Surface Acoustic Wave Optical Modulation

by

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Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

The lack of refractive optical elements at ultraviolet (UV) and X ray wavelengths has made the construction of high-performance optical systems such as microscopes and photolithography projectors difficult at wavelengths below 200 nm. Synthetic aperture optical systems potentially eliminate the need for refractive elements by using sets of electronically modulated laser beams to synthesize the front apertures of high-performance optical systems. However, the optical modulators typically used with synthetic aperture optics are themselves refractive elements. As a solution, this thesis developed surface acoustic wave optical modulation, an all-reflective technique for optical modulation that in principle scales from visible to UV and X ray wavelengths and is suitable for use in synthetic aperture optical systems.

Surface acoustic wave optical modulation uses surface acoustic waves propagating along the surface of optical mirrors to create diffraction gratings that diffract incident light. The basic principles were formulated in this thesis by studying surface acoustic waves and diffraction gratings. These principles were then tested with prototype modulators constructed by patterning deposited aluminum on substrates of lithium niobate using standard photolithographic techniques. Using a 633 nm HeNe laser at normal incidence, diffraction angles of 0.21 and 0.32 degrees were measured for prototype modulators with center frequencies of 19.77 and 29.66 MHz, respectively. The maximum diffraction efficiency obtained during testing was 2.1%. These results agree with theoretical predictions and demonstrate the practicality of surface acoustic wave optical modulation.

Thesis Supervisor: Dennis M. Freeman
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Chapter 1

Introduction

"Necessity is the mother of all invention."

(aphorism from Plato, The Republic)

Most conventional optical systems use lenses to produce magnified or demagnified images of illuminated objects. The telescope and the human eye are two examples of optical systems that fit this description. Lenses form images in these systems by performing a linear transformation on the positions and the slopes of light rays passing through them [1]. However, optical systems that achieve high levels of magnification or demagnification suffer from blurring caused by aberrations and diffraction.

Aberrations are fundamental to the way light propagates through a lens. A lens only approximates the linear transformation necessary for image formation when the lens surfaces are nearly planar and when the light rays are nearly normal to the lens surfaces (such that the small-angle approximations of trigonometric functions are valid). These conditions form the basis of the commonly used paraxial approximation, which is only accurate for rays passing straight through the center of the lens. Because the passage of light rays at large angles of incidence is necessary for achieving high resolution, aberrations caused by deviations from the paraxial approximation blur images formed with lenses at high magnifications. In general, aberrations caused by a lens become more severe as the resolution required of the lens increases.

However, lens aberrations can be corrected by using multiple lenses and lens ma-
terials. For example, the spherical and chromatic aberrations of a converging lens and a diverging lens can be designed to cancel when the two lenses are glued together. The resulting lens system is called an achromatic doublet [1]. In general, a lens system with many degrees of freedom (determined by the number of lenses and lens materials) can be corrected for many types of aberrations.

A microscope objective is a familiar example of a highly corrected lens system. A high-power flat-field microscope objective can consist of as many as fifteen elements polished and assembled with extremely precise tolerances [2]. The microscope objective aptly illustrates that aberration correction comes at a cost. High resolution lens systems can be complex and very difficult to design and construct. Furthermore, simply scaling the size of a lens to increase its aperture also increases its aberrations [1]. As a consequence, aberration correction places constraints on the working distance, field of view, depth of field, and depth of focus of a lens system. For example, increasing the size of a lens would obviously increase its working distance. Unfortunately, a more complex lens system would be required to correct for the larger aberrations.

In the absence of aberration, the maximum resolution of a conventional optical system is limited by diffraction. Every lens system has an aperture that most severely limits the passage of light through the system; diffraction dictates that that the size of this limiting aperture and the wavelength of light determine the maximum resolution of the system. When the size of the aperture is at its theoretical maximum, the smallest feature that can be resolved by a lens system is roughly half the wavelength of the light [3].

Since the maximum resolution of a conventional optical system is proportional to the wavelength of the light, resolution can be increased by simply reducing the wavelength of the light. For example, microprocessors are patterned by exposing a light sensitive substance called a photoresist with an image of the desired pattern using a lens system called a photolithographic projector. Reducing the size of the

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1Interestingly, blurring caused by diffraction can be used to measure motions much smaller than half the wavelength of the light. For example, a technique known as computer microvision measures the motions of hearing structures and microelectromechanical systems (MEMS) using light microscopy and can resolve motions as small as several nanometers [4].
smallest feature has been a primary focus of work in photolithography, and this has caused the wavelength of the light used during exposure to steadily decrease [5].

The maximum resolution of microscopes and photolithographic projectors can be increased by simply implementing these systems at ultraviolet (UV) and X ray wavelengths. However, conventional optical systems cannot be made below a certain critical wavelength because the indices of refraction for materials that are transmissive at UV and X ray wavelengths are nearly identical to that of vacuum [6]. The lenses that microscopes and photolithographic projectors rely on simply cannot be made. All-reflective optical systems have been constructed to replace lenses at wavelengths that lack refractive materials, but the level of physical perfection at which the reflecting surfaces must be constructed limits the feasibility of high resolution all-reflective optical systems. For example, a recent microlithography text states that error tolerances of less than a fourteenth of the wavelength (which is exceedingly small at X ray wavelengths) and “atomic level uniformity” is required to construct practical all-reflective X ray photolithography projectors [5]. However, new optical systems that utilize recent advances in computation and coherent illumination potentially achieve the diffraction limited resolution of lens systems at UV and X ray wavelengths.

Synthetic aperture optical systems developed at MIT use modulated laser beams to generate finely detailed interference patterns [7]. In synthetic aperture microscopy, these interference patterns can be used to illuminate unknown specimens. A computer can then reconstruct diffraction-limited images of the specimen from sequences of images obtained with low resolution optics. In synthetic aperture lithography, these interference patterns can be used to expose features in photoresist without the need for photomasks. Furthermore, constraints on the working distance, field of view, depth of field, and depth of focus caused by aberration correction do not apply to synthetic aperture optical systems. At a high level, synthetic aperture optics replace refractive optics and physical perfection with coherent illumination and computation. In particular, synthetic aperture optics make practical microscopes and maskless photolithographic projectors possible at UV and X ray wavelengths. This thesis represents a step towards making this possibility a reality.
The most successful synthetic aperture optical systems to date have utilized acousto-optic modulators (AOMs) to modulate coherent beams of light. However, because AOMs rely on refraction, they face the same limitations of lenses and do not scale to UV and X ray wavelengths. The implementation of synthetic aperture optical systems at UV and X ray wavelengths requires the development of all-reflective modulators.

Necessity was once called the mother of all invention; surface acoustic wave optical modulation was developed to fulfill the need for all-reflective optical modulators in synthetic aperture optical systems. A surface acoustic wave optical modulator (SAW-Mod) uses surface acoustic waves to deform the surface of a mirror. This propagating surface deformation acts as a grating that diffracts incident light and imparts a Doppler shift analogous to that in acousto-optic modulation. In short, a SAW-Mod performs all the functions of an AOM using only reflection and diffraction.

Previous Related Work

Modern acousto-optics was born in 1922 when Léon Brillouin predicted that light passing through a column of sound in solid or liquid would be diffracted at certain critical angles [8]. Theoretical and experimental work in acousto-optic interaction ensued in the following decades, most notably in a series of papers by C.V. Raman and N.S.N. Nath [9]. Acousto-optics is now a well-developed field, and acousto-optic modulators (AOMs) are currently available as “off the shelf” components from numerous manufacturers.

