the grating transmission upon removal of the PECVD hard mask layer (Step 9 of Figure 4.16). This step was required to allow the Al top electrodes to be probed during subsequent RF testing and also re-expose the silicon in the release pit, prior to the final XeF<sub>2</sub> release. Grating structures were tested prior to the etching of the PECVD hard mask, and after its etching/device release. This is shown in Figure 4.17. The increase of grating losses can possibly be attributed to a RIE overetch in the grating trenches (which can also explain the modification in peak transmissivity), but this was not measured. Although this effect was not as pronounced as in the case of the release window (measurable photonic device response could still be characterized), it was noted as another example of deficiency in the amended process flow.

### 4.5.3 Partial etch AlN masking



Figure 4.18: Grating transmissivity in 300 nm AlN for different partial thickness gratings

By partially etching the AlN it is thus possible to eliminate the hard mask layers altogether. With the use of partial etching, the waveguides become rib structures, as opposed to the ridge (fully etched) types previously used. In the final process, the partial thickness of the remaining slab serves as the etch mask for the release. The AlN thickness was also reduced to 300 nm. Since the gratings must also be partially etched, the previously implemented geometry (600 nm width gratings with 600 nm width fully-etched trenches) was tested for different partial etch thicknesses. As shown in Figure 4.18, fairly comparable peak grating transmission could be simulated for a partial thickness (which indicates the thickness of the AlN remaining in the etched trenches) of 75-100 nm. Measured transmissivities for the fabricated partial etch gratings produced a larger loss, where the peak transmissivity values typically ranged between -17 dB and -19 dB (an example of which may be seen in Figure 5.12). However, the difference between the simulated and measured results on the test setup used did not differ significantly in comparison with the use of the previous (fully etched) grating design. Based on the characterized PMMA:AIN etch selectivity of ~3:1, the partial etch gratings were also possible to produce without the need for the bilayer in the EBL steps.





Figure 4.19: Testing of CAD-specified gap dimensions in AlN on thermal oxide

Using 300 nm AlN and the targeted partial thickness of 75-100 nm, PMMA dosages needed to be characterized for the critical features defined with EBL – particularly the gaps. To maintain a buffer from the limits of the PMMA etch rate in the AlN recipe, the resist was spun at 3000 RPM to produce a thickness of ~800 nm. The processing and subsequent partial etching was then characterized on actual substrates with a series of trials in which gap sizes were varied from 25 nm – 100 nm in increments of 25 nm, and exposure dosages varied between  $325 - 475 \,\mu\text{C/cm}^2$  in increments of 25  $\mu$ C/cm<sup>2</sup>. Grating dimensions showed lower variability over this dosage range than the gaps. To test the repeatability of the gap definition, a single dosage at 415  $\mu$ C/cm<sup>2</sup> was selected and several structures were produced for each dimension. An example of this is shown in Figure 4.19. In general, gap sizes slightly smaller than what was laid out were measured. The 25

nm defined gaps were never possible to resolve, while the 50 nm, 75 nm and 100 nm layouts yielded gap dimensions on the order of 21-37 nm, 49-68 nm and 70-94 nm, respectively. The etch profile inside the gap was also verified with the use of FIB milling as shown in Figure 4.19. Finally, the patterning of the gap on an actual sample with topography remained to be tested. The layout dimension was fixed at 100 nm to produce a gap size slightly smaller at ~75 nm. This was found to demonstrate critical coupling as shown in Figure 4.20, and the parameter remained fixed in the subsequent processing of piezoelectrically-actuated structures. Relevant details of the EBL NPGS settings are provided in Appendix A.



Figure 4.20: (Left) FIB-milled gap for viewing sidewall, (Right) 100 nm laid-out gap implemented in actual device

# Chapter 5 Contour mode resonator based acousto-optic modulator

Applying the methods and framework developed in the previous sections, we now focus on the experimental demonstration of the integrated acousto-optic modulator with the use of piezoelectric actuation. To overcome fabrication challenges, the structure ultimately successful in supporting a traveling wave optical resonance simultaneously with an electromechanically generated acoustic wave separates the acoustic and optical ends of the device. The vehicle used to generate the acoustic wave is the laterally vibrating piezoelectric contour mode resonator (CMR) [9]. In contrast with other piezoelectric technologies such as the film bulk acoustic resonator (FBAR) [10], the CMR has a center frequency set by in-plane lithographic dimensions – a feature that allows it to be used to produce multiple frequencies on a single chip. As a result, there has been significant interest in recent years to develop this class of resonator for a variety of RF front end applications including filters [22] and oscillators [75] in addition to sensing purposes [76], [77]. In this chapter, we will briefly consider the operation of the CMR to identify the key parameters that characterize it. We will then discuss the implementation of the CMR in the acousto-optic modulator, and study its operation while input RF and optical parameters are varied.

## 5.1 Fundamentals of piezoelectric contour mode resonators

The term "contour mode" is used to describe vibrations in a body (e.g. a thin rectangular plate) where the displacements are in directions parallel to the major surfaces. In general, this motion can include both extension and shear, and includes a variety of different mode shapes [78]. For our purposes, we will specifically consider the extensional modes that are generated in the width direction of a long rectangular plate (having width *W*, length *L* and thickness *t*), as shown in Figure 5.1. When the plate is composed of a high-quality piezoelectric material, it can be driven into mechanical resonance through its  $d_{31}$  coefficient by applying a time-varying

electric field across its thickness (practically implemented through the use of top and bottom electrodes to which an AC voltage is applied). This manner of excitation is known as thickness field excitation (TFE). In this case, the structure expands laterally, and



Figure 5.1: Resonant width extensional mode of a thin rectangular AlN plate where  $V_{ac}$  is applied across terminals (shown for dimensions W=6 µm, L=232.5 µm, t=1 µm)

the vibrations occur at a frequency set by the width of the plate. The fundamental mode resonance frequency is described by

$$f_r = \frac{1}{2W} \sqrt{\frac{E}{\rho}}$$
(5.1)

where W is the width of the plate, E is the Young's modulus of the material and  $\rho$  is its density. The structure undergoes a sinusoidal displacement u in the x-direction, which has an associated strain shown in Figure 5.1. While it is possible to produce an electromechanical model from the piezoelectric and solid mechanics equations that describe the structure, an easier approach is to use a lumped parameter equivalent circuit model, as originally proposed by Mason [78], [79].



Figure 5.2: Electromechanical circuit model and equivalent mass-spring-damper system

The circuit model used to describe the resonator behavior is shown in Figure 5.2. By modeling the function of the transducer with a transformer that converts the input electrical energy into the mechanical domain, the motional characteristics of the device can be described by equivalent passive components in the electrical domain. Specifically, the input voltage V is supplied across the intrinsic capacitance  $C_o$  of the plate. Through the contribution of the transformer with a turns ratio defined by  $\eta$ , a "motional" voltage  $V_m$  appears across the passive components in the mechanical branch of the circuit. This is analogous to the force F that would be present in mass-spring-damper system. It thus becomes apparent that the  $\eta$  term can in fact be used to describe the electromechanical coupling of the device as

$$\eta = \frac{F}{V} = \frac{q}{u} \tag{5.2}$$

where q represents the charge stored on one electrode, and u is the corresponding displacement produced in the structure. The mass-spring-damper system is described by

$$F = m_{eq} \frac{d^2 u}{dt^2} + d_{eq} \frac{du}{dt} + k_{eq} u$$
(5.3)

where  $m_{eq}$ ,  $d_{eq}$  and  $k_{eq}$  represent the equivalent mass, damping and stiffness of the body, damper and spring, respectively. When mapped to electrical terms by the electromechanical coupling, the equation can be cast into the form of the constitutive equation for the RLC series circuit,

$$V = L_m \frac{di}{dt} + R_m i + \frac{q}{C_m} = L_m \frac{d^2 q}{dt^2} + R_m \frac{dq}{dt} + \frac{q}{C_m}$$
(5.4)

where  $L_m$ ,  $R_m$  and  $C_m$  represent the motional inductance, resistance and capacitance, respectively. These passive components can thus be expressed as

$$L_{m} = \frac{m_{eq}}{\eta^{2}} \qquad R_{m} = \frac{d_{eq}}{\eta^{2}} = \frac{m_{eq}\Omega_{m}}{\eta^{2}Q_{mech}} \qquad C_{m} = \frac{\eta^{2}}{k_{eq}} = \frac{\eta^{2}}{m_{eq}\Omega_{m}^{2}}$$
(5.5)

Here, the relations  $\Omega_m = \sqrt{\frac{k_{eq}}{m_{eq}}}$ ,  $\zeta = \frac{d_{eq}}{2\sqrt{m_{eq}k_{eq}}}$  and  $Q_{mech} = \frac{1}{2\zeta}$  from the solution to the free

vibration of the mass-spring-damper system are applied, where  $\Omega_m = 2\pi f_r$  is the angular resonance frequency,  $\zeta$  is the damping ratio and  $Q_{mech}$  is the mechanical quality factor. The  $m_{eq}$  may be determined by dividing the total kinetic energy of the structure at resonance by one-half of the squared velocity at a given point. It can also be approximated by  $m_{eq} = \frac{m_{static}}{2} = \frac{\rho WLt}{2}$ , where  $\rho$  is the material density [78]. Likewise, by relating the total charge stored on an electrode at the point of maximum displacement, an analytical approximation for electromechanical coupling may be determined as  $\eta = 2d_{31}E_{eq}L$  for the width-extensional mode, where  $E_{eq}$  is the equivalent Young's modulus of the structure [9].



Figure 5.3: Butterworth van Dyke and modified Butterworth van Dyke equivalent circuits

In a one-port configuration, the output port of the circuit model is terminated in a short. While the resonator can therefore be represented by a fixed capacitance in parallel with a motional arm, the equivalent circuit should also reflect the existence of series and parallel resonances. A suitable equivalent model to represent this behavior is the Butterworth van Dyke (BVD) circuit, as shown in Figure 5.3 [80]. In order to include the losses of the parasitic components such as the electrical routing pads and the material (e.g. AlN), the model is typically modified to include the parameters  $R_s$  and  $R_o$  respectively. There also exists a parasitic capacitance ( $C_p$ ) in parallel with the resonator branch, but the contribution of this term becomes negligible if the substrate resistivity is sufficiently high. For experimental measurements collected in a resonator, it is more convenient to express the motional components in terms which can be extracted from the admittance data. The values can thus be written as [81]

$$R_{m} = \frac{\pi^{2}}{8} \frac{1}{\Omega_{m}C_{o}} \frac{1}{k_{t}^{2}Q_{mech}},$$

$$L_{m} = \frac{\pi^{2}}{8} \frac{1}{\Omega_{m}^{2}C_{o}} \frac{1}{k_{t}^{2}},$$

$$C_{m} = \frac{8}{\pi^{2}}C_{o}k_{t}^{2},$$
(5.6)

where  $\Omega_m$  denotes the series resonance and  $k_t^2$  represents the electromechanical coupling coefficient. As the values of  $C_o$  and  $R_o$  represent the static capacitance and resistance through the device, they can be extracted from the off-resonance data and likewise  $R_m$  can also be determined from the peak of the admittance data. The electromechanical coupling coefficient can be determined by the expression  $k_t^2 = \frac{\pi^2}{4} \frac{f_p - f_s}{f_s}$ , where  $f_s$  and  $f_p$  are the series and parallel resonances, respectively. Mechanical quality factors can be determined in a manner similar to optical resonances by measuring the ratio  $\frac{f}{\Delta f_{FWHM}}$  (where the FWHM of the series resonance can be considered by looking at the -3 dB points of the admittance peak), or by

 $Q_{mech} = \frac{1}{\Omega_m (R_m + R_s)C_m}$ . Based on these values we can evaluate the figures of merit typically

assessed for acoustic resonators, namely the products  $kt^2 \cdot Qmech$  or  $f \cdot Q_{mech}$  – depending on the application of interest.

Finally we should note that while the above discussion considers the case of a long rectangular plate, this in fact provides a good approximation for a ring-shaped geometry (such as the ones we will consider), in which the structure vibrates across its width as shown in Figure 5.4.

This is true provided that the average radius  $R_{avg} = \frac{R_{out} + R_{in}}{2}$  of the ring is much larger than its width  $W = R_{out} - R_{in}$ , where  $R_{out}$  and  $R_{in}$  are the outer and inner radii of the ring, respectively. In this case, we may simply replace the plate length *L* with the term  $2\pi R_{avg}$  in the preceding discussion [9].



