DESIGN AND CHARACTERIZATION OF A MEMS BASED OPTICAL MICROPHONE FOR AEROACOUSTIC MEASUREMENT

By

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To my parents…
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This thesis presents the design and characterization of a MEMS based intensity modulated optical microphone. Sensors based on optical techniques are less susceptible to electromagnetic and radio frequency interference. They can thus operate in harsh environments where sensors based on electrical transduction principles cannot be used. Using MEMS technology to fabricate the microphones results in the batch fabrication of a large number of small devices with matched properties and low cost. The small size of the device improves the spatial resolution of the measured acoustic signal.

The optical microphone is a multi-domain system that involves the transduction of the pressure variations of the input acoustic signal to mechanical vibrations of a diaphragm. This in turn modulates the intensity of a reference laser beam that is converted to a modulated electrical signal using a photodetector. The design of each of the transduction stages is presented along with theoretical formulations for the key parameters such as sensitivity, linearity, and noise sources. An electrical equivalent circuit for the overall microphone system has been developed using lumped element modeling.
A process flow for the fabrication of the device was developed. A prototype system using a similar MEMS device was built and characterized. The results of the characterization performed on a prototype device in a normal incidence plane wave tube from 1kHz to 6.4kHz are presented. The optical microphone has a sensitivity of $151\mu V/Pa$ from 1kHz to 6.4kHz. The phase response of the optical microphone decreases from $10^\circ$ at 1kHz to $-41^\circ$ at 6.4kHz. A proof of concept of a MEMS based intensity modulated optical microphone has thus been demonstrated.
CHAPTER 1
INTRODUCTION

Acoustic sensors discussed herein refer to microphones used in audio, aeroacoustic, and ultrasonic applications [1]. This chapter introduces various optical techniques for acoustic sensors. The advantages and disadvantages of the optical technique for acoustic measurement are discussed along with the opportunities provided by micromachining techniques for fabricating the sensor. Previous work on various acoustic to optical transduction techniques and their implementation in the form of optical microphones is reviewed. A special emphasis is placed on the intensity modulated lever type of optical microphones, as it is the focus of this thesis. The chapter ends with the research objectives and an outline of the thesis.

A microphone is a transducer that converts acoustical energy into corresponding electrical energy. They can be classified based on the transduction mechanism used to convert a signal from the acoustic domain to the electrical domain. The transduction can be done via electrical transduction methods such as electrodynamic, piezoelectric, piezoresistive and capacitative [2] or via non-electrical transduction methods such as optical [3]. They can also be classified based on the fabrication of the sensor. The sensor can be manufactured using conventional large scale machining techniques or via micromachining techniques [2] used in microelectromechanical systems (MEMS) fabrication.

In this thesis, the focus is on the optical transduction approach for acoustic sensing due to its immunity to electromagnetic interference. An optical microphone is an
acoustic sensor that works by modulating the intensity, phase, or polarization of a reference light signal according to the pressure fluctuation of the input acoustic signal. The conversion from a modulated light signal to a useful electrical signal for further processing may be done far away from the acoustic source by transmitting the signal via fiber optic cables. The absence of any electronics at the acoustic source makes the optical method of acoustic measurement less susceptible to electromagnetic and radio frequency interference. Thus, they can operate in harsh environments [4, 5] where conventional microphones, which use electrical transduction principles, cannot be used.

The advantages obtained via the optical method of acoustic measurement come with its own set of problems. Optical microphones require a very stable reference optical source [6-8]. All the components of the optical microphone system such as light sources, wave-guides, optical sensor, and photo detectors must be well aligned and must be able to withstand minor vibrations that might occur during the normal course of use of the sensor. Also, the components must be robust, and their output must not drift with changes in ambient conditions such as temperature, pressure and humidity.