The diffraction of laser light by surface acoustic waves was reported as early as 1967 by E.P. Ippen [10]. This work coincided with an explosion of activity in surface acoustic wave research following the invention of a revolutionary type of surface acoustic wave transducer known as the interdigital transducer (IDT) by R.M. White and F.W. Voltmer in 1965 [11]. Although the majority of this research activity focused on the development of acoustic-electric devices which are currently used for radio frequency (RF) signal processing [12, 13, 14, 15], work involving the interaction of electromagnetic and surface acoustic waves continued.
The measurement of laser light diffracted by surface acoustic waves has long been a valuable tool in surface acoustic wave metrology [16]. Also, acousto-optic devices using surface acoustic waves to diffract light trapped in thin-film optical waveguides have been developed. Known as guided-wave or thin-film acousto-optic devices [17, 18], these devices, though similar to surface acoustic wave optical modulators, rely on refraction (like AOMs) and cannot scale to UV and X ray wavelengths. Additionally, the diffraction of incoherent X rays using surface acoustic waves in a multilayer mirror has recently been reported [19, 20]. X rays with a wavelength of 1.54 Angstroms were diffracted in a manner identical to surface acoustic wave optical modulation, and plans to develop an X ray chopper with MHz bandwidth have been proposed.

This thesis builds on previous work in acousto-optics, surface acoustic waves, and diffraction gratings to develop an all-reflective technique for optical modulation that in principle scales from visible to UV and X ray wavelengths. Chapter 2 outlines the basic principles of surface acoustic wave optical modulation. Chapter 3 reports on the design, construction, and testing of modulator prototypes. The concluding chapter discusses future applications of surface acoustic wave optical modulation.
Chapter 2

Principles of Operation

A surface acoustic wave optical modulator (SAW-Mod) controls the direction, amplitude, frequency, and phase of a laser beam. Seen in Figure 2-1, a SAW-Mod consists of a mirror and an electrically driven acoustic transducer. In the absence of an electrical drive, the mirror reflects light like an ordinary mirror. When an electrical signal is applied, the acoustic transducer creates waves that propagate along the surface of the mirror. Like ripples that distort the reflection on the surface of a pond, these propagating surface deformations affect the reflective properties of the mirror. If the electrical signal is periodic, then the resulting periodic deformations cause the mirror to act as a diffraction grating.

When a laser beam hits the diffraction grating created by the surface acoustic waves, a family of diffracted beams emerges. Changes in the diffraction grating cause changes in these diffracted beams. Since the diffraction grating is generated by an electrically driven acoustic transducer, the SAW-Mod allows an electrical signal to control a diffracted laser beam.

This chapter presents the basic principles behind surface acoustic wave optical modulation in two sections. The first section discusses surface acoustic waves, and the second section discusses diffraction gratings.
A bi-directional acoustic transducer generates surface acoustic waves, half of which propagate along the surface of a mirror. The surface acoustic waves deform the mirror and generate diffracted beams. For clarity, only two diffracted beams and the reflected beam are shown. Acoustic absorbers are used to stop the surface acoustic waves.
2.1 Surface Acoustic Waves

Surface acoustic waves are waves that travel along the free surface of a solid. The type of surface acoustic waves relevant to a SAW-Mod are called Rayleigh waves (named after the ubiquitous Lord Rayleigh who first predicted the existence of these waves) or “true” surface acoustic waves. While the term “surface acoustic wave” is commonly used to refer to several different types of surface waves, it will usually refer to Rayleigh waves in this thesis.

The use of the word “acoustic” can be a little misleading. While acoustic waves usually describe audible sound waves in air, surface acoustic waves differ from sound waves in at least three important ways:

1. Acoustic waves usually involve oscillations at frequencies ranging from tens of Hz to tens of kHz. Surface acoustic waves commonly involve frequencies from tens of MHz to several GHz.

2. Acoustic waves can propagate through gas or liquid. Surface acoustic waves can only propagate through elastic solids. For this reason, surface acoustic waves are occasionally referred to as surface elastic waves.

3. Acoustic waves are longitudinal (or compression) waves, with oscillations parallel to the direction of wave propagation. However, elastic solids also support transverse (or shear) waves, with oscillations perpendicular to the direction of wave propagation. Surface acoustic waves are actually a combination of both longitudinal and transverse waves.

The following two sections introduce the basic characteristics of surface acoustic waves and an efficient method of generating them.

\(^1\)Two other topics in this chapter bear the name of Lord Rayleigh. A common measure of resolution between two diffracted beams is known as the Rayleigh criterion, and a condition that validates certain calculations of diffraction grating efficiency is called the Rayleigh hypothesis [21].
2.1.1 Surface Acoustic Wave Characteristics

A derivation for the equations of motion describing surface acoustic waves can be very involved. However, a derivation for Rayleigh waves in isotropic materials is straightforward, involving only the wave equations for longitudinal and transverse waves and a boundary condition to represent the free surface [22, 23]. The results of this derivation aptly illustrate the characteristics of surface acoustic waves.

Equations of Motion in Isotropic Materials

As shown in Figure 2-2, suppose that the free surface of an isotropic material is defined by the plane $y = 0$ and that the direction of wave propagation is along the positive $\hat{z}$-axis. Assuming that the equations for the acoustic waves of interest are linear, the displacement of each “acoustic particle” $\mathbf{u}(x, y, z, t)$ can be represented as a complex phasor $\mathbf{u}(x, y, z)$ in time-harmonic form

$$\mathbf{u}(x, y, z, t) = \text{Re}\{\mathbf{u}(x, y, z)e^{j\omega t}\}.$$
Dropping the arguments \((x, y, z)\) to simplify notation, the complex phasor \(\mathbf{u}\) can be decomposed into an irrotational phasor \(\mathbf{u}_L\) and a compressionless phasor \(\mathbf{u}_S\), where

\[
\mathbf{u} = \mathbf{u}_L + \mathbf{u}_S. \tag{2.1}
\]

Since

\[
\nabla \times \mathbf{u}_L = 0 \quad \text{and} \quad \nabla \cdot \mathbf{u}_S = 0
\]

\(\mathbf{u}_S\) and \(\mathbf{u}_L\) can be expressed as scalar and vector potentials \(\phi\) and \(\psi\) defined as

\[
\mathbf{u}_L = \nabla \phi \quad \text{and} \quad \mathbf{u}_S = \nabla \times \psi. \tag{2.2}
\]

The \(L\) and \(S\) subscripts are used to suggest that pure longitudinal waves involve only irrotational particle motion and that pure shear waves involve only compressionless particle motion, and indeed wave equations for longitudinal and shear waves can be expressed as functions of \(\phi\) and \(\psi\) alone

\[
\nabla^2 \phi - \frac{1}{v_L^2} \frac{\partial^2 \phi}{\partial t^2} = 0
\]

\[
\nabla^2 \psi - \frac{1}{v_S^2} \frac{\partial^2 \psi}{\partial t^2} = 0
\]

where \(v_L\) and \(v_S\) denote longitudinal and shear wave velocity. Assuming that the longitudinal and shear wave components of the desired surface acoustic wave propagate at the same velocity (a defining characteristic of Rayleigh waves), solutions that satisfy the two wave equations will be of the form

\[
\phi = A e^{\gamma_L y} e^{-jkrz} \tag{2.3}
\]

\[
\psi = \hat{x} B e^{\gamma_S y} e^{-jkrz} \tag{2.4}
\]

where \(A\) and \(B\) are constant coefficients,
\[ \gamma_L = \sqrt{k_R^2 - k_L^2} \]

\[ \gamma_S = \sqrt{k_R^2 - k_S^2} \]

and \( k_L, k_S, \) and \( k_R \) are the wavenumbers for longitudinal, shear, and Rayleigh waves, respectively.