Figure 5.4: Mapping of plate parameters to ring geometry

# 5.2 Acousto-optic modulator design

A schematic representation of the CMR-based acousto-optic modulator is shown in Figure 5.5. The monolithic device consists of two AlN rings, in which the first ring functions as an acoustic CMR and the second is a whispering gallery mode (WGM) photonic resonator. An RF electrical signal is supplied to the input port of the device – namely the electrodes of the CMR ring. This excitation generates vibrations in the CMR, which are laterally transferred to the WGM



Figure 5.5: Schematic representation of the CMR-driven acousto-optic modulator

ring through a mechanical coupling spring. Simultaneously, telecom *C*-band light is coupled into the photonic ring, and the cavity is biased to a wavelength corresponding to one of the supported WGM resonances. As the RF excitation is applied, the mechanical deformations to the cavity path length generate a modulation in the frequency (or equivalently, wavelength) of the WGM resonator. This modulation may be detected as a change in the transmitted power ( $P_{out}$ ) that is collected at the output of the coupling waveguide. Piezoelectric excitation provides the dominant source of actuation forces in the WGM resonator, as opposed to the optical force generated by the circulating intracavity energy. Therefore we consider the radial displacements (dr) in the cavity to be generated by the root mean square (rms) voltage applied to the CMR. In order to estimate the effective transduction capability of the device, we define a coupling factor  $\eta_{om}$ , where  $\Delta r = \eta_{om}V_{rms}$ . The optical output modulation may thus be expressed by the transfer function discussed in Section 3.4.1:

$$P_{\rm mod} = \frac{dT}{d\lambda} \cdot \frac{d\lambda}{dr} \cdot \Delta r \tag{5.7}$$

In this expression,  $dT/d\lambda$  represents the slope of the cavity Lorentzian's transmission power evaluated at the detuning of the pump laser's wavelength with respect to the WGM resonant wavelength ( $\lambda_o$ ) and  $d\lambda/dr \approx \lambda_o/R_{out}$  as shown in Eq. (3.33). Using this formulation, we will consider the output power amplitude modulation generated by the modulator in the subsequent sections.

#### 5.2.1 Mechanical mode

For this initial demonstration, identical dimensions were selected for the two rings. The ring radius (40 $\mu$ m) and width (6 $\mu$ m) were determined based upon similar designs in Si<sub>3</sub>N<sub>4</sub> (a material with similar optical properties to AlN) and its ability to support high optical quality factors [37]. The rings are supported by a centrally-anchored hub, to which they are connected by 1 $\mu$ m wide spokes. In order to generate lateral vibrations through the  $d_{31}$  piezoelectric coefficient, the CMR ring must be sandwiched by top and bottom electrodes. This causes the resonant frequency of the excitation ring to differ from that of the WGM ring, due to mass loading [9]. Since the natural frequencies of the two rings differ, the coupling element does not affect the splitting of the mechanical mode. As a result, the two rings do not simultaneously deform with the same mode, but radial modes from the excitation ring generate modulated mechanical modes in the WGM ring, which are detected optically.

A 3D finite element method (FEM) simulation of the device using COMSOL is shown in Figure 5.6. Using a frequency domain sweep, the radial contour mode for the first ring may be determined by considering the input port voltage reflection. The mechanical mode in the WGM ring corresponding to the driven frequency at 653.7MHz is plotted to show its radial displacement profile. As the deformation shape in the Figure 5.6 inset shows, the WGM ring does not undergo uniform radial dilation, but rather exhibits expansions and contractions along its outer perimeter with respect to the ring's initial outer circumference. By plotting the position of the deformed ring's outer perimeter, we can determine an average radial displacement ( $\Delta r_{avg}$ ) that would



Figure 5.6: COMSOL simulation of primary mechanical mode appearing in frequency domain admittance sweep. Inset shows deformation in WGM ring (scaled 1000x) and plot of outer radius displacement as a function of azimuthal angle.

generate the same path length change as a uniform radial dilation in considering the device modulation capability. Based on the average radial displacement for a given rms voltage applied in the simulation, we estimate a  $\eta_{om}$  value ~10.1 pm/V. This value is then compared to experimentally determined values extracted from output power modulation. It should be noted however, that in the case of an ideally matched resonator, the  $\eta_{om}$  value can be significantly

higher. In the CMR, the effective displacement at resonance can be described by 
$$Q_{mech}\left(\frac{F_{piezo}}{m_{eq}\Omega_m^2}\right)$$
.

 $F_{piezo}$  is the force generated by piezoelectric actuation, which is given by  $\eta V_{rms}$ . As we have noted, for the width-extensional mode in a ring,  $\eta$  can be well-approximated by the term

$$2d_{31}E_{eq}(2\pi R_{avg})$$
. The  $\eta_{om}$  term at resonance may thus be re-cast as  $Q_{mech}\left(\frac{4\pi d_{31}E_{eq}R_{avg}}{m_{eff}\Omega_m^2}\right)$ . Based

on  $Q_{mech}$  and the material constants typically found in AlN CMRs [11], it is apparent that a  $\eta_{om}$  value that is 2-3 orders of magnitude higher can be attained. Thus the traditional advantages of piezoelectric actuation, including higher electromechanical coupling efficiency and large force generation for low operating voltages also benefit the electro-optomechanical transduction scheme.

## 5.2.2 Optical coupling

In order to implement a fully integrated device, light is coupled into the WGM ring through optical fibers with the use of on-chip grating couplers and a photonic wire waveguide. This enables the simultaneous probing of the RF and optical ends of the device, which can also facilitate future wafer-level testing. Several considerations for the optical design are closely linked to the device fabrication (covered in the following section). Figure 5.7 shows crosssectional views of the waveguides and the WGM ring, in which the 300 nm AlN thickness is selected to allow guiding of an optical mode in a rib waveguide geometry, while allowing selective partial etching without the use of hard mask layers. Likewise, the underlying silicon dioxide layer thickness was determined based on coupling efficiency for the grating couplers, which employ the geometry discussed in Chapter 2. Although the film was reduced in thickness, FDTD simulations did not show a significant reduction in theoretical peak coupling. A number of trade-offs are considered in selecting the single partial etch depth of ~220 nm. These include the ability to enable efficient coupling for the gratings in the C-band, define the rib waveguide structure and partially etch the WGM-waveguide gap, while simultaneously avoiding the use of a hard mask (based on the resist etching selectivity) and serving as an effective release mask. Using an AlN thickness of 300 nm and waveguides with 1 µm width, transverse electric (TE) modes are guided with a slab thickness of 80 nm. This is shown in Figure 5.7(a). In addition to the gratings,

the other critical feature for optical coupling is the WGM ring to waveguide gap. The WGM is simulated for the selected geometry with the use of the axisymmetric FEM model for the AlN ring. The first-order radial quasi-TE mode is plotted in Figure 5.7(b) for m=258, corresponding to a wavelength of 1538.5 nm (which has an effective index of 1.57, closely matching the guided effective index in the waveguide). As the profile indicates, the optical mode is largely confined to the periphery of the  $6\mu$ m ring. In addition, the surrounding vacuum creates tight confinement, ensuring that the evanescent mode is within a few hundred nanometers of the ring's edge. In order to achieve critical coupling – a preferred feature of the WGM resonator to produce maximal output modulation – a gap size of 75 nm was selected. Finally, the decision to partially etch the gap and leave a pedestal layer has been previously shown to enable strong coupling [64], while simultaneously ensuring that the waveguide and WGM ring remain on the same plane in the post-released structure.



Figure 5.7: (a) TE guided mode in AlN rib waveguide, (b) Axisymmetric FEM simulation of quasi-TE WGM in AlN ring for  $\lambda_o = 1538.5$  nm

## **5.3 Device fabrication**

As discussed in Chapter 4, the design choices selected in the preceding section are driven in large part by the requirements for both class of resonator to be produced simultaneously. While
the finalized process steps are described here in summary and depicted pictorially in Figure 5.8, a complete process flow may be found in Appendix A.



Figure 5.8: Fabrication process steps for piezoelectric CMR-driven acousto-optic modulator

Fabrication of the modulator begins with the use of a high resistivity (20,000  $\Omega$ ·cm) silicon wafer. The wafer is thermally oxidized to produce a 1.1 µm layer of silicon dioxide, which serves as a buffer layer to guide the optical signal through the rib waveguides on chip. Bottom electrodes are patterned on the wafer with the use of a Nikon G4 stepper. 40 nm of platinum (preceded by a 5 nm titanium adhesion layer) is deposited on the wafer with a Perkin-Elmer 6J sputtering system. A lift-off process is applied in order to complete the bottom electrode definition. The aluminum nitride thin film is then deposited on the wafer to a thickness of 300 nm using a Tegal Advanced Modular Sputtering (AMS) tool. Subsequent x-ray diffraction rocking curve measurements confirm c-axis orientation with a full-width at half maximum (FWHM) of 2.01° at AlN's 36° peak. Following the AlN deposition, top electrodes are patterned and lifted-off in the same manner as for the bottom electrodes. Chromium serves as an adhesion layer for the subsequent 115 nm of Gold used in the top electrodes. Subsequently, the AlN is patterned in the first of three steps. First, most large features are defined (down to a resolution of 1  $\mu$ m) with the use of stepper lithography – to form the outer definition of the resonators and the waveguides. This allows the rib waveguides for example, to be long enough for the gratings and RF pads to be simultaneously accessed during the subsequent testing when using the glass V-groove fiber array. Following the first AlN lithography, the wafer is etched with Cl<sub>2</sub>/BCl<sub>3</sub> chemistry in a PlasmaTherm inductively coupled plasma tool down to a thickness of 80 nm. At this point the wafer is diced, and individual dies are used for further processing.

In order to define the sub-micron features required for optical coupling, electron-beam lithography with the Nano Pattern Generation System (NPGS) on a FEI Sirion scanning electron microscope (SEM) is used in the subsequent steps. Prior to defining these critical features however, another lithography step is required to open up release and via windows through the 80 nm AlN film. The release windows are patterned along the periphery of the acoustic and photonic ring resonators, while via windows are patterned above the bottom electrode pads. By etching through the 80 nm AlN at this point, the underlying oxide and platinum, respectively are exposed. The critical optical features – namely the gratings and the gap between the waveguide and photonic resonator are then defined, and etched down to 80 nm as in the surrounding regions. Given the relatively short amount of etching (~220 nm), the e-beam resist PMMA is used as the only etch mask without the need for a separate hard mask. As a result, the partially etched gratings remain protected from lifting off in the subsequent release step, and the partially etched

gap allows the released photonic ring to remain in plane with the optical waveguide (thus mitigating problems associated with post-release residual stress).

Once the structures have all been defined, the final step is to release the rings to allow them to freely vibrate. The entire die is placed in a SPTS Primaxx HF vapor etcher, and the 80 nm AlN serves as a natural etch mask to the underlying silicon dioxide. The release is timed such that a pedestal of oxide remains under the central hub of each ring. SEM images of the completed device are shown in Figure 5.9.



Figure 5.9: SEM images of finalized acousto-optic modulator device. CMR and WGM rings (zoomed in at top right) are highlighted in red, gratings (zoomed in at bottom right) and rib waveguides are highlighted in green, top gold electrode highlighted in yellow and bottom platinum electrodes highlighted in blue. Figure inset highlights 75 nm WGM ring-waveguide gap.

## **5.4 Modulator characterization**

Device characterization is carried out on a probe station assembled to simultaneously test both acoustic and optical responses. A schematic of the complete experimental setup is shown in Figure 5.10. As seen in the device SEM of Figure 5.9, the dimensions of the device are laid out in order to allow simultaneous access to RF ground-signal-ground (GSG) probes and the optical grating couplers with the use of a glass fiber array. Due to the fact that the fiber array obscures a large portion of the device during testing, the rib waveguides (in which optical losses are relatively low) are elongated to allow the RF pads to be comparatively short, in order to minimize parasitic capacitances on chip. Independent characterizations of the acoustic and optical responses allow relevant device parameters to be extracted, which are used to analyze the power modulation in the composite structure.



Figure 5.10: Experimental setup for testing acoustic and photonic responses of modulator device

#### 5.4.1 Acoustic resonator

Response in the acoustic resonator is determined by using the vector network analyzer (VNA) to collect the  $S_{11}$  reflection coefficients for the device across a sweep of frequencies in a one-port configuration. This response is plotted in terms of admittance, as shown in Figure 5.11. The radial contour mode excited in the CMR ring shows up at 653.96MHz, with a mechanical quality factor for the composite structure of ~270. This electromechanically-determined quality

factor is later confirmed with the optomechanical measurement. Equivalent electrical parameters are extracted for the CMR through a fitting to the MBVD circuit model. Namely this allows the effective impedance of the device to be evaluated, which determines the rms voltage appearing across the AlN and the corresponding lateral displacements mapped through the  $\eta_{om}$  term.



Figure 5.11: Admittance response and fitting parameters to MBVD model

### 5.4.2 Photonic resonator

The optical resonator is characterized by collecting insertion loss measurements for the device through a sweep of wavelengths using a tunable laser source (Santec TSL-510). Polarization paddles are used to couple the TE mode to the input grating coupler, and the output is collected with an optical power meter (Exfo PM-1103). Optical transmission measurements are shown in Fig. 8, in which the grating coupler transmittance and fiber alignment account for the majority of losses. A finer sweep of wavelengths is performed to extract the response of the optical resonator at  $\lambda_o = 1539.247$  nm and the normalized transmission is least squares fit to a Lorentzian function. Loaded ( $Q_L$ ), coupling ( $Q_c$ ) and intrinsic ( $Q_o$ ) quality factors are extracted from the data, which are also used to derive the cavity decay ( $\kappa$ ) and coupling loss ( $\kappa_c$ ) rates for the resonator. The extracted optical quality factor is ~20,740, corresponding to a  $\kappa/2\pi$  of

9.39GHz. Based on these values, the amount of optical force  $(F_{opt})$  generated in the WGM ring may be calculated by  $|a|^2 g_{om}/\omega_o$ , where  $g_{om}$  is the optomechanical coupling coefficient  $(=\omega_o/R)$ and  $\omega_o$  is the optical cavity frequency. The intra-cavity field intensity is described by  $|a|^2 = \frac{2\kappa_c P}{\kappa^2 + \Delta^2}$ , where P is the optical input power, and  $\Delta = \omega_o - \omega_p$  is the detuning of the laser frequency  $(\omega_p)$  with respect to the cavity resonance frequency. Accounting for the gratings and the decay rates, the optical force is estimated to be ~0.27nN, which would produce an effective displacement that is a few orders of magnitude less than the piezoelectrically-induced values. As a result, the optically-generated forces may be disregarded in the present device.