Using micromachining techniques, a large number of similar sensors of very small form factor with closely matched geometrical and material parameters can be batch fabricated. The small size of the sensor facilitates localized measurement of the sound signal thus providing better spatial resolution [9] compared to sensors that are larger and fabricated using conventional machining techniques. When a large volume of sensors are needed, the batch fabrication of MEMS sensors also reduces the manufacturing cost per sensor as compared to conventional macro scale manufacturing techniques.
1.1 Optical Microphone Transduction Schemes

Optical microphone (OM) transduction schemes can be classified based on the property of light that is modulated [3]. This classification scheme divides OMs into those that modulate the intensity, phase and polarization of the light. Each category is then further subdivided.

1.1.1 Intensity Modulation

In this scheme of modulation, the light energy in the optical path is modulated according to the information in the acoustic signal. They are further classified as radiated wave and evanescent wave methods. In radiated wave intensity modulation, light energy from a source is reflected based on the pressure fluctuation of the input acoustic signal. The evanescent wave method involves the phenomenon of mode coupling, i.e. energy from the evanescent field of the optical wave is coupled from one waveguide to another based on the acoustic signal.

Intensity modulated OM can be further classified based on the actual physical construction of the device. Radiated wave methods are divided into lever, cantilever moving grating, and macrobend. The various types of radiated wave intensity modulation techniques are shown in Figure 1-1. The evanescent wave method consists of the coupled wave guide and microbend schemes.

The commonly used radiated wave method is the lever and cantilever arrangement. This is because of the ease of construction as compared to that of the moving grating and macro bend configurations. The lever type of arrangement uses a set of transmit and receive fibers as shown in Figure 1-1(a). One of the fibers carries the input unmodulated reference light signal and the other carries the output intensity-modulated signal. A reflective surface is positioned to face both fibers. They are aligned
at equal angles to the normal of the reflective surface. Light from the transmit fiber impinges on the reflective membrane. The intensity of the light reflected into the receive fiber is modulated by the displacement of the reflective surface from the neutral plane by the impinging acoustic pressure wave.

Figure 1-1 Radiated wave intensity modulation schemes. (a) Lever type (b) Cantilever (c) Moving grating (d) Macro bend. \( P_i \) represents the input unmodulated light. \( P_o \) represents the intensity modulated output light 3.

1.1.2 Polarization Modulation

The common types of polarization modulation based optical microphones are based on the polarization properties of a liquid crystal and a differential index shifter. Figure 1-2 shows the schematic of polarization modulation based optical microphones.

In the liquid crystal method, a liquid crystal is attached to a vibrating membrane. The polarization of the light passing through the crystal varies according to the vibration of
the crystal. A polarizer is used to measure the acoustic signal based on the variation in polarization of light transmitted through the liquid crystal layer. In the differential index shifter method, differential index shifting occurs through the integrated optical (IO) nano mechanical effect. A membrane or cantilever dielectric plate is suspended above a waveguide at a small distance of few microns. Applying a pressure on the top dielectric varies this gap by a few nanometers. The effective refractive index of the waveguide is a function of the gap distance modulating the penetration of the evanescent wave in the wave guide.

Figure 1-2 Polarization modulation schemes. (a) Liquid crystal (b) Differential index shifter. $P_i$ represents the input unmodulated light. $P_o$ represents the polarization modulated output light.

1.1.3 Phase Modulation

This modulation scheme is divided into two main types based on the physical structure that is used to modulate the phase of the reference signal. They are the grating based phase modulated OMs and interferometric phase modulated OMs.

The grating based phase modulated optical microphone works on the principle of an optical modulator. In this scheme, light is incident at a small angle to the normal of the
waveguide surface with corrugations that form the gratings. For a certain combination of wavelength, grating spacing, and waveguide refractive index, the light gets coupled into the waveguide. The presence of a vibrating waveguide next to a stationery waveguide varies the effective index of refraction of the stationery waveguide thus modulating the optical signal with the pressure fluctuations of the input acoustic signal.