Attention is now focused on the boundary condition imposed by the free surface. Since the volume above the surface is empty, the \( \hat{y} \) components of stress at the surface can be set to zero

\[ T_{yx} = T_{yy} = T_{yz} = 0 \quad \text{at} \quad y = 0 \]

with \( T_{ij} \) indicating the \( i \) component of stress on the \( j \) oriented face of a cube-shaped acoustic particle. With a few algebraic manipulations, the boundary condition \( T_{yz} = 0 \) can be expanded into

\[ \frac{2\partial^2 \phi}{\partial y \partial z} + \frac{\partial^2 \psi_x}{\partial z^2} - \frac{\partial^2 \psi_x}{\partial y^2} = 0 \]

and combined with equations 2.3 and 2.4 to solve for \( B \) in terms of \( A \). Eliminating \( B \), the resulting expressions for \( \phi \) and \( \bar{\psi} \) can be plugged into the original definition of \( \bar{u} \) given by equations 2.1 and 2.2 to obtain the desired equations of motion

\[ u_y(y, z, t) = U_y(y) \cos(\omega t - k_R z) \]

\[ u_z(y, z, t) = U_z(y) \sin(\omega t - k_R z) \]

where

\[ U_y(y) = A \gamma_L e^{\gamma_L y} - \frac{2k_R^2}{k_R^2 + \gamma_S^2} e^{\gamma_S y} \]

\[ U_z(y) = A k_R e^{\gamma_L y} - \frac{2\gamma_L \gamma_S}{k_R^2 + \gamma_S^2} e^{\gamma_S y}. \]

Note that the solution is only valid for \( y < 0 \) and that \( U_y(y) \) and \( U_z(y) \) are functions of \( y \) that decay exponentially as \( y \) becomes negative.

This solution for surface acoustic waves in isotropic materials demonstrates characteristics common to all Rayleigh waves:
1. A Rayleigh wave is a coupling of a longitudinal wave and a $\hat{y}$-polarized shear wave, both propagating in the $\hat{z}$ direction and 90 degrees out of phase. The resulting motion of each acoustic particle is elliptical.

2. The amount of particle motion decays exponentially beneath the surface. Typically, almost all of the energy in a surface acoustic wave is concentrated within one wavelength of the surface.

3. The velocity of a Rayleigh wave is always less than the velocities of the corresponding longitudinal and shear waves [23]. This property is evident from equations 2.3 and 2.4 in light of the fact that the amount of particle motion decays exponentially for $y < 0$. The velocity of the Rayleigh wave can also be calculated exactly by combining the unused boundary condition $T_{yy} = 0$ with equations 2.3 and 2.4 [23].

4. At any given point in time, the profile of the surface is nearly sinusoidal.

**Effects of Anisotropy and Piezoelectricity**

The derivation of the previous section illustrated the behavior of Rayleigh waves in the most fundamental case. However, the surface acoustic waves used in a SAW-Mod differ from this simple case due to two material properties, anisotropy and piezoelectricity.

For reasons outlined in the next section, every SAW-Mod to date has been made from lithium niobate, which is anisotropic. However, pure, longitudinal, shear, and Rayleigh waves can still propagate along any one of several “pure mode” directions.2 The SAW-Mod ensures that only pure Rayleigh waves are excited by launching waves along a pure mode axis. Interestingly, surface acoustic waves can also propagate in non-pure mode directions. Referred to as “pseudo surface acoustic waves,” these

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2Lithium niobate has a trigonal crystal symmetry, meaning it has three indistinguishable pure mode directions which lie 120 degrees of one another in a plane normal to a fourth pure mode direction [24].
waves have varying coupling efficiencies and propagation velocities and could potentially add flexibility to SAW-Mod design. For example, various types of "leaky" surface acoustic waves have coupling coefficients up to 3.8 times higher and wave velocities up to 31% faster than that of Rayleigh waves [12]. However, much of the energy in a leaky surface acoustic wave is contained in a sub-surface shear wave polarized parallel to the free surface, resulting in reduced surface displacement and low diffraction efficiency.

Lithium niobate is also piezoelectric. While this property is useful for electronically exciting surface acoustic waves (see next section), strong piezoelectric coupling complicates the surface acoustic wave model. A surface acoustic wave propagating in a piezoelectric material is shadowed by an electric potential both above and below the free surface. Patterns of metal deposited on the surface produce electric boundary conditions that affect the behavior of the surface acoustic wave. In fact, the difference in propagation velocity caused by "shorting out" the surface is a common method of measuring the electromechanical coupling coefficient of a material [12].

Because of the complexities involved in accurately modeling surface acoustic waves in lithium niobate, many of its acoustic properties are usually determined experimentally or computed numerically [25]. Two Rayleigh wave properties essential to SAW-Mod design are wave velocity and surface displacement as a function of acoustic power. In recent literature, the velocity of Rayleigh waves propagating along the Z-axis of lithium niobate with the surface normal to the Y-axis (referred to as YZ-LiNbO3) is cited as

\[ v_R = 3488 \text{ m/s} \]  \quad (2.5)

\[ v_0 = 3410 \text{ m/s} \]  \quad (2.6)

where \( v_R \) and \( v_0 \) correspond to unmetallized and completely metallized surfaces, respectively [12].

The mean-to-peak surface displacement amplitude \( u \) of completely metallized YZ-
LiNbO$_3$ is

$$u = 2.62 \times 10^{-6} \times \sqrt{\frac{P}{w \omega}} \text{ m} \tag{2.7}$$

where $P$ is the power in the Rayleigh wave in Watts, $w$ is the width of the acoustic beam in meters, and $\omega$ is the angular frequency of the Rayleigh wave in radians per second [26].

### 2.1.2 Excitation Using Interdigital Transducers

From the time they were first proposed by Lord Rayleigh in 1885 [22] until the 1960s, surface acoustic waves were primarily of interest to seismologists. Surface acoustic waves caught the attention of a wider range of scientists in 1965 when R.M. White and F.W. Voltmer developed an ingeniously simple method of generating and detecting surface acoustic waves using what are now called interdigital transducers (IDTs) [11]. IDTs soon led to straightforward implementations of RF tapped delay line filters that were small, efficient, and suitable for mass production using integrated circuit manufacturing technology. IDTs have since enabled a range of RF signal processing devices known collectively as “surface acoustic wave devices.” The SAW-Mod borrows from the success of surface acoustic wave devices by employing the IDT.

**Acoustic Properties of Interdigital Transducers**

Seen in Figure 2-3, an IDT consists to two sets of interdigitated fingers deposited on a flat piezoelectric substrate using photolithographic techniques. A voltage applied to one set of fingers produces periodic deformations that propagate along the surface of the substrate. If the voltage oscillates within a particular range of frequencies, the propagating periodic deformations add constructively, efficiently generating surface acoustic waves.