Figure 5.12: Optical insertion loss for WGM resonator and isolated resonance at  $\lambda_0 = 1539.27$  nm with extracted loaded, coupling and intrinsic quality factors

#### 5.4.3 Electro-optomechanical response

The complete structure is tested by using the VNA to provide the input electrical excitation across a range of frequencies, while the WGM resonator is simultaneously biased to a wavelength corresponding to a maximum in the  $dT/d\lambda$  function. The modulated optical transmission is fed into a 1GHz bandwidth avalanche photodetector (APD – New Focus 1647), to convert the power

modulation back into the electrical domain. Conversion gain in the APD is adjusted based on its bias setting, and is typically fixed to 14,000 V/W based on the input optical power level. The



Figure 5.13: S<sub>21</sub> insertion loss showing the electro-optomechanical device response up to 1GHz for cavity detuning with respect to optical resonance at 1503.057 nm. Insets show simulated mechanical modes corresponding to peaks observed in the transmission plot.

APD output is then sent back into the VNA (to determine the  $S_{21}$  forward transmission characteristic of the device) or an electrical spectrum analyzer to measure the output modulation power. The  $S_{21}$  response of the device up to 1GHz is shown in Figure 5.13. In addition to the electromechanically-measured mode appearing at 654MHz, several other mechanical modes of vibration are also detected. These modes do not appear in the electromechanically-generated admittance response, due to the fact that their detection depends on the strength of the mode's electromechanical coupling given the specific electrode layout of this work. Based on these factors, only the modes with sufficient motional current are possible to detect electrically. The optical detection scheme however, is sensitive to any source of displacements – which are

generated as the VNA is swept across the frequency spectrum. Namely, there are a number of low-frequency (<100MHz) modes, the most prominent of which occurs at 35MHz, and another peak appearing at 884MHz. In the case of the latter, it should be noted that this frequency matches the natural vibrational frequency of the non-electroded AlN ring, which can be analytically estimated by  $f = \frac{1}{2W} \sqrt{\frac{E}{\rho(1-\sigma^2)}}$ , where W is the width of the ring and E,  $\rho$  and  $\sigma$ 

are the equivalent Young's modulus, density and Poisson's ratio, respectively of the AlN.



Figure 5.14: S<sub>21</sub> response for the electromechanically observed resonance at 654MHz

A zoomed-in S<sub>21</sub> response of the electromechanically-detected mode is shown in Figure 5.14. The main peak is fitted with a Gaussian function, and a mechanical quality factor of 247 is extracted, which is in close agreement with the result previously obtained through electrical characterization. The corresponding optical resonance is also shown, along with the effect on the S<sub>21</sub> output response for cavity detuning values where  $dT/d\lambda$  is maximized or closer to zero. It should be noted that different optical resonances were selected for detuning the cavity in the plots of Figures 5.13 and 5.14. The optical resonance shown in Figure 5.14 exhibits a high-*Q* similar to the one isolated in Figure 5.12 (which is also used in the characterization shown in the following

section). However, a lower wavelength resonance (with lower optical Q but corresponding to lower optical insertion losses as shown in Figure 5.12) was used to plot Figure 5.13. This produces the difference in amplitudes for the 654MHz peak between the two plots, and also highlights the impact of the grating coupler transmission response in determining the magnitude of the  $dT/d\lambda$  value.

### 5.5 Power level sweeping

Modulation capability in the device is characterized in terms of the  $\eta_{om}$  value, which is defined by the amount of average radial displacement produced in the WGM ring for a given rms input voltage. In addition to the optical transmission power level, the modulator peak output is also a function of the input RF power. Effects of increasing RF power can be measured by monitoring the output optical power amplitude from the photodetector. The value of  $\eta_{om}$  can also be directly manipulated by modifying the mechanical Q of the device. These effects are studied here experimentally.

### 5.5.1 Wavelength variation

By varying the input RF power to the device, it is possible to collect a range of peak modulation levels, from which an averaged  $\eta_{om}$  value may be extracted. RF powers specified in this and the following section indicate the nominal values emitted from the VNA port, assuming matching to a 50 $\Omega$  load. As the device impedance is not perfectly matched however, the actual power delivered to the device is much lower (this consideration is taken into account in all calculations involving input RF power). In addition, the VNA is not swept across frequency, but rather operated in CW mode corresponding to the mechanical resonance frequency determined from the admittance plot. The variation in output power is then measured by sending the output of the APD into an electrical spectrum analyzer and monitoring the peak power value. In order to increase the magnitude of the output power modulation, the input laser power is increased to +15 dBm and the corresponding transmission characteristic of the WGM resonator is shown in Figure 5.15. The increased laser power however causes the resonator to heat up, which generates a red shift in the optical resonance wavelength ( $\lambda_o = 1539.276$  nm), and the non-linear response seen in the transmission plot. While this maximizes the  $dT/d\lambda$  function for red-detuned wavelengths, biasing the cavity at these points only generates an increase in power modulation when sweeping the wavelength in the positive direction, due to the instability of the resonator. The wavelength is swept in 10 pm steps, and corresponding peak modulation powers are plotted in Figure 5.15. As the average radial displacement is directly related to the applied RF power, the output optical power modulation also exhibits proportional increases corresponding to the increases in RF power input.



Figure 5.15: Optical resonator transmission for +15dBm laser input power (left) and corresponding peak optical output modulations collected from electrical spectrum analyzer at 10 pm wavelength intervals for various RF input powers

The measured power levels on the spectrum analyzer correspond to the voltages generated at the 50 $\Omega$  terminated output of the photodetector. This power level ( $P_{sig}$ ) can thus be described in terms of Eq. (5.8) and the conversion gain (G) as

$$P_{sig} = \frac{1}{Z_o} \left( \frac{\partial T}{\partial \lambda} \cdot \frac{\partial \lambda}{\partial r} \cdot \Delta r_{avg} \cdot G \right)^2$$
(5.8)

where  $Z_0 = 50\Omega$ . The average radial displacement is therefore

$$\Delta r_{avg} = \sqrt{\frac{P_{sig}Z_o}{\left(\frac{\partial T}{\partial \lambda} \cdot \frac{\partial \lambda}{\partial r} \cdot G\right)^2}}$$
(5.9)

In order to determine  $\Delta r_{avg}$  for each RF power level, we need to evaluate  $dT/d\lambda$  for the tested detuned wavelengths. Using an average off-resonance insertion loss level of -21.5 dBm and the loaded optical Q of 20,740, the  $dT/d\lambda$  function of Eq. (3.32) is evaluated for the tested wavelength range and plotted in Figure 5.16.



Figure 5.16:  $dT/d\lambda$  for tested wavelength range and VNA source representation

The  $\eta_{om}$  can then be extracted for each  $\Delta r_{avg}$ , by dividing out the  $V_{rms}$  corresponding to the RF input power applied. A representation of the VNA is also shown in Figure 5.16, where  $V_g$  is determined for each  $P_{RF}$  assuming  $Z_L = 50\Omega$ .  $V_{rms}$  applied to the device can therefore be determined by assessing  $V_g$  and the actual  $Z_L$  of the modulator collected from the admittance data of Figure 5.11. Dividing out  $V_{rms}$  from  $\Delta r_{avg}$  corresponding to each input RF power level for the thus yields  $\eta_{om}$ . This is shown in Figure 5.17. The average of the  $\eta_{om}$  for all data points in Figure 5.17 yields 12.4 pm/V. As a result of the thermo-optic nonlinearity in the optical resonance, the  $dT/d\lambda$  function does not fit the data as closely for the red-detuned wavelengths. In order to improve accuracy at these wavelength values, a moving average filter is applied to the optical transmission data, and its derivative is evaluated directly. This produces an average  $\eta_{om}$  value of 10.2 pm/V, which is similar to the FEM simulated result.



Figure 5.17:  $\Delta r_{avg}$  and  $\eta_{om}$  corresponding to RF powers and wavelengths of Figure 5.15

For comparison with the electrostatic case of [30], we can estimate an effective  $\eta_{om}$  value of ~247 pm/V from the peak modulation data provided. It should be noted that this larger value is largely due to a mechanical Q that is about 5x the one of the piezoelectric implementation reported here, and only produced when a 20V DC bias is used. As a result, it is still orders of magnitude lower than what could be achieved with piezoelectric actuation if the mechanical modes were to be matched, without the use of any DC bias voltage. This again highlights the benefits of utilizing piezoelectric actuation.

#### 5.5.2 Additional release

Displacements may also be increased in the device by reducing damping losses associated with the anchors, for example. In order to test this, devices were prepared in which an additional post-processing release step was performed with the use of  $XeF_2$  gas to partially remove the

underlying silicon. The release was timed such that the rings would remain fixed from their center hubs, but reduced the amount of anchoring. The electromechanical and optomechanical responses for the device with additional release are shown in Figure 5.18. This demonstrates an increase in the mechanical quality factor for the primary mode of the device, indicating a reduction of



Figure 5.18: Device responses after additional XeF<sub>2</sub> release to improve mechanical quality factors. Acoustic resonator admittance shown in plot on left (with SEM of the device in inset). Electro-optomechanical response shown on right, in terms of average radial displacement and fitted mechanical quality factor for acoustically-driven mode.

damping losses. Other factors limiting the mechanical quality factor besides the anchoring may include the contribution of the metal electrodes through dissipation mechanisms of thermoelastic nature, (see for example [82]). Additional release also reduces the stiffness of the anchoring beams, as a result of which there may be increased coupling into spurious modes in close proximity to the main resonance peak. In addition, the transmission (S<sub>21</sub>) through the device is increased in comparison with that of the original device in Figure 5.14. This can be explained in part by the increase in  $\eta_{om}$  coupling – as it is itself is a function of the mechanical quality factor. In fact,  $\eta_{om}$  roughly doubles as does the mechanical Q. Peak modulation for the XeF<sub>2</sub>-released devices is also measured using CW mode for the input, with the RF power and input laser power varied for a single wavelength. This is shown in Figure 5.19. As a result of the thermo-optic shift in the WGM resonance and the variation in transmitted power, the value of the  $dT/d\lambda$  term changes for each level of input laser power. This modifies the power modulation transfer function and the corresponding slope for each curve is slightly different. However, the peak optical output modulation shows the expected linear trend with respect to the input RF power across all levels.



Figure 5.19: Peak optical power modulation plotted for various levels of input RF and Laser power in XeF<sub>2</sub> released device. Optical resonator response shown for different power levels on left, with fixed bias wavelength (1527.320 nm) selected for all measurements highlighted in red. Plot of peak modulation produced from electrical spectrum analyzer shown on right, with linear relationship between applied RF power and optical modulation.

# Chapter 6 Piezoelectric opto-acoustic oscillator

Oscillators deliver a periodic signal converted from a continuous source of energy. Virtually all communication systems require highly stable reference oscillators producing spectrally pure signals in the range of MHz to GHz. Traditionally, quartz resonators have been applied in radio frequency (RF) systems thanks to extremely high Q-factors in the range of 10-100 MHz. Their use however suffers from the need to perform frequency multiplication to operate in higher bands, which also multiplies oscillator noise, as well as a lack of on-chip integration. Two promising technological alternatives, which have addressed different drawbacks associated with the state of the art, include the use of photonic-based and MEMS-based oscillators. In the case of the former, such as the opto-electronic oscillator [83], excellent phase noise performance has been achieved thanks to the use of a high-Q energy storage element, such as a long (km range) optical fiber loop. On the other hand, MEMS technology [84] benefits from compatibility with prevailing semiconductor fabrication techniques to enable single-chip oscillator solutions [8]. While these oscillators typically operate in different ranges, piezoelectric transduction offers the possibility to bridge this gap by scaling to higher operational frequencies in an integrated photonic platform. In this chapter, we consider the application of the acousto-optic modulator in an opto-acoustic oscillator loop. This can form a necessary component in an RF Photonic front end or serve other applications with improvements to the phase noise performance.

## **6.1 Oscillator Background**

The basic configuration for an oscillator is to form a feedback loop around a resonator or delay element, as shown in Figure 6.1. Use of a high Q resonator allows for improved stability and spectral purity. Various types of resonators have been used for stabilization of electronic circuits including mechanical resonators, electromagnetic resonators and acoustic delay lines.