The various interferometric optical microphones are named after the corresponding interferometer used. The commonly used types are Fabry-Perot, Mach-Zehnder, and Michaelson. Figure 1-3 shows a schematic of the various interferometric optical microphones schemes. In the Fabry-Perot interferometric optical microphone, a Fabry Perot cavity is formed between two parallel surfaces. One of the surfaces is free to vibrate in accordance with the acoustical signal and is usually a reflective membrane. The other surface is the end of a fiber optic cable. The interference pattern generated from the phase shift between the incident wave and the reflected wave is detected as an intensity variation. In the Michaelson type of interferometric optical microphone, the reference light signal is split into a reference beam and a test beam. The test beam impinges on a reflecting vibrating membrane while the reference signal reflects off a simple mirror. The two reflected signals interfere with each other, and the interference pattern is detected as an intensity variation. In Mach-Zehnder interferometric phase modulation optical microphones, an optical beam is split into a test and a reference beam using a beam splitter or a coupler. The path length of the test beam varies according to the position of the vibrating membrane, causing a phase shift. When the two beams interfere after merging, the interference patterns are detected as an intensity variation.
Figure 1-3 Interferometric phase modulation schemes. (a) Fabry Perot (b) Michaelson (c) Mach Zehnder. $P_i$ represents the input unmodulated light. $P_o$ represents the phase modulated output light.

1.2 Comparison of OM Transductions Techniques for MEMS Implementation

The various OM transduction schemes presented in the previous section have various advantages and disadvantages in terms of implementation using MEMS technology. The key aspects to be considered for selecting one out of the three possible transduction schemes for implementation are the material, ease of fabrication of the structure, ease of positioning the input and output waveguides with respect to the sensing structure, and ease of packaging the final device. Another requirement is that signal processing required for converting the modulated optical signal to a modulated electrical signal be minimal. In this section, the rationale for choosing the optical lever based intensity modulation (IM) technique is discussed.
1.2.1 Material for the Sensing Structure

The intensity modulation and phase modulation techniques employ a geometric effect due to structural deflection modulating an optical carrier. In the case of polarization modulation, the material property of liquid crystals is modified. The fabrication of liquid crystals is not readily available in current MEMS technology. Hence the use of polarization modulation poses a serious disadvantage as compared to intensity modulated and phase modulated OMs in terms of fabrication.

1.2.2 Orientation of Input and Output Waveguides

Various possible orientations of the input and output waveguides are readily available in the literature for intensity modulated OM [5, 10-14] [15] and for phase modulated OM [15-17]. For the Fabry-Perot phase modulated OM [16], the input waveguide must be positioned perpendicularly at a distance less than the coherence length from the reflecting structure for phase modulation to occur. The coherence length is approximately 40\(\mu\)m the wavelength of the operation, which was chosen to be 1550nm. This requires considerable skill as compared to the intensity modulated OM proposed by Cuomo [18] and Cook and Hamm [10] where the perpendicularity and distance of the waveguides from the membrane can be tuned by measuring the received power in the output waveguides using a photodetector. Furthermore, once the proper orientation is obtained, positioning the waveguides at the optimal position is possible by fabricating the device with a mechanical stop to lock the position of the waveguides at the required distance. This is difficult in phase modulated systems as the degree of phase modulation cannot be easily monitored and optimized by varying the orientation and position of the waveguides in fractions of a wavelength.
1.2.3 Signal Processing at the Output

All the modulation schemes discussed must finally reduce to an intensity modulation because that is the only property to which photodiodes and phototransistors, which convert the optical signal to a corresponding electrical signal can respond. To recover the phase information from the output intensity of the phase modulated OM, homodyne and heterodyne techniques [17] need to be used. This is an extra step required to extract the information from the modulated optical signal in phase modulated systems as compared to intensity modulated systems where the output of the photodetector can be directly related to the pressure fluctuation of the input acoustic signal. Based on these considerations discussed in this section, it can be concluded that a intensity modulated optical microphone is better suited for MEMS fabrication and has simpler requirements for the processing of the modulated output optical signal.