The most fundamental property of an IDT is its center frequency. The center frequency of an IDT is defined by the surface acoustic wave velocity $v_T$ and the
Figure 2-3: Photograph of an interdigital transducer. This photograph shows 12 finger pairs of an IDT from a SAW-Mod prototype. The complete IDT had 30 finger pairs and a center frequency of 19.77 MHz (equation 2.8). The IDT was made by patterning a thin layer of aluminum evaporated onto a wafer of lithium niobate. The photograph was taken through a 3.5×, 0.1 NA microscope objective.

The principal transducer period \( \lambda \) as

\[
f_0 = \frac{1}{T_0} = \frac{v_T}{\lambda_0} \quad \text{Hz.} \tag{2.8}
\]

The approximate frequency response of an IDT can be determined by representing each periodic section of an IDT as an individual source [27]. Assuming that each of \( N \) regularly spaced acoustic sources is excited with the same input signal \( x(t) \), the output signal \( y(t) \) that emerges from the end of the IDT will be the sum of several time-delayed duplicates of \( x(t) \). Stated mathematically,

\[
y(t) = x(t) \ast \sum_{n=0}^{N-1} \delta(t - T_0 n) \tag{2.9}
\]

where "\( \ast \)" denotes convolution, \( \delta(t) \) is the Dirac delta function, and \( T_0 \) is the spacing in time (or delay) between each source. The Fourier transform of 2.9 can be written as

\[
\frac{Y(e^{j\omega})}{X(e^{j\omega})} = \sum_{n=-\infty}^{+\infty} h[n] e^{-j\omega T_0 n} \tag{2.10}
\]
where \( h[n] \) is one for \( n \) between 0 and \( N - 1 \) and zero elsewhere. This result states that the system function of an IDT can be approximated by the discrete-time Fourier transform of \( h[n] \) evaluated at \( \omega T_0 \) [28].

The discrete function \( h[n] \) can be interpreted physically as a function describing the “weight” of each acoustic source. While \( h[n] \) is a rectangle function for every SAW-Mod discussed in this thesis, the value of each term in \( h[n] \) can be varied by simply altering the length of overlap between each pair of electrodes. Such an IDT implements a tapped delay line or transversal filter with a finite impulse response of \( h[n] \); this is the fundamental design principle behind many surface acoustic wave filters.

**Electrical Properties of Interdigital Transducers**

The electrical properties of an interdigital transducer can be summarized by a model of the electric driving port impedance. Illustrated in Figure 2-4, an IDT can be modeled as a static interelectrode capacitance \( C_T \) in parallel with an acoustic radiation resistance \( R_a \). The equivalent series-circuit model can also be employed when convenient [12, 29].

For a uniformly weighted, uniformly spaced, straight electrode, quarter wave IDT
(discussed in section 3.1.2 on IDT design), $R_a$ can be calculated as

$$R_a(f) = \left[ 8K^2C_Tf_0N \left| \frac{\sin[N\pi(f - f_0)/f_0]}{N\pi(f - f_0)/f_0} \right|^2 \right]^{-1} \Omega$$

where $K^2 = 0.045$ is the electromechanical coupling coefficient of $YZ$-$LiNbO_3$ and $N$ is the number of periodic sections (or "finger pairs") in the IDT [12]. Since the approximate system function of the IDT is expected to be the Fourier transform of a rectangle function, the appearance of a sinc function in the radiation resistance of the IDT is no surprise.

In general, the input impedance of an IDT is not matched to the output impedance of its electrical drive, and a matching circuit is needed to maximize electric-to-acoustic energy conversion and to minimize electrical reflections back toward the source. Most matching circuits are designed to produce a perfect match at the center frequency of the IDT where $R_a$ reaches a minimum value of

$$R_a(f = f_0) = [8K^2C_Tf_0N]^{-1} \Omega.$$  \hspace{1cm} (2.11)
2.2 Diffraction Gratings

A diffraction grating is a periodically corrugated structure used to disperse wave energy, usually light. A typical diffraction grating consists of a mirror with closely-spaced parallel grooves formed into the surface. The grooves are usually mechanically ruled with a diamond cutting tool or holographically patterned. However, the diffraction grating used in a SAW-Mod is generated entirely by the profile of the surface acoustic waves traveling along the surface of a mirror.

The following sections answer three basic questions about diffraction gratings. First, how many beams emerge from a diffraction grating, and in what directions do these beams propagate? Second, what are the amplitudes of these diffracted beams? Third, how do the frequencies and phases of these beams change when the grating is in motion?

2.2.1 The Grating Equation

When a laser beam strikes a diffraction grating, several beams can emerge. Illustrated in Figure 2-5, the directions of these beams are described by the grating equation

$$\sin \theta_i + \sin \theta_d = \frac{n \lambda}{d}$$  (2.12)

where $\theta_i$ is the angle of the incident beam, $\theta_d$ is the angle of the diffracted beam, $n$ is the order of the diffracted beam, $\lambda$ is wavelength of the incident laser beam, and $d$ is spatial period of the diffraction grating.\(^3\) The specular reflected beam is assigned an order of 0, and the first diffracted beams to the left and right of the specular beam are assigned orders of $-1$ and $+1$, respectively.

Although an infinite number of diffracted orders is defined, the grating equation indicates that all beams above a certain order will aim below the surface of the grating,

\(^3\)Note that in Figure 2-5 the sign of $\theta_i$ is positive and the sign of $\theta_d$ is negative (following a consistent coordinate system). The grating equation then clearly defines the sign of the order describing each diffracted beam. Every other possible sign convention seems to be in use, causing the grating equation to appear in various forms in different texts.
Figure 2-5: Illustration of the grating equation. The grating equation can be derived by equating the difference in the path lengths of two parallel rays to an integral number of optical wavelengths. For clarity, only the incident and +1 order diffracted beams are shown.

$|\theta_d| > \frac{\pi}{2}$. These orders are referred to as “cut-off” and are evanescent. They can be detected only a short distance from the grating and do not transmit any power.

### 2.2.2 Diffraction Efficiency

After determining the number of beams and their directions of propagation, the next logical question to ask is, how bright is each beam? This deceptively simple question turns out to be very difficult to answer, depending the order of the diffracted beam, the wavelength, direction, and polarization of the incident beam, and the shape and spacing of each groove in the diffraction grating. In certain simple cases, the diffraction efficiency of a grating can be solved quite elegantly using Fourier optics. Virtually all other cases can be solved with methods based on electromagnetic theory. The following sections describe two methods of calculating diffraction efficiency in cases relevant to a SAW-Mod. The first method is based on Fourier optics, and the second method is based on electromagnetic theory.
Fraunhofer Diffraction Pattern of a Sinusoidal Phase Grating

The diffraction pattern generated by a distribution of light can be determined using approximations of diffraction theory that relate the diffraction pattern to the Fourier transform of the distribution. The two most commonly used Fourier optics approximations are the Fresnel (or near field) and the Fraunhofer (or far field) approximations.

Surface acoustic waves traveling through the surface of a mirror produce nearly sinusoidal deformations. If the deformations are very small and the incident beam is nearly perpendicular to the grating surface, the resulting diffraction grating can be modeled as an optical element that affects only the phase of the reflected beam. Such a grating is called a phase grating. The Fraunhofer approximation of a sinusoidally phase-modulated plane wave is straightforward to calculate \[ \eta_n = J_n^2 \left( \frac{2u \pi}{\lambda} \right) \] where \( J_n \) is a \( n \)th order Bessel function of first kind, \( n \) is the order of the diffracted beam, \( u \) is the mean-to-peak amplitude of the surface acoustic wave, and \( \lambda \) is the wavelength of the incident beam. Surprisingly, this result predicts that the diffraction efficiency of a grating at a fixed wavelength is a function of groove height alone. The diffraction efficiency of a sinusoidal phase grating is independent of groove spacing.