Figure 6.1: Oscillator feedback loop

Resonator losses are compensated by an amplifier with gain A at a given frequency  $v_o$  (angular frequency  $\omega_o$ ). In order for the signal to be periodic, the loop phase must be zero, or a multiple of  $2\pi$  when  $\omega = \omega_o$ . The conditions required for oscillation of a complex signal  $A\beta(j\omega)$  are called the Barkhausen criteria, described by

$$|A\beta(j\omega)| = 1$$
  
arg  $A\beta(j\omega) = 0$  (6.1)

Oscillations start from noise, which requires  $|A\beta(j\omega)| > 1$  at  $\omega = \omega_0$  for small signals. As the oscillation grows, a control mechanism such as clipping of the signal reduces the loop gain to produce the stationary condition  $|A\beta(j\omega)| = 1$ . In general, the noise of a system can perturb both the amplitude and the phase of the oscillator output. Due to the amplitude-limiting mechanism however, the phase noise generally dominates. Consequently, this becomes the primary consideration in evaluating an oscillator's performance.

The phase noise can be modeled by considering the influence of random time-varying phase fluctuations,  $\psi(t)$ , on the oscillator response. The output of the oscillator can be described by

$$v(t) = V_{\rho} \cos[\omega_{\rho} t + \varphi(t)]$$
(6.2)

where v(t) is the output voltage with respect to time,  $V_o$  is the peak amplitude voltage and  $\varphi(t)$  is the phase with respect to time. For an ideal resonator, the relaxation time is described by

$$\tau = \frac{2Q}{\omega_o} \tag{6.3}$$

This is similar to the cavity decay rate described in Eq. (3.10) for the photonic resonator. In the case of slow fluctuations, where  $\psi(t)$  is slower than the inverse of the relaxation time, it can be shown [85], [86] that the oscillator's phase-fluctuation spectrum is given by

$$S_{\varphi}(f) = \frac{1}{f^2} \left(\frac{\nu_o}{2Q}\right)^2 S_{\psi}(f) \tag{6.4}$$

where  $S_{\varphi}$  and  $S_{\psi}$  are the power spectral densities of the phase of the gain element and the phase fluctuations of the closed-loop oscillator, respectively. For the fast fluctuations of  $\psi(t)$  (greater than the inverse of the relaxation time), the resonator does not respond and no noise regeneration takes place under these conditions, producing

$$S_{\varphi}(f) = S_{\psi}(f) \tag{6.5}$$

The combination of the slow and fast phase fluctuations is described by the Leeson formula, which relates the oscillator's output phase spectrum to the phase fluctuations of the amplifier as

$$S_{\varphi}(f) = \left[1 + \frac{1}{f^2} \left(\frac{\nu_o}{2Q}\right)^2\right] S_{\psi}(f)$$
(6.6)

From this formula, we can identify a cutoff value called the Leeson frequency,  $f_L = \frac{v_o}{2Q}$ , up to which point the phase noise has a  $1/f^2$  dependency. Beyond this frequency, or close-in region, only additive processes contribute to the phase noise. In the absence of amplifier flicker and

disregarding the noise of the resonator, this provides a complete description for the phase noise variation with respect to frequency.



Figure 6.2: General schematic of an opto-electronic oscillator (OEO)

In the case of an opto-electronic oscillator (OEO), a delay-line replaces the resonator of Figure 6.1. In the frequency domain a delay  $\tau$  is represented by  $\beta(j\omega) = e^{-j\omega t}$ . Since the loop can sustain oscillation for any frequency  $\omega$  where  $\arg A\beta(j\omega) = 0$ ,

$$\omega_n = \frac{2\pi n}{\tau},$$
 for integer *n* (6.7)

Therefore, a selection element is required to oscillate at a specific frequency. In addition, the oscillator's response to slow and fast phase fluctuations are not as straightforward as in the case of a resonator-based circuit, since the device is inherently wide-band and does not stop fast phase fluctuations. Nevertheless, since optical components can provide very high energy-decay times, the equivalent quality factor of a delay-line oscillator can also be very high. A generic schematic for the opto-electronic oscillator is shown in Figure 6.2. Here, the high-Q optical storage element can be an optical fiber as originally demonstrated in [83], or a whispering-gallery mode resonator, as has been demonstrated with the use of crystalline bulk materials in [87]. The frequency selective element is the RF filter in the case of the former, and the FSR of the resonator for the

latter. One of the benefits of the OEO is that it is a versatile architecture, which allows for the exchange of components (such as necessary gain) in the optical loop with electronic counterparts, or vice versa. We can also adapt the architecture used in the OEO to construct an opto-acoustic oscillator based on the CMR-based acousto-optic modulator. This case serves as a sort of hybrid between a conventional MEMS-based oscillator and a photonic oscillator, as the frequency selective element is still the mechanical resonator. Theoretically, the delay of the opto-acoustic case could be described by  $\tau = \frac{2Q_{mech}}{\Omega_{mech}} + \frac{2Q_L}{\omega_o}$ , where Eq. (6.3) is adapted to include the response

of the mechanical resonance and the circulation of photons in the WGM (here  $\omega_o$  denotes the optical frequency of the WGM resonance). Since the optical resonance frequency is orders of magnitude higher than our mechanical modulation frequency, we can effectively consider the mechanical resonance as the frequency selective parameter. As in the case of the OEO however, the additional degrees of freedom afforded by optical integration can offer benefits for the piezoelectric opto-acoustic oscillator, which we shall consider in Section 6.4.

## 6.2 Opto-acoustic oscillator loop



Figure 6.3: Optical resonance selected for oscillator testing and corresponding  $S_{21}$  response

Prior to setting up the oscillator loop, we first characterize the modulator that we will be implementing. In order to utilize the higher mechanical Q, we implement the XeF<sub>2</sub> released modulator shown in Section 5.5.2. In order to increase the output transmission power, +15 dBm of optical power is supplied from the laser source. A high optical quality factor ( $Q_L = 25,400$ ) resonance at 1528.042 nm is selected for the testing. The bias-point for the cavity detuning is selected experimentally by monitoring the wavelength corresponding to a peak in output power modulation when RF excitation is provided. This wavelength is determined to be 1528.020 nm, and remains fixed for the subsequent testing. The biasing of the optical cavity resonance and the corresponding S<sub>21</sub> response are shown in Figure 6.3.



Figure 6.4: Piezoelectrically-actuated opto-acoustic oscillator loop

The modulator is then configured as an oscillator by closing the loop from the output of the APD with SMA components in a manner similar to the OEO. The corresponding schematic is shown in Figure 6.4. Bias conditions for the APD remain fixed with respect to the preceding modulator characterization (G = 14,000 V/W). In order to satisfy the Barkhausen criteria of Eq. (6.1), the loop must achieve unity gain and zero phase shift. The first requirement is met by using

an RF amplifier to compensate for losses in the modulator transmission. In order to provide sufficient gain, two amplifiers (Mini-Circuits ZKL-1R5+) are cascaded in series. The second criterion is met by sending the amplified output through a phase shifter (Colby Instruments PDL-100A). This signal can then be routed through a power splitter to feed back into the modulator input, and monitor the oscillation simultaneously. While testing the oscillator response, the voltage bias of the two amplifiers is varied in order to achieve the necessary gain condition. The bias voltages ultimately used were +12V and +6.6V, which yield a collective gain of ~66 dB. In addition, the oscillator locks more readily to the low frequency mechanical mode seen in Figure 5.12. In order to observe the oscillation at 652.8 MHz, a high-pass filter (Mini Circuits SHP-400+) with a cutoff frequency of 395 MHz is introduced in the oscillator loop. The test setup is shown in Figure 6.5.



Figure 6.5: Test setup for oscillator testing

Oscillation is monitored at the output of the splitter with a spectrum analyzer (Agilent 8562EC). The carrier signal is measured at 652.8 MHz with an RF power of +6.51 dBm. The associated phase noise was also measured with a signal source analyzer (Agilent 5052B). This showed a noise floor of -106 dBc/Hz and a phase noise at 10 kHz offset of -72 dBc/Hz. These

responses are shown in Figure 6.6. We expect to observe the Leeson corner frequency as  $f_c/(2Q_{mech})$ , where  $f_c$  is the carrier frequency and  $Q_{mech}$  is the device mechanical quality factor. Based on the carrier frequency of 652.8 MHz and  $Q_{mech} \sim 450$ , the corner frequency is approximately 725 kHz, which roughly corresponds to the observation in the phase noise plot for the intersection point between the floor noise and the close-in region.



Figure 6.6: Oscillation spectrum and associated phase noise for carrier at 652.8 MHz

# 6.3 Phase noise model



Figure 6.7: Noise and signal generation at photodetector output

In order to evaluate the oscillator response, it is useful to analyze the sources of the noise. Similar to the OEO [83], noise in the opto-acoustic oscillator loop can primarily be attributed to the photodetector, the laser and the amplifier used to overcome the transmission losses through the modulator. Since the photodetector is directly connected to the RF amplifier, the noise to signal ratio can be considered at the input of the amplifier. This is shown schematically in Figure 6.7. To generate a description of the phase noise with respect to frequency, we will start with the Leeson formula of Eq. (6.6). In this expression, we assess the power spectral density of the random phase fluctuations  $(S_{\psi})$  by taking the ratio of the mean-square noise voltage density ( $\overline{v_n^2}/\Delta f$ ) to the mean-square carrier voltage ( $\overline{v_{sig}^2}$ ) [88]. We express the power density of the input noise for all additive processes originating at the photodetector as  $\rho_N$ . Likewise, the carrier power emanating from the photodetector is indicated by  $P_{sig}$  (as described in Eq. 5.8). In evaluating the single-sideband noise spectral density, we can consider one-half the contribution of  $\rho_N$ . This generates the following expression for  $S_{\psi}$  as

$$S_{\psi}(f) = \frac{\overline{v_{n}^{2}}/\Delta f}{\overline{v_{sig}^{2}}} = \frac{\left(\frac{1}{2}\right)\rho_{N}R_{PD}}{P_{sig}R_{PD}} = \frac{\rho_{N}}{2P_{sig}}$$
(6.8)

where  $R_{PD}$  is the termination resistance of the photodetector.

The fundamental contributors to the input noise power density are thermal noise, shot noise and the laser's relative intensity noise (RIN). These sources can be expressed as

$$\rho_{N} = Thermal \ noise + Shot \ noise + Laser \ RIN$$

$$\rho_{N} = (4k_{B}T \cdot NF) + (2eMF_{A}I_{APD}R_{PD}) + (N_{RIN}I_{APD}^{2}R_{PD})$$
(6.9)

In the first term, describing the thermal noise,  $k_B$  is the Boltzmann constant, T is the ambient temperature and *NF* is the noise figure of the amplifiers. The second term expresses the shot noise in the avalanche photodiode receiver [46] used in the experiment, where e is the electron charge, M is the multiplication factor,  $F_A$  is the excess noise factor and  $I_{APD}$  is the photocurrent across the load resistor of the APD (note that here we assume  $I_{APD} = MRP_{in}$ , where R is the responsivity of the detector, and  $P_{in}$  is the incident optical power). Relative intensity noise (RIN) is likewise normalized to the power at the receiver output, where  $N_{RIN}$  is the RIN of the pump laser. In addition, the noise figure of the amplifiers can be expressed by the Friis formula

$$NF_{total} = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1G_2} + \frac{NF_4 - 1}{G_1G_2G_3} + \dots + \frac{NF_n - 1}{G_1G_2\dots G_{n-1}}$$
(6.10)

where  $NF_n$  and  $G_n$  are the noise figure and gain, respectively of the n<sup>th</sup> amplifier. This means that the contribution from the second amplifier can effectively be neglected. It is useful to re-express  $\rho_N$  in terms of the signal power as

$$\rho_N = (4k_B T \cdot NF) + (2eMF_A \sqrt{P_{sig}R_{PD}}) + (N_{RIN}P_{sig})$$
(6.11)

Therefore, we should estimate  $P_{sig}$  in order to evaluate  $S_{\psi}$  and the corresponding phase noise response with respect to offset frequency ( $\Delta f$ ) as

$$L(\Delta f) = 10 \log \left[ \frac{\rho_N}{2P_{sig}} \left\{ 1 + \left( \frac{f_c}{2Q_{mech} \Delta f} \right)^2 \right\} \right]$$
(6.12)

#### 6.3.1 Measurement of component losses

Based on the carrier power measured in the spectrum analyzer, we can estimate the  $P_{sig}$  value at the APD output by traversing the loop and considering the component losses as shown in Figure 6.8. The gain of the amplifier chain was previously measured with the selected bias voltages, and the insertion loss through the phase shifter is measured at the tested frequency (-1.9 dB). Since the connection to the device from the power splitter takes place through a short SMA cable, the insertion loss through the modulator in the oscillator circuit includes the losses of the RF probes and cable – which are normally calibrated out during S<sub>21</sub> characterization. To account for these losses, calibration was repeated up to the plane of the connecting SMA cable and the peak S<sub>21</sub> at the oscillation frequency was determined to be -56 dB. Finally, the splitter is designed to operate with 50 $\Omega$  matched loads, but since the CMR device impedance is not matched, there will be additional reflections originating at this connection. To estimate the insertion loss generated by the splitter for both output ports, a model splitter was simulated in ADS for loads at output ports 2 and 3 of 50 $\Omega$  (corresponding to the signal source analyzer) and 355 $\Omega$  (the approximate impedance of the CMR at resonance as shown in Figure 5.17), respectively. This produces an estimate for the insertion losses from ports 1 to 2 and from ports 1 to 3. There are still some unaccounted losses (0.8 dB) which can be seen by traversing the loop with the determined values. However, we can estimate  $P_{sig}$  from the measured carrier power ( $P_{carrier} =$ +6.51 dBm) as -54.29 dBm.