1.3 Review of Intensity Modulated Optical Microphone

The earliest work on intensity modulated OM was reported in 1975 by Fulenwider and Gonsalves [12]. In their intensity modulated OM, the light source used was a LED with constant intensity output operating in the visible and infrared wavelengths, and the detector used was a silicon PIN diode operating in the 400-1150nm wavelength. Fulenwider’s patent [12] reports a lever and cantilever based optical microphone. The performance specifications have not been provided in the patent. Cuomo, Zuckerwar and colleagues developed an optical microphone [4, 19, 20] based on the lever type intensity modulation scheme. In their lever optical microphone, a single transmit fiber surrounded by multiple receive fibers was placed perpendicular to the reflecting membrane. They reported a sensitivity of 36mV/Pa and a bandwidth of 3kHz. A pulsed 850nm LED source
with an output power of $2.4mW$ was used. In addition, Cuomo and He developed light intensity distribution functions based on geometrical optics for multimode fibers [21] and theoretical formulations for the sensitivity [22], frequency response, and minimum detectable signal [23]. Cuomo [18] also reported a pressure gradient hydrophone using the same principle. The resonant frequency of the device was varied by adjusting the tension in the reflective membrane via extended screws. The accuracy of tension control in a macro scale membrane is limited. Dietmar [24] described a two fiber arrangement for a lever microphone with a gradient index lens between the fiber endface and the membrane and reported a sensitivity of $0.3\%/Pa$, a bandwidth of $4.3kHz$, and a noise equivalent pressure level of $42dB(A)$. The optical source used was an $830nm$ LED. Using a new processing technology based on polymethylmethacrylate (PMMA) polymer [25], Garthe and Kobiela reported an intensity modulated optical microphone with a flat response in the audio range with a noise equivalent pressure level of $38dB(A)$. However, polymers often exhibit adverse effects in the presence of humidity (swelling). Thus, stability is an issue. Paritsky and Kots [5,26] report a two-fiber lever type optical microphone with a SNR of $75dBSPL$ and a bandwidth in excess of $4kHz$ using an LED light source with multi-mode fibers. Different arrangements of the tip of the transmit and receive fibers [13, 14] were reported in which the arrangement and shape of the tip of the transmit and receive fibers have been varied to obtain higher sensitivity. A quantitative figure for the improvement in sensitivity and the specifications of the light source, fibers, and detector used in the various cases is not available in the patent [13, 14]. Budal [27] describes a lever type OM with a focusing lens, exhibiting a frequency response from $0$ to $20kHz$ and a sensitivity of $60mV/Pa$. The OM uses a lamp with a tungsten filament as the
light source and photocells for detecting the intensity modulated output. Bucholz [28] reports an intensity modulation based optical microphone consisting of a lens coupled onto the center of the vibrating membrane using an LED. The specification of the LED and performance specifications of the OM is not specified in the patent [28].

Recent development of lever type optical microphones [5, 10, 13, 14, 20, 27] suggest a significant trend towards developing instrumentation grade optical microphones with increased sensitivity, dynamic range, and bandwidth. Table 1-1 lists the dimensions, frequency response, sensitivity, and noise floor of commercial optical microphones and those listed in the literature.

Table 1-1 Recent developments in lever type intensity modulated optical microphone systems.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Type of Intensity Modulation</th>
<th>Membrane Material</th>
<th>Membrane Dimension</th>
<th>Frequency Range</th>
<th>Sensitivity</th>
<th>Noise Level</th>
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</thead>
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<tr>
<td>Budal (1974)[27]</td>
<td>Lever with focusing lens</td>
<td>Metallized Mylar Membrane</td>
<td>7mm diameter and 8um thick</td>
<td>0-10kHz</td>
<td>NA</td>
<td>44dB</td>
</tr>
<tr>
<td>Cook et al (1979)[10]</td>
<td>Lever</td>
<td>BeCu Reflector</td>
<td>--</td>
<td>0-1Mhz</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Garthe D (1991) [24].</td>
<td>Lever</td>
<td>Mylar</td>
<td>25mm dia 2um thickness</td>
<td>20-3.4kHz</td>
<td>0.04%/P</td>
<td>57dbSpl</td>
</tr>
<tr>
<td>Zuckerwar et al. (1992) [4]</td>
<td>Lever</td>
<td>Metallized Mylar Membrane</td>
<td>3.175mm diameter</td>
<td>0-2.5kHz</td>
<td>23mV/Pa</td>
<td>NA</td>
</tr>
<tr>
<td>Bucholz (1993)[Buchholz, 1993 #4</td>
<td>Lever with lens</td>
<td>Oriented Polyester</td>
<td>1.91cm diameter</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Paritsky, A., et al. (1998) [26]</td>
<td>Lever</td>
<td>NA</td>
<td>1.6mm diameter</td>
<td>250-4kHz</td>
<td>0.3-1.8V/Pa</td>
<td>65dB</td>
</tr>
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</table>
1.4 Research Objectives