The simplicity of this diffraction efficiency calculation is limited to thin sinusoidal gratings with normally incident beams. In practice however, diffraction gratings are seldom so simple. Groove profiles can be rectangular or triangular, and even sinusoidal gratings appear non-sinusoidal when the incident beams are not normally incident. Also, the phase grating approximation breaks down as the grooves deepen. Furthermore, the Fresnel and Fraunhofer approximations cannot predict polarization effects. A method of calculating diffraction efficiency based on electromagnetic theory can take all these factors into account. One of the simplest methods based on
electromagnetic theory is known as the point-matching method.

**Point-Matching Method**

At the surface of a diffraction grating, a relationship between the electric fields created by the incident beam and by the reflected and diffracted beams is defined by electromagnetic boundary conditions. The point-matching method enforces this relationship at several regularly spaced points along one spatial period of the grating surface to solve for the total electric field [31, 32].

The point-matching method can be used to calculate the diffraction efficiency of a grating as follows. Assuming that the incident beam is a transverse electric (TE) polarized plane wave, the electric field created by the incident beam can be written in time-harmonic form as

\[ E^i(x, y) = e^{jk(x \sin \theta_i - y \cos \theta_i)}. \]  

(2.14)

Assuming that the resulting electric field is the sum of \(2N + 1\) plane waves with complex amplitudes \(R_n\) and directions predicted by the grating equation, the electric field created by the reflected and diffracted beams can be written as

\[ E^d(x, y) = \sum_{n=-N}^{N} R_n e^{jk_x n x + k_y n y}. \]  

(2.15)

where

\[ k_{xn} = k \sin \theta_i + nK \quad \text{and} \quad k_{yn} = \sqrt{k^2 - k_{xn}^2} \]

with \(K = 2\pi/d\). The \(2N + 1\) plane waves represent \(N\) positive diffracted orders, \(N\) negative diffracted orders, and the single specular reflected beam. Since \(R_n\) represents the amplitude of the \(n\)th diffracted beam, the diffraction efficiency of the grating can be found by calculating \(R_n\).

If the surface of the grating is a perfect conductor, solving for \(R_n\) is straightforward. The total electric field on the surface of the grating can be written as a function
of $x$ alone

$$E_{tot}(x) = E^i(x, g(x)) + E^d(x, g(x))$$ (2.16)

where

$$g(x) = u \sin(Kx).$$

$E^i$ and $E^d$ are defined in equations 2.14 and 2.15, and $g(x)$ is the profile of a sinusoidal diffraction grating. Since the sum of the tangential electric fields on the surface of a perfect conductor must be zero, we can enforce this boundary condition by setting $E_{tot}^i(x) = 0$ at every point on the surface of the grating. Doing this at $2N + 1$ regularly spaced points along one period of the grating surface produces a set of $2N + 1$ linear equations with $2N + 1$ unknown $R_n$’s. Any computer code that can invert a square matrix does the rest.

The results of the point-matching method have been verified for a wide range of gratings [33]. Several notable properties of reflective sinusoidal gratings are revealed from the results of the point-matching method:

1. Diffraction efficiency is not a function of groove spacing (this was also predicted by the Fourier optics method for nearly normal angles of incidence and diffraction).

2. A maximum diffraction efficiency of 34% in each first order beam can be achieved when the groove depth (or the peak-to-peak amplitude of the surface acoustic wave) is 29% of the optical wavelength.

3. Diffraction efficiency is maximized when the diffracted beam is directed back toward incident beam ($\theta_i = \theta_d$). This common arrangement is often referred to as the Littrow mount or the autocollimation mount.4

4. Polarization effects are negligible for gratings with shallow grooves and are minimized at normal angles of incidence and diffraction.

4The optical arrangement of a diffraction grating is referred to as a mount.
2.2.3 Doppler Shift

Although the profile of a diffraction grating created by surface acoustic waves moves rigidly across the mirror, neither of the previous sections have taken this motion into account. However, since the surface acoustic wave velocity is very small compared to the speed of light, the movement of the grating can be accounted for simply by studying the non-relativistic Doppler shift of the diffracted beam.

The Doppler shift of a diffracted beam in the Littrow mount can be calculated quite easily. In the Littrow mount, $\theta_i = \theta_d$ for the +1 order diffracted beam. Combined with the grating equation (equation 2.12), the Littrow mount is equivalent to the condition

$$2 \sin \theta_d = \lambda/d \quad (2.17)$$

The change in frequency of a wave reflected by a moving object caused by the Doppler effect is

$$\Delta f = 2f \frac{v \sin \theta_d}{c} \quad (2.18)$$

where $f$ is the frequency of the wave, $v \sin \theta_d$ is the tangential speed of the object (in this case the diffraction grating), and $c$ is the speed of the wave [34]. To clarify, the quantities describing the frequency, wavelength, and velocity of the laser beam are $f \lambda = c$, and the quantities describing the frequency, wavelength, and velocity of the surface acoustic wave are $f_a d = v$.

Substituting the value of $\sin \theta_d$ from equation 2.17 into equation 2.18,

$$\Delta f = 2f \frac{v}{c} \left( \frac{\lambda}{2d} \right) = f_a.$$

Simply stated, the frequency of the laser beam is shifted by an amount equal to the frequency of the surface acoustic wave.

The situation above describing the non-relativistic Doppler shift of a laser beam caused by a moving reflective diffraction grating in Littrow mount is directly analogous to that of an acousto-optic modulator (AOM) mounted at a Bragg angle. Similar proofs of frequency and phase control based on Doppler shift and more concise
“conservation of energy” proofs based on quantum-mechanical photon/phonon anni-
hilation and creation are commonly used to demonstrate frequency and phase control
of a laser beam by Bragg diffraction from an AOM [3, 23]. In particular, the frequen-
cies of the nth order diffracted beams are shifted by $n f_a$, and the phases of the nth
order diffracted beams are shifted by $n(-\pi/2 + \phi)$ where $\phi$ is the phase of the surface
acoustic wave [8].
2.3 Summary

A surface acoustic wave optical modulator allows an electrical signal to control the direction, amplitude, frequency, and phase of a laser beam. This chapter outlined the basic acoustic, electrical, and optical principles behind a SAW-Mod. A detailed explanation of how a SAW-Mod operates can now be summarized.

The direction of the laser beam controlled by a SAW-Mod is determined by the frequency of the electrical drive signal. The frequency of the drive signal determines the wavelength of the surface acoustic wave (equation 2.8). The acoustic wavelength then defines the groove spacing of the diffraction grating created by the surface acoustic wave, which in turn predicts the direction of the beam according the grating equation (equation 2.12). In effect, increasing the frequency of the electrical drive increases the laser beam’s angle of diffraction, and conversely, decreasing the frequency of the electrical drive decreases the laser beam’s angle of diffraction.