Figure 6.8: Measurement of individual component losses and S<sub>21</sub> response with RF probe losses

### 6.3.2 Noise contributions

Using the estimated signal power, we can now assess the individual contributions to  $\rho_N$ , and plot the phase noise with the Leeson formula. In Eq. (6.11), we assume T = 293K and NF = 3.05 dB (for the amplifier chain). In addition, we apply the empirical relationship  $F_A = M^x$ , where x =0.7 for the InGaAs APD used (New Focus 1647), which has a quoted  $F_A = 5$ . The APD is terminated in a 50 $\Omega$  load ( $R_{PD}$ ) and the RIN of the laser (Santec TSL-510) is -145 dB/Hz. Based on these values, the components of  $\rho_N$  are Thermal noise density =  $3.26 \times 10^{-20}$  W/Hz, Shot noise density =  $6.88 \times 10^{-21}$  W/Hz and RIN density =  $1.17 \times 10^{-23}$  W/Hz. This produces a collective  $\rho_N = 3.95 \times 10^{-23}$  W/Hz and the corresponding noise floor of -113 dBc/Hz, which is plotted in Figure 6.9.



Figure 6.9: Measured phase noise and modeled response from estimation of  $P_{sig}$ 

It is apparent from the noise power density components, that the thermal noise is the dominant term. This can be explained by the fact that a relatively low photocurrent is generated at the output of the APD. As shown in Eq. (6.9) thermal noise is independent of photocurrent, while shot noise and RIN are proportional to the photocurrent and square of the photocurrent respectively. Consequently, the dominant noise term also corresponds to the occurrence of low, moderate or high photocurrent. In order to improve the oscillator's phase noise, the photocurrent (or  $P_{sig}$ ) must be increased from the modulator output.

# 6.4 Improvements to phase noise

In considering the approaches to improve  $P_{sig}$  we should again consider the modulator transfer function. This can be expressed in terms of its components as

$$P_{\rm mod} = \frac{dT}{d\lambda} \cdot \frac{d\lambda}{dr} \cdot \Delta r = P_{trans} H_{cav} \cdot g_{om\lambda} \cdot \eta_{om} V_{rms}$$
(6.13)

Here,  $P_{trans}$  is the off-resonance power level, and  $H_{cav}$  is the transfer function of the Lorentzian



Figure 6.10: Optical resonance with fitted parameters and modulator block from oscillator loop

with respect to wavelength (an equivalent representation with respect to frequency is  $P_{trans}H_{opt} \cdot g_{om} \cdot \eta_{om}V_{rms}$ ). The fitting of the optical resonance is shown in Figure 6.10. The  $\eta_{om}$  in the loop can be extracted from the measured S<sub>21</sub> value from the relation

$$S_{21,dB} = 20\log(P_{trans}H_{cav}g_{om\lambda}\eta_{om}G)$$
(6.14)

Using the optical quality factor and assuming the detuning of the cavity  $\lambda$ -  $\lambda_o$  (with the bias wavelength used in the experiment) we can determine the  $H_{cav}$  value and assess the other operating conditions ( $P_{trans} = -22.5$ dBm, G = 14,000 V/W) to extract  $\eta_{om} = 26$  pm/V. As noted in Chapter 5, this efficiency is diminished on account of the mechanical mode mismatch between the rings. The first possibility to increase the  $P_{sig}$  for the oscillator would thus be to improve  $\eta_{om}$ by utilizing the width-extensional mode of the ring. If we were to assume all the experimental conditions remain the same, the described by and  $\eta_{om}$ at resonance was

$$\eta_{om} = Q_{mech} \left( \frac{4\pi d_{31} E_{eq} R_{avg}}{m_{eff} \Omega_{mech}^2} \right)$$
 the value increases to ~6650 pm/V. Since the modulator operates

along the slope of the resonance, the collective  $\Delta\lambda$  (described by  $g_{om\lambda}\eta_{om}V_{rms}$ ) should not exceed one-half the bandwidth of the cavity. For the demonstrated device, this corresponds to about 30 pm. In the case of the matched modes with a much higher  $\eta_{om}$ , this implies that a lower excitation voltage can be utilized. The corresponding result on the phase noise response is shown in Figure 6.11. Here the same experimental conditions are assumed, but the photocurrent increase causes shot noise to become the dominant noise contribution. Aside from the  $\eta_{om}$ , another approach to amplify the modulator output could be to increase the optical Q of the cavity. Pursuing a higher optical Q however, may only be useful to compensate for lower values of  $\eta_{om}$ . This is because collectively, if we assume a critically-coupled optical resonator operating at its 3dB point (which produces a maximum output of  $\frac{dT}{d\lambda} = \frac{P_{rans}Q_L}{\lambda_o}$ ) and a  $\Delta\lambda$  which is maximized to one-half the

cavity bandwidth (or  $\frac{\lambda_o}{2Q_L}$ ), we see total the modulation capacity is determined by  $P_{trans}$ . However, in a non-idealized state, increased optical Q can certainly be advantageous to reduce the requirements of laser input power that would be required to increase  $P_{trans}$ .

Another way to improve the oscillator response would be to increase the mechanical Q of the structure. If for example, a  $Q_{mech}$  of 2000 could be achieved, which is commonly found in CMR devices operating in this frequency range, the Leeson frequency would also shift (~163 kHz), further reducing the oscillator phase noise. This is shown in Figure 6.11 by considering the original  $\eta_{om}$  scaled by the effect of an increased  $Q_{mech}$ , but not considering matching of the modes. To operate the oscillator in the RIN-limited regime, we could consider the effect of having matched mechanical modes in addition to  $Q_{mech} = 2000$ . In addition, we could replace the APD with a conventional photodetector with lower conversion gain (e.g. New Focus 1544 with G = 850 V/W), which would allow the  $P_{trans}$  to be increased above the saturation limit for the APD.

Here we assume  $P_{trans} = -10$  dBm and remove the effect of the excess noise factor. As a result, the noise floor drops to -147 dBc/Hz, and the oscillator becomes RIN limited. Although it is possible to increase the  $P_{trans}$  further and still operate under the saturation limit of the detector (increasing  $P_{sig}$ ), the noise floor of the oscillator cannot be reduced. Therefore similarly to the OEO, there are multiple degrees of freedom to improve the performance of piezoelectrically-driven opto-acoustic oscillators as well.



Figure 6.11: Phase noise plots of initial data and potential device improvements to operate in the different noise regimes of the photodetector.

# **Chapter 7 Conclusions and future work**

### 7.1 Thesis contributions

This dissertation has presented the realization of a fully integrated platform to enable the modulation of whispering gallery mode resonators with piezoelectrically actuated laterally vibrating MEMS devices for the first time. This method of electrically controlling optomechanical structures through the strong electromechanical coupling afforded by piezoelectric actuation should enable new possibilities for future integrated RF-Photonic modulators. As a result, it can be considered a building block towards the realization of a future RF-Photonic front-end that combines the filtering and frequency reference capabilities of MEMS resonators with photonic integrated circuits. With regard to the current demonstration, there are numerous ways to improve the modulation response. These include the reduction of coupling losses and increasing optical quality factors as well as structural re-designs to match the mechanical modes and reduce damping losses. Nevertheless, the current process that has been demonstrated should be able to accommodate all these changes, and also enable scaling to higher frequencies of operation. In summary, this thesis has made the following original contributions in aluminum nitride:

- Demonstration of low loss, wide 1 dB bandwidth C-band optical grating couplers
- High- $Q_L$  (>10<sup>4</sup>) 2D traveling wave evanescently coupled integrated photonic resonators
- Development of a robust, CMOS-compatible fabrication process for concurrent production of acoustic and photonic resonators to enable optomechanics
- Piezoelectrically actuated acousto-optic modulator at 653 MHz
- Opto-acoustic oscillator based on piezoelectric modulation

 Approach towards enabling super high frequency (SHF) operation of photonic modulators and reference oscillators in an integrated platform based on a new class of piezoelectric optomechanical devices

### 7.2 Future Research Directions

The area of integrated piezoelectrically actuated optomechanical systems is only in its early stages, and multiple possibilities abound for various applications that extend beyond the realm of RF-Photonics. Nevertheless, based on the concepts presented in the optomechanical modulation model of Chapter 3 there are a number of possibilities that we can envision for generating new approaches to acousto-optic modulation. In addition, we can also enhance the performance of the devices already presented. A few of these ideas are presented here for future work.

### 7.2.1 Elasto-optic modulation

It is well-known that mechanical strains are generated in piezoelectric materials when they undergo electrical excitation. This fact may be exploited to produce optical modulation that does not rely on displacement changes at all, but only on the refractive index changes that are induced by strains via the elasto-optic effect. By demonstrating an AlN optomechanical resonator in which transmission changes are only produced through the contribution of the  $\Delta n$  component, we will also be able to extract the relevant elasto-optic coefficients. These coefficients have previously only been theoretically derived [21], and while they have been applied for predicting the diffraction of optical waves by surface acoustic waves in AlGaN [26], there are no experimental verifications in pure AlN. In order to demonstrate this effect, we propose to modify an AlN CMR and integrate it into a photonic racetrack resonator, which is conceptually similar to the electro-optic modulator of [89]. This is depicted in Figure 7.1.



Figure 7.1: (a) Elasto-optic modulation of racetrack resonator via waveguide integrated into CMR body, (b) Finite element simulation of strain distribution along CMR and waveguide cross-section at 157.1MHz resonant frequency, (c) Intensity of optical field in ridge waveguide used to determine interaction with strain, (d) Theoretical modulation of elasto-optic racetrack resonator.

In order to generate refractive index changes in a section of waveguide, we will rely on inplane strains, which are produced in the body of a CMR. This is described in bulk materials by perturbations to the index ellipsoid, given by  $\Delta n_i = -0.5n_i^3 p_{ij}S_j$ . In this case, the CMR will generate a strain  $S_I$ , which will interact with TE polarized light in an optical waveguide to generate a change in the effective index of AlN, described by  $\Delta n_{eff} = -0.5n_{eff}^3 p_{11}S_1$ . As a result of the in-plane symmetry of the material, we can consider changes to the ordinary refractive index only, and the coefficient  $p_{II} = p_{22}$  will be utilized. The CMR-integrated waveguide section will be part of the racetrack resonator, which will be optically isolated from the remainder of the CMR body through an isolation region. The isolation will be formed by a partial etch of the AlN, which will generate a ridge waveguide structure integrated into the body of the CMR. The partially etched region should be kept to a minimum to prevent acoustic reflections, while producing sufficient optical isolation. Considering a 1 µm width for the waveguide section, 2 µm of partial etch on either side is assumed. The waveguide should be positioned at approximately  $\lambda_a/2$  from the end of the electroded section of the CMR, where  $\lambda_a$  is the acoustic wavelength in AlN, in order to correspond to a relative maximum of the strain distribution along the width of the resonator. The same structure is mirrored on the other side of the CMR to preserve symmetry in the vibrating structure, although it is not used as a waveguide.



Figure 7.2: AlN racetrack resonator with partially etched slab thickness and critically coupled resonance for 900 nm waveguide to resonator coupling gap

Assuming  $\lambda_a/2 = 20 \ \mu\text{m}$  for the electrode placement, the width of the CMR with symmetric waveguides is 100 µm. For AlN film thickness = 400 nm, a CMR length of 200 µm, AC electrical excitation of 0.5V and  $Q_m = 1000$ , the resonant frequency is ~157 MHz, which produces the lateral strain distribution along a cross-section of the resonator (seen in Figure 7.1). From this cross-section, the strain produced in the waveguide portion is the main consideration. In order to determine an "effective strain" that can be used to estimate the change in refractive index, the overlap of  $S_I$  with the guided TE optical mode must be considered. This can be estimated by

$$S_{1, eff} = \frac{\iint S_1 \cdot E_{x,op}^2 dx dy}{E_{x,op}^2 \cdot A}, \text{ where } S_I \text{ is the strain distribution in the waveguide, } E_{x,op} \text{ is the optical}$$

field distribution, and A is the area of the waveguide cross-section. Based on the effective index in the ridge waveguide ( $n_{eff} = 1.576$ ) and the estimated value for  $p_{11} = -10 \cdot 10^{-2}$  [21],  $\Delta n_{eff} = -$  4.57  $\cdot 10^{-5}$ . This value may then be supplied to the optomechanical modulation model. Assuming a non-resonant optical insertion loss level of -25 dB, and a photodetector conversion gain of 14,000 V/W (e.g. New Focus 1647), the peak modulation output power is plotted as a function of optical quality factor ( $Q_L$ ). As the plot of the expected output shows, it should be possible to detect resonant modulation at levels which are fairly high in comparison to the required optical Q. Preliminary demonstrations of the proposed racetrack resonator used in the structure (in which 400 nm thick AlN is partially etched to a slab thickness of ~100 nm) show critical coupling is possible to achieve with a waveguide to racetrack coupling gap of 900 nm, as shown in Figure 7.2. Here, the use of the directional coupler relaxes the lithography resolution required for the coupling gap, while still producing an optical quality factor ( $Q_L$  of ~5500) that is sufficient to measure an output level comparable to the modulators demonstrated in this thesis. This proposed device can provide an experimental quantification of the  $p_{11}$  coefficient, which as reported in [26] may also be underestimated from calculations. In addition, it can become an interesting new device architecture for integrated AlN acousto-optic modulators.