The amplitude of the laser beam controlled by a SAW-Mod is determined by the amplitude of the electrical drive signal. The amplitude of the drive signal determines the total energy in the surface acoustic wave; this can be predicted with an electrical model of the IDT and its impedance matching circuitry. The energy density of the surface acoustic wave reveals its amplitude (equation 2.7). This amplitude is equivalent to the groove depth of the diffraction grating created by the surface acoustic wave and predicts the diffraction efficiency of the grating (equation 2.13). The diffraction efficiency of the grating then determines the amplitude of the diffracted beam. Simply stated, making the surface acoustic wave louder makes the diffracted laser beam brighter, and conversely, making the surface acoustic wave quieter makes the diffracted laser beam dimmer.

The frequency and phase of the laser beam controlled by the SAW-Mod is determined by the frequency and phase of the electrical drive signal. The frequency of the electrical drive signal determines the frequency of the surface acoustic wave. As predicted by acousto-optic scattering, the frequency of the diffracted laser beam is simply shifted by the frequency of the surface acoustic wave, and the phase of the
diffracted laser beam is simply shifted by the phase of the surface acoustic wave.
Chapter 3

Design, Construction, and Testing

Several surface acoustic wave optical modulator (SAW-Mod) prototypes were designed, built, and tested. The SAW-Mod prototypes demonstrated the practicality of surface acoustic wave optical modulation and validated the principles of operation developed in the previous chapter. Although the prototypes were fully-functional optical modulators, they were intended to be "proof of concept" devices and were not optimized for a particular application. The process of design, construction, and testing described in this chapter will serve as a basis for the development of SAW-Mods optimized for use in future applications.

3.1 Prototype Design

The SAW-Mod prototypes were designed to maximize angle of diffraction, bandwidth, and diffraction efficiency. The angle of diffraction must be large enough to make the diffracted beams well separated from the specular beam. The bandwidth must be large because it limits the number of resolvable beams that a SAW-Mod can produce. A large diffraction efficiency is needed to maximize the amount of diffracted light and to minimize drive power.

The following three sections describe the process of prototype design. The first section discusses the choice of surface acoustic wave transducers and materials. The second section outlines the trade-offs involved in interdigital transducer design. The
third section considers the optical design of the prototypes.

### 3.1.1 Transducers and Materials

Several types of surface acoustic wave transducers were considered for use in the SAW-Mod prototypes. These included surface wedge transducers [23], focused bulk wave transducers [35], comb transducers [23], meander line transducers [23], and interdigital transducers (described in Chapter 2). In the end, interdigital transducers (IDTs) were chosen for four main reasons:

1. IDTs operate at a suitable range of frequencies.
2. When patterned on strongly piezoelectric substrates like lithium niobate, IDTs have a high electric to acoustic energy conversion efficiency.
3. IDTs can be reliably fabricated using widely available photolithographic techniques.
4. IDTs are already in widespread use in surface acoustic wave devices [12].

After the IDT was selected, materials were chosen for the substrate, transducer, and mirror. Lithium niobate was selected as the substrate material not only for its high electromechanical coupling coefficient, but also because of low acoustic attenuation at high frequencies and its low surface acoustic wave velocity [36]. A lower surface acoustic wave velocity results in a shorter acoustic wavelength and therefore a higher angle of diffraction at a given frequency. Because surface acoustic wave devices and most first surface optical mirrors are coincidentally both made with thin films of aluminum on flat substrates, aluminum proved to be the most appropriate patterning material for the transducer and mirror.

### 3.1.2 Interdigital Transducer Design

IDT design presented a large number of options due to the extensive development of IDTs for use in surface acoustic wave filters. To simplify matters, the most basic
type of IDT (a uniformly weighted, uniformly spaced, straight electrode, quarter wave
design) was selected. A picture of this type of IDT is seen in Figure 2-3. Nonuniform weighting, usually accomplished through apodization, and nonuniform spacing, commonly a chirp, are frequently used to shape the frequency response of an IDT. Curved electrodes, such as those used in focused transducers [37], are occasionally used for applications that benefit from higher acoustic energy densities. Electrode designs other than the quarter wave design, frequently the eighth wave (or “double-electrode”) design, are used to reduce interelectrode reflections [29]. Once the general type of IDT was chosen, each individual IDT could be specified with three principal characteristics.

The first principal characteristic of an IDT is its operating center frequency. Introduced in chapter 2, the center frequency is specified by the principal period of the IDT and corresponds to the frequency at which the SAW-Mod achieves its highest diffraction efficiency. The practical range of center frequencies is bounded by the size of the substrate (since the IDT must fit completely on the substrate) and the width of the thinnest line that can be fabricated. The prototypes were designed with center frequencies of 9.89, 19.77, 29.66, 39.54, and 79.08 MHz. While increasing the center frequency increases the angle of diffraction, it also decreases the diffraction efficiency. For this reason, most prototypes were designed with a center frequency of 19.77 MHz.

The second principal characteristic of an IDT is its acoustic aperture. The acoustic aperture is specified by the width of the IDT. Decreasing the acoustic aperture increases the energy density of the surface acoustic wave and increases the diffraction efficiency. It also increases the number of SAW-Mods that can fit on one substrate. The prototypes were designed with acoustic apertures of 0.5, 1.0, 1.5, and 2 mm. However, as the acoustic aperture decreases, the propagation pattern begins to spread out due to diffraction, leading to decreased diffraction efficiency and increased acoustic cross-talk between adjacent SAW-Mods. For these reasons, most of the prototypes were designed with a relatively large acoustic aperture of 2 mm, or about 11.5 acoustic wavelengths at 19.77 MHz.

The third principal characteristic of an IDT is its length. The transducer length
is typically specified by the number of periodic sections (or "finger pairs") in the IDT and determines the bandwidth of the SAW-Mod. Increasing the number of periodic sections narrows the bandwidth. Although most of the prototypes were designed with 30 finger pairs, transducer lengths of 10, 22, 46, and 100 finger pairs were also explored.

The acoustic aperture and length of an IDT are typically constrained by the electrical properties of the IDT. The three principal characteristics of an IDT (center frequency, acoustic aperture, and length) collectively determine the acoustic radiation resistance. Because the electric driving port impedance of the IDT must be matched to the output impedance of the electric drive to maximize electric-to-acoustic energy conversion, the acceptable range of radiation resistance places a constraint on the relative width and length of an IDT. For example, reducing the width of an IDT to increase the acoustic energy density would require lengthening the IDT to compensate for the decrease in radiation resistance. Conversely, reducing the length of an IDT to increase the bandwidth of the SAW-Mod would require widening the transducer. Additionally, a broadband SAW-Mod would require a rather complex matching circuit to achieve an overall broadband frequency response.

3.1.3 Optical Considerations

The wavelength of the light used with a SAW-Mod has several effects on design. For example, using a shorter optical wavelength decreases the angle of diffraction but at the same time increases the diffraction efficiency. Also, the orientation of the SAW-Mod with respect to incident and diffracted beams (called a mount when applied to diffraction gratings) also affects the performance of the SAW-Mod. Increasing the angle of incidence increases the separation between the diffracted and specular beams. However, diffraction efficiency is lowest at high angles of incidence and highest in the Littrow mount ($\theta_i = \theta_d$). Because diffraction efficiency was a primary concern, all of the prototypes were designed for use in the Littrow mount.
3.2 Prototype Construction

Seen in Figure 3-1, a SAW-Mod consists of a mirror and an electrically driven acoustic transducer (compare to Figure 2-1). Both the mirror and transducer were fabricated using photolithography to pattern a thin film of aluminum on a wafer of lithium niobate. The wafer was then mounted to satisfy the acoustic, electrical, and optical requires of the SAW-Mod. This section details the process of prototype construction.

Developed primarily for semiconductor manufacturing, photolithography consists of coating a substrate with a thin film of a light sensitive substance called a photoresist, exposing the photoresist through a patterned glass plate called a photomask, and developing the exposed photoresist to produce a copy of the photomask pattern on the substrate [38, 39]. This pattern can then be used as a template for etching parts of the substrate or for depositing thin films of material onto the substrate.

The photolithographic processes used in producing SAW-Mod prototypes is summarized as follows:

1. A layer of aluminum ranging in thickness from approximately 600 to 2400 Angstroms was deposited onto lithium niobate substrates using a thermal evaporator. The lithium niobate substrates were three inch wafers of Y-cut, Z-oriented, SAW grade lithium niobate (part number 99-30002-01: Crystal Technology, Inc., Palo Alto, CA).

2. A layer of negative photoresist (NR8-1500: Futurrex, Inc., Franklin, NJ) approximately 1.5 \( \mu \text{m} \) thick was applied to the metallized substrate using a spin coater.

3. After baking the wafer to harden the photoresist, the wafer was exposed through a photomask containing the patterns of 24 SAW-Mod prototypes (0.060 inch chrome and glass plate: Advance Reproductions Corporation, North Andover, MA) and immediately developed (RD2: Futurrex, Inc.).

4. After further baking to harden the patterned photoresist, the exposed aluminum was etched away in a mixture of phosphoric, acetic, and nitric acids.
Figure 3-1: A wafer of SAW-Mod prototypes. The rectangular region in the center of the wafer is the SAW-Mod mirror, while the vertical strips directly above and below the mirror are 24 individual IDTs. The wafer is held in a mount made from aluminum and cast acrylic and secured with nylon-tipped set screws. A dual spring-loaded contact probe assembly used to connect an IDT to a BNC cable is visible in the foreground.
5. The remaining photoresist was then removed with acetone.

After the photolithographic steps were complete, the wafers (each patterned with 24 SAW-Mod prototypes) were placed in a mount made from alloy 2024 aluminum, cast acrylic, a tip/tilt optical mount (600A-2R: Newport Corporation, Irvine, CA), and a one-axis translation stage (436: Newport Corporation). Seen in Figure 3-1, the mount interfaced with the flat edge of each wafer for easy orientation with the Z-axis, held each wafer securely using nylon-tipped set screws, and allowed for quick optical alignment and switching from one prototype to the next.

Acoustic absorbers were required to prevent the formation of standing surface waves and to dampen spurious acoustic signals. Absorbers were made by applying a thin layer of mounting wax (multiwax W-835: Witco, Petrolia, PN) in the path of the surface acoustic waves at the ends of the substrate.

Each IDT was connected to the drive electronics with an assembly made of two spherically-tipped spring-loaded contact probes (type SOJ2.2G spring contact probe, Interconnect Devices, Inc., Kansas City, KS) held in a block of cast acrylic. The two contact probes were connected to a BNC connector, and both the connector and the probes were mounted on a small section of prototyping board. The contact probes could be firmly pressed onto the IDTs without causing damage, and the prototyping board provided a convenient location to build matching circuitry in close proximity to the IDT. The entire assembly was attached to a three-axis translation micromanipulator to aid the accurate positioning of the probes.
Figure 3-2: Optical setup for testing SAW-Mod prototypes. The beam of HeNe laser was spatially filtered and then diffracted by the SAW-Mod. The diffracted beam “picked off” by a rectangular mirror and directed onto an observation screen or power meter (not shown).

3.3 Testing

The principles of operation described in Chapter 2 predict the angle of diffraction, center frequency, bandwidth, and diffraction efficiency of a SAW-Mod. This section summarizes the testing of these predictions with the SAW-Mod prototypes.

3.3.1 Test Setup

The testing apparatus for the SAW-Mod prototypes consisted of radio-frequency (RF) drive electronics, a laser, basic lenses and mirrors, and measurement equipment. The RF drive was generated with a synthesized RF signal generator (6060A: Fluke Corporation, Everett, WA) and amplified by a 5W power amplifier (ZHL-5W-1: Mini-Circuits, Brooklyn, NY). The laser used in testing was a 632.8nm HeNe laser with a maximum output of 30 mW (Melles Griot, Irvine, CA). As illustrated in Figure 3-2, the laser beam was spatially filter, diffracted by the SAW-Mod, and directed onto an observation screen. Beam intensity measurements were made using a power meter (Coherent, Inc., Santa Clara, CA), and electrical measurements were made using an digital oscilloscope (TDS 724D: Tektronix, Beaverton, Oregon).

Each SAW-Mod also required a matching circuit for testing. Because the input
impedance of an IDT is typically not matched to the output impedance of its electrical drive, a matching circuit is required to maximize electric-to-acoustic energy conversion efficiency and to minimize electrical reflections back toward the source. A typical matching circuit is shown in Figure 3-3.

### 3.3.2 Angle of Diffraction

The angle of diffraction produced by an operating SAW-Mod was measured by marking the locations of the specular and +1 order diffracted beams on a distant observation screen. This measurement was repeated for two SAW-Mod prototypes near their respective center frequencies of 19.77 and 29.66 MHz. Both measured angles of diffraction agreed with their theoretically predicted angles of 0.21 and 0.32 degrees to within measurable tolerances.
3.3.3 Frequency Characteristics

The diffraction efficiency of a SAW-Mod as a function of frequency is dominated by the electric to acoustic conversion efficiency of the IDT. Since an IDT can be modeled as a transversal filter, the overall frequency response of the SAW-Mod (from input electrical frequency to output optical power) should approximate the frequency response of an equivalent transversal filter.

The frequency responses of several SAW-Mod prototypes were measured by varying the frequency of the RF drive and measuring the resulting optical power in the diffracted beam. Seen in Figures 3-4 and 3-5, the shapes of the measured frequency responses generally match the predictions of the transversal filter model. The closest fitting equal tap weight transversal filters were determined by varying the lengths and center frequencies of the predicted filters and manually comparing the locations of each of the minimums. The locations of the measured and predicted minimums generally coincided with less than 0.1 MHz error.

Two deviations from the predictions of the transversal filter model are apparent from the measured frequency responses in Figures 3-4 and 3-5. First, the number of sources in the closest fitting transversal filters are larger than expected; the SAW-Mod with 22 finger pairs is best fit by a transversal filter with 24 sources, and the SAW-Mod with 100 finger pairs is best fit by a transversal filter with 106 sources. Second, the upper half of the frequency response is generally higher in amplitude and somewhat distorted, especially near the center frequency. In fact, the upper side lobes of the SAW-Mod with 22 finger pairs hardly resemble the predicted frequency response. Also, the first upper side lobe of the SAW-Mod with 100 finger pairs is much greater in amplitude than its lower counterpart. These and other deviations point out deficiencies in the basic transversal filter approximation. Possible causes of these deviations include effects at the edges of IDTs, bulk acoustic wave generation, and non-linear acoustic behavior of the substrate caused by the large amplitudes of the surface acoustic waves.

The center frequencies of the SAW-Mod prototypes could also be determined
Figure 3-4: Frequency response of a SAW-Mod with a center frequency of 19.77 MHz, a width of 2 mm, and 22 finger pairs. Measured data points are indicated with circles connected by dashed lines, and the frequency response of the best fitting transversal filter is indicated with the solid line.