7.2.2 Piezoelectric control of integrated photonic waveguides

Figure 7.3: Released cantilever beams integrated into AlN optical waveguide and corresponding insertion loss measurement

An alternate approach for enabling piezoelectric control of optical structures is through the direct modulation of integrated waveguides. As shown in Figure 7.3, optical transmission through released AlN cantilevers with a separation gap of <100 nm has been demonstrated. In this case, axial offsets to end-coupled waveguides (with a gap in between) will generate a change in

transmission according to  $T = exp\left[-\left(\frac{t}{w}\right)^2\right]$ , where *t* is the offset amount, and *w* is the Gaussian

mode field radius [31]. If we consider an AlN waveguide with a thickness of 350 nm and a width of 1  $\mu$ m, the transmission characteristics as a function of the offset may be considered, and additional gaps will create an effective cascade of these transmissions as shown in Figure 7.4. In order to modulate a section of the waveguide, it may be possible to use a cantilever beam attached to the waveguide at a small connection point (to prevent unintended losses). As the end of the beam will no longer be free but guided, the lengths required to achieve appreciable transmission modulation may be up to ~100  $\mu$ m [90]. This will likely pose a problem due to stresses bending



Figure 7.4: Piezoelectric modulation of AlN waveguides: (a) Net transmission through 350nm x 1000nm waveguide with two gaps, (b) Schematic of cantilever actuated waveguide with gaps, (c) Unimorph cantilever used to deflect beams with deflection for a free-end, (d) Modulation of beam coupled to one arm of a Mach-Zehnder interferometer.

the released beams, but a folded-flexure design [91] can be used to alleviate this effect.

Another possibility for modulating transmission is by using cantilevers to modulate a beam which is coupled to one arm of a Mach-Zehnder interferometer. For example, with a gap of 100 nm between two waveguides, an offset of 100 nm out of the plane will generate an effective index change of  $2.1 \cdot 10^{-3}$ . Over an arm length of 200 µm, this will generate a phase shift of  $\sim \pi/2$ , which will be detectable as an output intensity modulation.

#### 7.2.3 Opto-acoustic oscillator enhancement

As noted in Chapter 6, the phase noise of the oscillator is directly related to the photocurrent generated at the detector, which in turn is limited by the modulator insertion losses. Therefore, it is important to reduce these insertion losses by implementing improvements to optical coupling,  $Q_{opt}$ ,  $\eta_{om}$  and  $Q_{mech}$ . Specifically, it could be worthwhile to study the source of losses in the optical Q of the photonic resonator. This could be done by implementing changes to the fabrication process to reduce sidewall roughness [16]. With increased optical Q in the device, it could be possible to reduce the amount of electrical amplification in the loop. However, a more interesting possibility would be to generate self-oscillation through radiation pressure. It is possible this could be used to supplement the oscillation produced through electrical feedback, as has been demonstrated for electrostatic optomechanical resonators [92], [93], and consequently improve phase noise performance.
## **Appendix A: AlN acousto-optic modulator process flow**

The following is a step-by-step flow for the final process developed to fabricate the piezoelectrically-actuated acousto-optic modulator presented in Chapter 5. All devices were fabricated in the Carnegie Mellon Nanofabrication Facility and equipment references are made to tools located therein. Additional characterization (XRD and AFM measurements) was performed in the JEMR Microstructural Characterization Suite in the Carnegie Mellon Department of Materials Science and Engineering.

- Preparation: Begin with 4" silicon test (10-20Ω·cm) and high-resistivity (20,000 Ω·cm) wafers Thermal oxidation of wafers to 1.1 µm thickness [shipped to UC Berkeley NanoLab - ETR ATMOSWETOX2 module (1-2 um) on Tystar2]
  - Bottom electrode lithography: Acetone-IPA-DI water (AID) rinse, N<sub>2</sub> dry, Spin-Rinse-Dry (SRD) wafers 5 min HMDS Oven Vapor Prime Spin: AZ4110, 30 sec 5k RPM, 1min 100°C bake Nikon G4 Stepper: ALNMEMS2, METAL1, 250ms exposure, +0.75 Focus Offset Develop: 1min 2:1 AZ Developer:DI Water, Gentle agitation, 15sec DI rinse, N<sub>2</sub> dry Optical microscope: Inspect IPC Barrel Etcher: 1min, 100W, O<sub>2</sub> plasma Descum
  - Bottom metal deposition (Perkin-Elmer 6J): Pump to base pressure: <10<sup>-7</sup> T for HR wafers Titanium: 300sec/200W Presputter, 35sec/100W Sputter Platinum: 120sec/50W Presputter, 115sec/50W Sputter

 Ti/Pt Lift-off: Ultrasonic bath in acetone: 30min, Face-down in concave bottom Pyrex beaker Ultrasonic bath in acetone: 5min, Face-up in plastic beaker AID rinse, SRD

4. AlN deposition:

Flexus: Measure wafer without thin film Tegal AMS: (Optimized Deep Poison mode recipe) – Pump to base pressure  $<3x10^{-6}$  T, Preetch: 90sec, 150W RF, 15sccm Ar, Sputter: 253sec, 7kW AC/Tap setting 3, 21sccm Ar, 45sccm N<sub>2</sub> Nanospec: Recipe 6/Nitride on Oxide – Measure film thickness Flexus: Post-deposition stress measurement

Panalytical X'Pert Pro XRD rocking curve measurement: ½ degree slit, 2mm mask,  $12^\circ$  range,  $0.02^\circ\!/\!\text{step}, 1\text{sec/step}, 0.02^\circ\!/\!\text{s}$ 

5. Top electrode lithography: Acetone-IPA-DI water (AID) rinse, N<sub>2</sub> dry, Spin-Rinse-Dry (SRD) wafers
5 min HMDS Oven Vapor Prime Spin: AZ4110, 30 sec 5k RPM, 1min 100°C bake Nikon G4 Stepper: ALNMEMS2, RETICLE5, 250ms exposure, +0.75 Focus Offset, Set Mark shift (X & Y) Develop: 1min 2:1 AZ Developer:DI Water, Gentle agitation, 15sec DI rinse, N<sub>2</sub> dry Optical microscope: Inspect IPC Barrel Etcher: 1min, 100W, O<sub>2</sub> plasma Descum

- Top metal deposition (Perkin-Elmer 6J): Pump to base pressure: ~3x10<sup>-7</sup> T for HR wafers Chromium: 600sec/200W Presputter, 60sec/50W Sputter Gold: 60sec/50W Presputter, 120sec/50W Sputter
- Cr/Au Lift-off: Ultrasonic bath in acetone: 30min, Face-down in concave bottom Pyrex beaker Ultrasonic bath in acetone: 5min, Face-up in plastic beaker AID rinse, SRD
- AIN Partial Etch lithography: Acetone-IPA-DI water (AID) rinse, N<sub>2</sub> dry, Spin-Rinse-Dry (SRD) wafers 5 min HMDS Oven Vapor Prime Spin: AZ4110, 5k sec RPM, 1min 100°C bake Nikon G4 Stepper: ALNMEMS2, RETICLE5, 250ms exposure, +0.75 Focus Offset, Set Mark shift (X & Y) Develop: 1min 2:1 AZ Developer:DI Water, Gentle agitation, 15sec DI rinse, N<sub>2</sub> dry Optical microscope: Inspect IPC Barrel Etcher: 1min, 100W, O<sub>2</sub> plasma Descum
   AlN Partial Etch 1 (PlasmaTherm Versaline):
- And Partial Etch 1 (Plasma Therm Versame):
  Remove edge photoresist with acetone swab (or dice wafer into quadrants & mount on carrier)
  AlN\_Part\_Sid: 65sec, 5mT, 25sccm Cl<sub>2</sub>, 5sccm BCl<sub>3</sub>, 70sccm Ar, 0sccm O<sub>2</sub>, 125W RF, 400W ICP, 25°C electrode, 120°C lid, 70°C liner, 120°C spool
  Nanospec: Recipe 6/Nitride on Oxide Measure film thickness
  IPC Barrel Etcher: 5min, 300W, O<sub>2</sub> plasma PR strip, AID rinse, N<sub>2</sub> dry
- 10. Dice wafer into individual dies for subsequent e-beam lithography/processing
- 11. AID rinse, N<sub>2</sub> dry
- 12. Spin: PMMA A7, 30sec 3k RPM, 1min 180°C bake
- Pads lithography (FEI Sirion 400 with Nanometer Pattern Generation System (NPGS)): System Parameters (used in all subsequent NPGS steps): Auto-Align3 (AA3), 7 scans before align
  - Fracture entity: Field size 450 µm, AA3

Write – Spot Size 5, Magnification 480x, Center-Center Distance & Line Spacing 50nm, Dose: 415  $\mu C/cm^2$ 

Alignment to Au markers (Coarse Layers 10-13) – Spot Size 3, Magnification 480x, Center-Center Distance & Line Spacing: 400nm, Counts 20

- 14. Release window lithography (FEI Sirion 400 with NPGS): Fracture entity: Field size 250 μm, AA3 Write – Spot Size 3, Magnification 700x, Center-Center Distance & Line Spacing 15nm, Dose: 415 μC/cm<sup>2</sup> Alignment to AlN markers (Coarse Layers 10-13) – Spot Size 3, Magnification 700x, Center-Center Distance & Line Spacing: 400nm, Counts 20
  15 Develop: 1min 1:3 MIRK/IBA Centle agitation 15 and IBA rings. N. dry
- 15. Develop: 1min 1:3 MIBK:IPA, Gentle agitation, 15sec IPA rinse, N<sub>2</sub> dry Optical microscope: Inspect
- 16. AlN Partial Etch 2 (PlasmaTherm Versaline): Mount die on carrier wafer with thermal grease AlN\_Part\_Sid: 30sec, 5mT, 25sccm Cl<sub>2</sub>, 5sccm BCl<sub>3</sub>, 70sccm Ar, 0sccm O<sub>2</sub>, 125W RF, 400W ICP, 25°C electrode, 120°C lid, 70°C liner, 120°C spool DC Probe Station: Measure pads resistance

Remove from carrier, Rinse backside with acetone to remove grease IPC Barrel Etcher: 3min, 300W, O<sub>2</sub> plasma PR strip, AID rinse, N<sub>2</sub> dry

- 17. Spin: PMMA A7, 30sec 3k RPM, 1min 180°C bake
- 18. Gratings lithography (FEI Sirion 400 with NPGS):
- Fracture entity: Field size 300 μm, Border size 20 μm, AA3
  Write Spot Size 2, Magnification 600x, Center-Center Distance & Line Spacing 5nm, Dose: 415 μC/cm<sup>2</sup>
  Alignment to AlN markers (Coarse Layers 10-13) Spot Size 2, Magnification 600x, Center-Center Distance & Line Spacing: 400nm, Counts 50
- 19. Gaps lithography (FEI Sirion 400 with NPGS): Fracture entity: Field size 250 μm, AA3 Write – Spot Size 1, Magnification 870x, Center-Center Distance & Line Spacing 4nm, Dose: 415 μC/cm<sup>2</sup> Alignment to AlN markers (Coarse Layers 10-13) – Spot Size 1, Magnification 870x, Center-Center Distance & Line Spacing: 400nm, Counts 60 Alignment to AlN markers (Fine Layers 14-17) – Spot Size 1, Magnification 870x, Center-Center Distance & Line Spacing: 20nm, Counts 2
  20. Develop: 1min 1:3 MIBK:IPA, Gentle agitation, 15sec IPA rinse, N<sub>2</sub> dry
- 20. Develop: 1min 1:3 MIBK:IPA, Gentle agitation, 15sec IPA rinse, N<sub>2</sub> dry Optical microscope: Inspect
- 21. AIN Partial Etch 3 (PlasmaTherm Versaline): Mount die on carrier wafer with thermal grease AlN\_Part\_Sid: 60sec, 5mT, 25sccm Cl<sub>2</sub>, 5sccm BCl<sub>3</sub>, 70sccm Ar, 0sccm O<sub>2</sub>, 125W RF, 400W ICP, 25°C electrode, 120°C lid, 70°C liner, 120°C spool Remove from carrier, Rinse backside with acetone to remove grease IPC Barrel Etcher: 3min, 300W, O<sub>2</sub> plasma PR strip, AID rinse, N<sub>2</sub> dry
  22 Vanor HE Balansa (SDTS Primaw):
- 22. Vapor HF Release (SPTS Primaxx): Place on hot plate before etch: 3min, 250°C Recipe 5 (880sccm N<sub>2</sub>, 325sccm EtOH, 720sccm HF): 1050sec x 2cycles Optical microscope: Inspect

# Appendix B: MATLAB Photonic Resonator Fitting Code

The following MATLAB scripts are used to do least square fitting of optical resonator data to a Lorentzian function, and to the Transmission function of Eq. (3.28) to extract intrinsic ( $Q_o$ ) and coupling ( $Q_c$ ) quality factors. This applies to data that is in the format of a two-column text file ('sample.txt') collected from Labview in terms of wavelength (nm) and transmission power (dBm).

### B.1. Lorentzian fitting

Fitting of the data is done to a Lorentzian absorption lineshape normalized for an integral of

1 with the formula  $f_L(x) = \frac{2}{\pi\sqrt{3}} \frac{1}{c} \left[ 1 + \frac{4}{3} \left( \frac{x - x_o}{c} \right)^2 \right]^{-1}$ , where  $x_o$  is the center and c is the distance

between inflection points. The FWHM is related by  $c = FWHM / \sqrt{3}$ . An initial guess is made for the value c, and this is passed to function lorentzfunc\_cmt.m.

```
clear; close all; clc;
a = load('sample.txt');
                                         % Wavelength data (nm)
xa = a(:,1);
alinear = 10.^(a(:,2)/10);
alinearnorm = alinear/(max(alinear)); % Normalized data
minnorm = min(alinearnorm);
                                        % Minimum value
                                         % Guess value
cguess = 1;
[m,n] = min(alinear);
xa0 = a(n,1);
                                         % Resonant wavelength
% Least square fit Lorentzian function based on data and c guess value
[params,fval] = fminsearch(@(x)
lorentzfunc_cmt(x,xa0,xa,alinearnorm,minnorm,1),[cguess]);
k1=params(1);
% Display fitted FWHM and QL and plot normalized data & fitting:
FWHM = k1*sqrt(3)
QLfit = xa0/FWHM
figure;
plot(xa,alinearnorm,'r');
hold;
lflsq = lorentzfunc_cmt(k1, xa0,xa,alinearnorm,minnorm,0);
plot(xa,lflsq);
```

```
title('Normalized data 0-1 (Red) and Normalized LSQ fit (Blue)');
% Plot Normalized Transmission for original and fit data in dB:
figure;
axes('FontSize',16,'FontWeight','bold');
plot(xa,10*log10(alinearnorm),'.b');
hold;
plot(xa,10*log10(lflsq),'r');
title('Original data (Red) and Fit data (Blue) in dB');
xlabel('Wavelength (nm)','fontsize',16,'FontWeight', 'bold');
ylabel('Normalized Transmission (dB)','fontsize',16,'FontWeight',
'bold');
text(xa(20),10*log10(minnorm)+2.5,strcat('FWHM=',
num2str(FWHM*1000),'pm'));
text(xa(20),10*log10(minnorm)+1,strcat('Q_L=', num2str(QLfit)));
```

Function lorentzfunc\_cmt.m:

```
function L = lorentzfunc_cmt(params,xa0,xdata,alinearnorm,minnorm,mode)
cp=params(1);
% General Lorentzian:
absorbfit = ((2/(pi*sqrt(3)))*(1/cp))./((1+((4/3)*((xdata-
xa0)/cp).^2)));
% Normalize function to 1:
absorbfitnorm = absorbfit/(max(absorbfit));
% Match peak value to data transmission minimum:
maxnorm = 1-minnorm;
% Scale to this peak value
absorbfitnorm = absorbfitnorm*maxnorm;
% Lorentzian in terms of through transmission:
L = 1-absorbfitnorm;
if(mode==1)
    L=sqrt(sum((L-alinearnorm).^2));
end
```

#### **B.2.** Transmission function

Guess values are supplied for  $Q_o$  as q(1) and  $Q_L$  as q(2). Based on reported values,  $Q_c$  can be determined from Eq. (3.28). Overcoupled and undercoupled regimes can be determined from testing resonators with various coupling gaps and comparing the extinction ratios. Note that the frequency w0 should be supplied to the function transfer.m.

```
clear; close all; clc;
a = load('sample.txt');
xa = a(:,1);
alinear = 10.^(a(:,2)/10);
alinearnorm = alinear/(max(alinear));
c = 299792458;
[m,n] = min(alinear);
xa0 = a(n,1); % Resonant wavelength
```

```
% Angular frequency conversion
w = 2*pi*(c./xa);
w0 = 2*pi*(c/xa0);
q(1) = 10000;
                            % Qo initial guess
q(2) = 100000;
                            % QL initial guess
% Least square with the data and guess
[k,resnorm,residual,exitflag] = lsqcurvefit(@transfer,q,w,alinearnorm);
Tw2 = transfer(k,w);
figure;
plot(xa,alinearnorm,'r');
hold;
plot(xa,Tw2);
title('Plot of Least Square T(\omega)');
legend('Normalized data','Transmission fitting');
 Display on screen: k(2) = QL, k(2) = Qo, ER = Extinction ratio
QL = k(2)
Qo = k(1)
ER = 10*log10(min(alinearnorm))
% Plot normalized original data with fitting in dB
figure;
axes('FontSize',20,'FontWeight', 'bold');
% Normalized original data:
plot(xa,10*log10(alinearnorm),'ro','LineWidth',4);
hold;
% Transmission fitting:
plot(xa,10*log10(Tw2),'k','LineWidth',3);
xlabel('Wavelength (nm)','fontsize',20,'FontWeight', 'bold');
ylabel('Normalized Transmission (dB)', 'fontsize', 20, 'FontWeight',
'bold');
grid on;
```

Function transfer.m:

```
function T = transfer(q,w)
% q(1) is Qo and q(2) is QL
w0 = 1.232722377597509e+06; % Manually supply resonance
frequency
T = (abs([j*2*(w-w0)/w0+(2/q(1))-(1/q(2))]./[j*2*(w-w0)/w0+(1/q(2))]).^2;
```

### **Bibliography**

- [1] J. Capmany and D. Novak, "Microwave photonics combines two worlds," *Nat. Photonics*, vol. 1, no. 6, pp. 319–330, Jun. 2007.
- [2] D. Wake, D. Johansson, and D. G. Moodie, "Passive picocell: a new concept in wireless network infrastructure," *Electron. Lett.*, vol. 33, no. 5, pp. 404–406, Feb. 1997.
- [3] A. Fehske, G. Fettweis, J. Malmodin, and G. Biczok, "The global footprint of mobile communications: The ecological and economic perspective," *IEEE Commun. Mag.*, vol. 49, no. 8, pp. 55–62, Aug. 2011.
- [4] S. Iezekiel, Ed., Microwave Photonics: Devices and Applications, 1 edition. Chichester, U.K.; Hoboken, NJ: Wiley-IEEE Press, 2009.
- [5] R. C. Williamson and R. D. Esman, "RF Photonics," J. Light. Technol., vol. 26, no. 9, pp. 1145–1153, May 2008.
- [6] D. Marpaung, C. Roeloffzen, R. Heideman, A. Leinse, S. Sales, and J. Capmany, "Integrated microwave photonics," *Laser Photonics Rev.*, vol. 7, no. 4, pp. 506–538, Jul. 2013.
- [7] C. T.-C. Nguyen, "MEMS technology for timing and frequency control," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 54, no. 2, pp. 251–270, Feb. 2007.
- [8] C. T.-C. Nguyen and R. T. Howe, "An integrated CMOS micromechanical resonator high-Q oscillator," *IEEE J. Solid-State Circuits*, vol. 34, no. 4, pp. 440–455, Apr. 1999.
- [9] G. Piazza, P. J. Stephanou, and A. P. Pisano, "Piezoelectric Aluminum Nitride Vibrating Contour-Mode MEMS Resonators," J. Microelectromechanical Syst., vol. 15, no. 6, pp. 1406–1418, Dec. 2006.
- [10] R. C. Ruby, P. Bradley, Y. Oshmyansky, A. Chien, and I., J.D. Larson, "Thin film bulk wave acoustic resonators (FBAR) for wireless applications," in 2001 IEEE Ultrasonics Symposium, 2001, vol. 1, pp. 813–821 vol.1.
- [11]G. Piazza, V. Felmetsger, P. Muralt, R. H. Olsson III, and R. Ruby, "Piezoelectric aluminum nitride thin films for microelectromechanical systems," *MRS Bull.*, vol. 37, no. 11, pp. 1051– 1061, Nov. 2012.
- [12]W. Werdecker and F. Aldinger, "Aluminum Nitride-An Alternative Ceramic Substrate for High Power Applications in Microcircuits," *IEEE Trans. Compon. Hybrids Manuf. Technol.*, vol. 7, no. 4, pp. 399–404, Dec. 1984.
- [13]R. F. Davis, "III-V nitrides for electronic and optoelectronic applications," *Proc. IEEE*, vol. 79, no. 5, pp. 702–712, May 1991.
- [14]G. Piazza, P. J. Stephanou, and A. P. Pisano, "Single-chip multiple-frequency ALN MEMS filters based on contour-mode piezoelectric resonators," *Microelectromechanical Syst. J. Of*, vol. 16, no. 2, pp. 319–328, 2007.
- [15]M. Rinaldi, C. Zuniga, C. Zuo, and G. Piazza, "Super-high-frequency two-port AlN contourmode resonators for RF applications," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 57, no. 1, pp. 38–45, Jan. 2010.
- [16]M. Rinaldi, C. Zuo, J. Van der Spiegel, and G. Piazza, "Reconfigurable CMOS Oscillator Based on Multifrequency AlN Contour-Mode MEMS Resonators," *IEEE Trans. Electron Devices*, vol. 58, no. 5, pp. 1281–1286, May 2011.
- [17]J. Cardenas, C. B. Poitras, J. T. Robinson, K. Preston, L. Chen, and M. Lipson, "Low loss etchless silicon photonic waveguides," *Opt. Express*, vol. 17, no. 6, p. 4752, Mar. 2009.
- [18] A. Polman, B. Min, J. Kalkman, T. J. Kippenberg, and K. J. Vahala, "Ultralow-threshold erbium-implanted toroidal microlaser on silicon," *Appl. Phys. Lett.*, vol. 84, no. 7, pp. 1037– 1039, Feb. 2004.
- [19] A. Gondarenko, J. S. Levy, and M. Lipson, "High confinement micron-scale silicon nitride high Q ring resonator," *Opt. Express*, vol. 17, no. 14, p. 11366, Jul. 2009.

- [20]H. Inoue, K. Hiruma, K. Ishida, T. Asai, and H. Matsumura, "Low loss GaAs optical waveguides," *IEEE Trans. Electron Devices*, vol. 32, no. 12, pp. 2662–2668, Dec. 1985.
- [21]A. Stolz, E. Cho, E. Dogheche, Y. Androussi, D. Troadec, D. Pavlidis, and D. Decoster, "Optical waveguide loss minimized into gallium nitride based structures grown by metal organic vapor phase epitaxy," *Appl. Phys. Lett.*, vol. 98, no. 16, p. 161903, Apr. 2011.
- [22]C. Wang, M. J. Burek, Z. Lin, H. A. Atikian, V. Venkataraman, I.-C. Huang, P. Stark, and M. Lončar, "Integrated high quality factor lithium niobate microdisk resonators," *Opt. Express*, vol. 22, no. 25, p. 30924, Dec. 2014.
- [23]C. Xiong, W. H. P. Pernice, X. Sun, C. Schuck, K. Y. Fong, and H. X. Tang, "Aluminum nitride as a new material for chip-scale optomechanics and nonlinear optics," *New J. Phys.*, vol. 14, no. 9, p. 095014, Sep. 2012.
- [24]S. Y. Davydov, "Evaluation of physical parameters for the group III nitrates: BN, AlN, GaN, and InN," *Semiconductors*, vol. 36, no. 1, pp. 41–44, Jan. 2002.
- [25] Y. Taniyasu, M. Kasu, and T. Makimoto, "An aluminium nitride light-emitting diode with a wavelength of 210 nanometres," *Nature*, vol. 441, no. 7091, pp. 325–328, May 2006.
- [26]G. Bu, M. S. Shur, D. Čiplys, R. Rimeika, R. Gaska, and Q. Fareed, "Guided-wave acoustooptic diffraction in AlxGa1-xN epitaxial layers," *Appl. Phys. Lett.*, vol. 85, no. 12, pp. 2157– 2159, Sep. 2004.
- [27]M. Hossein-Zadeh, H. Rokhsari, A. Hajimiri, and K. J. Vahala, "Characterization of a radiation-pressure-driven micromechanical oscillator," *Phys. Rev. A*, vol. 74, no. 2, p. 023813, Aug. 2006.
- [28]D. Van Thourhout and J. Roels, "Optomechanical device actuation through the optical gradient force," *Nat. Photonics*, vol. 4, no. 4, pp. 211–217, Apr. 2010.
- [29]M. Tomes and T. Carmon, "Photonic Micro-Electromechanical Systems Vibrating at X-band (11-GHz) Rates," *Phys. Rev. Lett.*, vol. 102, no. 11, p. 113601, Mar. 2009.
- [30]S. Sridaran and S. A. Bhave, "Electrostatic actuation of silicon optomechanical resonators," *Opt. Express*, vol. 19, no. 10, pp. 9020–9026, May 2011.
- [31]M. W. Pruessner, N. Siwak, K. Amarnath, S. Kanakaraju, W.-H. Chuang, and R. Ghodssi, "End-coupled optical waveguide MEMS devices in the indium phosphide material system," *J. Micromechanics Microengineering*, vol. 16, no. 4, p. 832, Apr. 2006.
- [32]S. Tallur and S. A. Bhave, "Partial Gap Transduced MEMS Optoacoustic Oscillator Beyond Gigahertz," *J. Microelectromechanical Syst.*, vol. 24, no. 2, pp. 422–430, Apr. 2015.
- [33]J. Bochmann, A. Vainsencher, D. D. Awschalom, and A. N. Cleland, "Nanomechanical coupling between microwave and optical photons," *Nat. Phys.*, vol. 9, no. 11, pp. 712–716, Nov. 2013.
- [34]C. Xiong, L. Fan, X. Sun, and H. X. Tang, "Cavity piezooptomechanics: Piezoelectrically excited, optically transduced optomechanical resonators," *Appl. Phys. Lett.*, vol. 102, no. 2, p. 021110, Jan. 2013.
- [35]X. Han, C. Xiong, K. Y. Fong, X. Zhang, and H. X. Tang, "Triply resonant cavity electrooptomechanics at X-band," New J. Phys., vol. 16, no. 6, p. 063060, Jun. 2014.
- [36] A. H. Safavi-Naeini and O. Painter, "Proposal for an optomechanical traveling wave phonon–photon translator," *New J. Phys.*, vol. 13, no. 1, p. 013017, Jan. 2011.
- [37]S. Tallur, S. Sridaran, and S. A. Bhave, "A monolithic radiation-pressure driven, low phase noise silicon nitride opto-mechanical oscillator," *Opt. Express*, vol. 19, no. 24, p. 24522, Nov. 2011.
- [38]P. K. Tien, "Light Waves in Thin Films and Integrated Optics," Appl. Opt., vol. 10, no. 11, p. 2395, Nov. 1971.
- [39]A. Mekis, S. Gloeckner, G. Masini, A. Narasimha, T. Pinguet, S. Sahni, and P. De Dobbelaere, "A Grating-Coupler-Enabled CMOS Photonics Platform," *IEEE J. Sel. Top. Quantum Electron.*, vol. 17, no. 3, pp. 597–608, May 2011.
- [40]C. Pollock and M. Lipson, Integrated Photonics. Springer Science & Business Media, 2003.