Figure 3-5: Frequency response of a SAW-Mod with a center frequency of 19.77 MHz, a width of 2 mm, and 100 finger pairs.
from the frequency response measurements by noting the center frequencies of the closest fitting transversal filters. Using this method, the center frequencies of three prototypes with a predicted center frequency of 19.77 MHz and one prototype with a predicted center frequency of 29.66 MHz were estimated at 19.8, 19.4, 19.6, and 29.55 MHz.

Early testing of the prototypes before the addition of acoustic absorbers suggested the presence of standing waves caused by reflections off the edges of the substrate. Figure 3-6 shows a detail of the frequency response of a SAW-Mod with 30 finger pairs and a center frequency of 19.77 MHz without acoustic absorbers; large variations occur at regular spacings of approximately 80 kHz. This spacing can be predicted by examining the standing wave formed by the forward propagating wave and its reflection off the end of the substrate; assuming that the IDT is roughly 5 cm from the end of the substrate, the standing wave ratio inside the resulting cavity resonator would have regular variations at a spacing of about 70 kHz. Considering that surface acoustic wave attenuation in YZ-LiNbO$_3$ is negligible at frequencies below 1 GHz [36], the formation of a standing wave pattern is not surprising. Figure 3-7 shows the frequency response of the same SAW-Mod after the addition acoustic absorbers at both ends of the substrate. The original variations can still be detected but are highly attenuated.

### 3.3.4 Diffraction Efficiency

The diffraction efficiencies of the SAW-Mod prototypes were measured and compared with theoretical predictions based on the SAW-Mod designs and electrical measurements made at the inputs. The measured diffraction efficiencies closely matched the predicted values. The maximum diffraction efficiency achieved during testing was 2.1%.

The diffraction efficiency of an operating SAW-Mod could be predicted by measuring the amplitude of the drive signal. The amplitude of the drive signal could then be used to calculate the power dissipated by the IDT by analyzing the IDT electric driving port impedance and the matching circuit. Then, assuming all of the electrical
Figure 3-6: Frequency response of a SAW-Mod with a center frequency of 19.77 MHz, a width of 2 mm, and 30 finger pairs before the addition of acoustic absorbers. Note the change in frequency scale from Figures 3-4 and 3-5. The large, regularly spaced variations suggest the presence of a standing wave formed by the surface acoustic wave and its reflection off the end of the substrate.

Figure 3-7: Frequency response of the same SAW-Mod as in Figure 3-6 after the addition of acoustic absorbers. Variations can still be detected but are highly attenuated.
energy was converted into surface acoustic wave energy, the amplitude of the surface acoustic wave could be predicted using equation 2.7. Finally, the amplitude of the surface acoustic wave could be used to predict the resulting diffraction efficiency using equation 2.13.

Figures 3-8 and 3-9 show the diffraction efficiency of several SAW-Mod prototypes as a function of input amplitude. Superimposed are curves for the theoretically predicted diffraction efficiencies multiplied by an experimentally determined loss factor. This loss factor was necessary to take into account various sources of loss including imperfect electrical matching, loss in electric-to-acoustic energy conversion, generation of undesired acoustic signals (including pseudo surface acoustic waves and bulk acoustic waves), and beam diffraction. For a well-matched transducer, an appropriate loss factor typically ranged from 0.3 to 0.6.

The maximum diffraction efficiency achieved by a SAW-Mod prototype was 2.1%. This limit was reached by driving the power amplifier to its damage threshold limit. Because the diffraction efficiency increased in a predictable manner up to 2.1%, one could expect that further testing would continue to produce higher diffraction efficiencies until some untested fundamental limit is reached.

3.3.5 Acoustic Propagation Pattern

The acoustic propagation pattern of a SAW-Mod was measured to explore the effects of beam diffraction. The propagation pattern was determined by measuring the acoustic beam profile at three different locations on the SAW-Mod mirror; the beam profile was determined by incrementally translating the SAW-Mod to make the laser beam “walk” across the mirror and then measuring the diffraction efficiency at each position.

Seen in Figure 3-10, the propagation pattern measurement indicates that little beam spreading could be detected after a propagation distance of approximately 1.5 cm. The IDT had an acoustic aperture of 2 mm, or approximately 11.5 acoustic wavelengths at the measurement frequency of 19.77 MHz. This conclusion is in agreement with results in the surface acoustic wave filter design literature [27].
Figure 3-8: Diffraction efficiency as a function of amplitude for a SAW-Mod with a center frequency of 19.77 MHz, a width of 2 mm, and 100 finger pairs. Measured data points are indicated with circles. The line indicates the theoretically predicted diffraction efficiency assuming 40% of the measured input power was utilized. This experimentally determined loss factor was necessary to account for various sources of loss that were difficult to predict.

Figure 3-9: Diffraction efficiency as a function of amplitude for a SAW-Mod with a center frequency of 29.25 MHz, a width of 2 mm, and 30 finger pairs. The theoretically predicted diffraction efficiency incorporates a loss factor of 43%.
Figure 3-10: Normalized optical power as a function of position across the mirror at three distances from the IDT. The IDT had a center frequency of 19.77 MHz, a width of 2 mm, and 100 finger pairs. The three distances ranged from approximately 5 to 20 mm from the end of the IDT. Normalization was necessary because moving the beam to the three different distances required changes in the optical setup.
Chapter 4

Conclusion

This thesis developed an all-reflective optical modulator that in principle scales from visible to UV and X ray wavelengths. The basic principles of surface acoustic wave optical modulation were formulated by studying surface acoustic waves, diffraction gratings, and acousto-optics. Several surface acoustic wave optical modulator (SAW-Mod) prototypes were also designed, built, and tested. The prototypes were fully-functional optical modulators. Using a 633 nm HeNe laser at normal incidence, diffraction angles of 0.21 and 0.32 degrees were measured for prototype modulators with center frequencies of 19.77 and 29.66 MHz, respectively. The maximum diffraction efficiency obtained during testing was 2.1%. Theses results agreed with theoretical predictions.

SAW-Mods could supplant acousto-optic modulators (AOMs) in many current applications. For example, since surface acoustic wave devices can operate at frequencies of several GHz, SAW-Mods could be used as frequency modulators with bandwidths that are larger than possible with AOMs. SAW-Mods could also be used as beam deflectors or beam scanners with angles of diffraction that are larger than possible with AOMs. Additionally, since SAW-Mods can be made on very large substrates, spectrum analyzers and tunable optical filters made with SAW-Mods could have higher resolutions than those made with AOMs. In another application, SAW-Mods could be used as non-dispersive optical modulators in mode-locked laser systems that typically employ AOMs.

SAW-Mods could also find a number of novel applications. For example, since
hundreds or thousands of SAW-Mods could be fabricated on a single wafer, an array (or other geometric arrangement) of SAW-Mods could be used to construct a spatial light modulator. In another application, a SAW-Mod could be used as the adjustable dispersive element of a tunable laser [44]. Also, since the output couplers in many types of lasers transmit only a small percent of incident light [45], SAW-Mods could be used as laser output couplers.

Finally, since SAW-Mods are all-reflective optical components, they could allow many of the aforementioned applications to scale to UV and X ray wavelengths, a point that returns to the original purpose of this thesis. Surface acoustic wave optical modulation was developed to fulfill the need for all-reflective optical modulators in synthetic aperture optical systems. The author hopes that this need has been fulfilled and looks forward to working on the next generation of synthetic aperture optical systems.
Bibliography