- [41] V. R. Almeida, R. R. Panepucci, and M. Lipson, "Nanotaper for compact mode conversion," Opt. Lett., vol. 28, no. 15, pp. 1302–1304, Aug. 2003.
- [42] T. Tamir, Guided-wave optoelectronics. Springer, 1988.
- [43]D. Taillaert, "Grating couplers as interface between Optical Fibers and Nanophotonic Waveguides," PhD thesis, Ghent University, Ghent, Belgium, 2004.
- [44]Z. Zhu and T. Brown, "Full-vectorial finite-difference analysis of microstructured optical fibers," Opt. Express, vol. 10, no. 17, p. 853, Aug. 2002.
- [45]F. A. Jenkins and H. E. White, Fundamentals of Optics. McGraw-Hill, 1976.
- [46]G. P. Agrawal, Fiber-Optic Communication Systems. John Wiley & Sons, 2012.
- [47]C. R. Doerr, L. Chen, Y.-K. Chen, and L. L. Buhl, "Wide Bandwidth Silicon Nitride Grating Coupler," *IEEE Photonics Technol. Lett.*, vol. 22, no. 19, pp. 1461–1463, Oct. 2010.
- [48]S. Mishin, D. R. Marx, B. Sylvia, V. Lughi, K. L. Turner, and D. R. Clarke, "Sputtered AIN thin films on Si and electrodes for MEMS resonators: relationship between surface quality microstructure and film properties," in 2003 IEEE Symposium on Ultrasonics, 2003, vol. 2, pp. 2028–2032 Vol.2.
- [49]S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, "Whispering-gallery mode microdisk lasers," *Appl. Phys. Lett.*, vol. 60, no. 3, pp. 289–291, Jan. 1992.
- [50]L. Feng, Z. J. Wong, R.-M. Ma, Y. Wang, and X. Zhang, "Single-mode laser by parity-time symmetry breaking," *Science*, vol. 346, no. 6212, pp. 972–975, Nov. 2014.
- [51]B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, "Microring resonator channel dropping filters," J. Light. Technol., vol. 15, no. 6, pp. 998–1005, Jun. 1997.
- [52] T. Barwicz, M. Popović, P. Rakich, M. Watts, H. Haus, E. Ippen, and H. Smith, "Microringresonator-based add-drop filters in SiN: fabrication and analysis," *Opt. Express*, vol. 12, no. 7, pp. 1437–1442, Apr. 2004.
- [53]F. Vollmer, D. Braun, A. Libchaber, M. Khoshsima, I. Teraoka, and S. Arnold, "Protein detection by optical shift of a resonant microcavity," *Appl. Phys. Lett.*, vol. 80, no. 21, pp. 4057–4059, May 2002.
- [54] P. B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Lončar, "High quality factor photonic crystal nanobeam cavities," *Appl. Phys. Lett.*, vol. 94, no. 12, p. 121106, Mar. 2009.
- [55]H. Lee, T. Chen, J. Li, K. Y. Yang, S. Jeon, O. Painter, and K. J. Vahala, "Chemically etched ultrahigh-Q wedge-resonator on a silicon chip," *Nat. Photonics*, vol. 6, no. 6, pp. 369–373, Jun. 2012.
- [56]Lord Rayleigh, "CXII. The problem of the whispering gallery," *Philos. Mag. Ser.* 6, vol. 20, no. 120, pp. 1001–1004, Dec. 1910.
- [57] D. H. Staelin, A. W. Morgenthaler, and J. A. Kong, *Electromagnetic Waves*. Prentice Hall, 1994.
- [58]K. Kakihara, N. Kono, K. Saitoh, and M. Koshiba, "Full-vectorial finite element method in a cylindrical coordinate system for loss analysis of photonic wire bends," *Opt. Express*, vol. 14, no. 23, p. 11128, 2006.
- [59]M. Oxborrow, "Traceable 2-D Finite-Element Simulation of the Whispering-Gallery Modes of Axisymmetric Electromagnetic Resonators," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 6, pp. 1209–1218, Jun. 2007.
- [60] M. Oxborrow, "How to simulate the whispering-gallery modes of dielectric microresonators in FEMLAB/COMSOL," in SPIE Proceedings, 2007, vol. 6452, p. 64520J–64520J–12.
- [61]M. Soltani, "Novel integrated silicon nanophotonic structures using ultra-high Q resonators," PhD thesis, Georgia Institute of Technology, Atlanta, GA, 2009.
- [62] P. Rabiei, W. H. Steier, C. Zhang, and L. R. Dalton, "Polymer micro-ring filters and modulators," J. Light. Technol., vol. 20, no. 11, pp. 1968–1975, Nov. 2002.
- [63] H. A. Haus, Waves and fields in optoelectronics. Prentice Hall, Incorporated, 1984.

- [64]M. Soltani, S. Yegnanarayanan, Q. Li, and A. Adibi, "Systematic Engineering of Waveguide-Resonator Coupling for Silicon Microring/Microdisk/Racetrack Resonators: Theory and Experiment," *IEEE J. Quantum Electron.*, vol. 46, no. 8, pp. 1158–1169, Aug. 2010.
- [65]E. Shah Hosseini, S. Yegnanarayanan, A. H. Atabaki, M. Soltani, and A. Adibi, "High quality planar silicon nitride microdisk resonators for integrated photonics in the visible wavelength range," *Opt. Express*, vol. 17, no. 17, p. 14543, Aug. 2009.
- [66]E. Shah Hosseini, S. Yegnanarayanan, A. H. Atabaki, M. Soltani, and A. Adibi, "Systematic design and fabrication of high-Q single-mode pulley-coupled planar silicon nitride microdisk resonators at visible wavelengths," *Opt. Express*, vol. 18, no. 3, p. 2127, Feb. 2010.
- [67]K. Preston, B. Schmidt, and M. Lipson, "Polysilicon photonic resonators for large-scale 3D integration of optical networks," *Opt. Express*, vol. 15, no. 25, p. 17283, 2007.
- [68]M. C. Larciprete, A. Bosco, A. Belardini, R. L. Voti, G. Leahu, C. Sibilia, E. Fazio, R. Ostuni, M. Bertolotti, A. Passaseo, B. Potì, and Z. D. Prete, "Blue second harmonic generation from aluminum nitride films deposited onto silicon by sputtering technique," *J. Appl. Phys.*, vol. 100, no. 2, p. 023507, Jul. 2006.
- [69] M. Borselli, T. J. Johnson, and O. Painter, "Accurate measurement of scattering and absorption loss in microphotonic devices," *Opt. Lett.*, vol. 32, no. 20, p. 2954, 2007.
- [70] T. J. Kippenberg and K. J. Vahala, "Cavity Opto-Mechanics," Opt. Express, vol. 15, no. 25, pp. 17172–17205, Dec. 2007.
- [71]M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, "Cavity Optomechanics," *Rev. Mod. Phys.*, vol. 86, no. 4, pp. 1391–1452, Dec. 2014.
- [72] J. Rosenberg, "Applications of micro/nanoscale optical resonators: plasmonic photodetectors and double-disk cavity optomechanics," PhD thesis, California Institute of Technology, Pasadena, CA, 2009.
- [73]X. Sun, X. Zhang, and H. X. Tang, "High-Q silicon optomechanical microdisk resonators at gigahertz frequencies," *Appl. Phys. Lett.*, vol. 100, no. 17, p. 173116, Apr. 2012.
- [74] V. V. Felmetsger, P. N. Laptev, and S. M. Tanner, "Design, operation mode, and stress control capability of S-Gun magnetron for ac reactive sputtering," *Surf. Coat. Technol.*, vol. 204, no. 6–7, pp. 840–844, Dec. 2009.
- [75]C. Zuo, N. Sinha, J. Van der Spiegel, and G. Piazza, "Multifrequency Pierce Oscillators Based on Piezoelectric AlN Contour-Mode MEMS Technology," J. Microelectromechanical Syst., vol. 19, no. 3, pp. 570–580, Jun. 2010.
- [76]C. Zuniga, M. Rinaldi, S. M. Khamis, A. T. Johnson, and G. Piazza, "Nanoenabled microelectromechanical sensor for volatile organic chemical detection," *Appl. Phys. Lett.*, vol. 94, no. 22, p. 223122, 2009.
- [77] Y. Hui, T. Nan, N. X. Sun, and M. Rinaldi, "High Resolution Magnetometer Based on a High Frequency Magnetoelectric MEMS-CMOS Oscillator," 2014.
- [78]R. A. Johnson, *Mechanical filters in electronics*. John Wiley & Sons Australia, Limited, 1983.
- [79]G. Piazza, P. J. Stephanou, and A. P. Pisano, "One and two port piezoelectric higher order contour-mode MEMS resonators for mechanical signal processing," *Solid-State Electron.*, vol. 51, no. 11, pp. 1596–1608, 2007.
- [80] J. Rosenbaum, Bulk Acoustic Wave Theory and Devices. Artech House, 1988.
- [81]C. C. Enz and A. Kaiser, *MEMS-based Circuits and Systems for Wireless Communication*. Springer Science & Business Media, 2012.
- [82] J. Segovia-Fernandez and G. Piazza, "Damping in 1 GHz laterally-vibrating composite piezoelectric resonators," in 2015 28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS), 2015, pp. 1000–1003.
- [83]X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," J. Opt. Soc. Am. B, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.

- [84]J. T. M. van Beek and R. Puers, "A review of MEMS oscillators for frequency reference and timing applications," *J. Micromechanics Microengineering*, vol. 22, no. 1, p. 013001, Jan. 2012.
- [85]D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE*, vol. 54, no. 2, pp. 329–330, Feb. 1966.
- [86]E. Rubiola, *Phase noise and frequency stability in oscillators*. Cambridge, UK; New York: Cambridge University Press, 2009.
- [87] A. B. Matsko, L. Maleki, A. A. Savchenkov, and V. S. Ilchenko, "Whispering gallery mode based optoelectronic microwave oscillator," *J. Mod. Opt.*, vol. 50, no. 15–17, pp. 2523–2542, Oct. 2003.
- [88] T. H. Lee and A. Hajimiri, "Oscillator phase noise: a tutorial," *IEEE J. Solid-State Circuits*, vol. 35, no. 3, pp. 326–336, Mar. 2000.
- [89]J.-B. You, M. Park, J.-W. Park, and G. Kim, "12.5 Gbps optical modulation of silicon racetrack resonator based on carrier-depletion in asymmetric p-n diode," *Opt. Express*, vol. 16, no. 22, pp. 18340–18344, Oct. 2008.
- [90] D. L. DeVoe and A. P. Pisano, "Modeling and optimal design of piezoelectric cantilever microactuators," *J. Microelectromechanical Syst.*, vol. 6, no. 3, pp. 266–270, Sep. 1997.
- [91]T. Nagano, M. Nishigaki, K. Abe, K. Itaya, and T. Kawakubo, "Fabrication and Performance of Piezoelectric MEMS Tunable Capacitors Constructed with AlN Bimorph Structure," in *Microwave Symposium Digest, 2006. IEEE MTT-S International*, 2006, pp. 1285–1288.
- [92]M. J. Storey, S. Tallur, and S. A. Bhave, "Radiation-pressure enhanced opto-acoustic oscillator," in 2014 IEEE 27th International Conference on Micro Electro Mechanical Systems (MEMS), 2014, pp. 1209–1212.
- [93] T. Beyazoglu, T. O. Rocheleau, A. J. Grine, K. E. Grutter, M. C. Wu, and C. T.-C. Nguyen, "A super-regenerative optical receiver based on an optomechanical oscillator," in 2015 28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS), 2015, pp. 976–979.