The standard to which instrumentation grade microphones are usually compared are the condenser microphones made by Brüel and Kjaer. The Brüel and Kjaer microphones operate on the principle of capacitance variation with applied acoustic signal. Compared to the Brüel and Kjaer Type 4138 1/8” condenser microphone used in conjunction with a Brüel and Kjaer 2670 preamp which has a nominal sensitivity of 1mV/Pa, bandwidth of 100kHz, and noise floor of approximately 30dBSP in a 3.16Hz bin width [29], optical microphones lag behind in terms of noise floor, sensitivity, and bandwidth.

Table 1-2 Specifications for microphone used in aeroacoustic measurement.

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Range</td>
<td>60-160dBspl</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>&gt;50kHz</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-7 – 55 C</td>
</tr>
<tr>
<td>Relative Humidity Range</td>
<td>10-95 %</td>
</tr>
<tr>
<td>Diaphragm Size</td>
<td>&lt;0.5mm</td>
</tr>
</tbody>
</table>

The specifications [30] of a microphone for use in aeroacoustic measurement are listed in Table 1-2. The design, fabrication, and characterization of a MEMS based intensity modulated lever type optical microphone which meets the specifications listed in Table 1-2 are the primary goals of this thesis. Other requirements for the optical microphone are immunity to external vibrations as well as external conditions such as temperature, pressure, and humidity. The optical microphone must also be immune to changes in ambient light and changes in the reference signal. The microphone package therefore must be rugged and able to withstand the demands of a harsh environment.
1.5 Thesis Outline

The thesis is organized into six chapters. This chapter presents the motivation, background, and application of optical microphones. Chapter 2 presents the theory of the lever type optical microphone and details the design of the microphone including the mechanical, optical, and electrical design. Two different configurations of the fiber assembly have been investigated and are presented in the optical design. Theoretical formulations for the sensitivity, linearity, minimum detectable signal (MDS), and frequency response of the microphone are also developed. Chapter 3 presents the steps involved in fabricating the device including the process flow and masks. Chapter 4 presents the experimental setup used for testing and characterizing the optical microphone and discusses the experimental results of the lever OM prototype. Chapter 5 presents concluding remarks and outlines proposed design modifications, system enhancements, and future work for the second-generation optical microphone.
CHAPTER 2
DESIGN OF AN OPTICAL MICROPHONE SYSTEM

The main focus of this chapter is the mechanical, optical, and electrical design of the overall microphone system.

Figure 2-1 shows the overall block diagram of the optical microphone system. At the left, the key component is the MEMS optical microphone device that consists of a compliant silicon nitride membrane on top of a cavity that is deflected by an acoustic pressure fluctuation. At the right, a laser beam is split into two beams of equal power using a 1x2 beam splitter after passing through an optical isolator. One optical beam is coupled to the transmit fiber (Tx Fiber). This beam is directed towards the membrane that deflects linearly with respect to the acoustic pressure signal, modulating the intensity of the reflected light. The light reflecting off the vibrating membrane is coupled into the receive fiber (Rx fiber) and is converted into an electrical signal by a photodetector. The other optical beam from the beam splitter is converted into a reference voltage signal using a second photodetector. The voltage signals corresponding to the intensity modulated optical signal and the reference optical signal are fed into the numerator and
denominator channels respectively of an analog divide circuit. The output of the analog divide circuit thus provides an output voltage signal that corresponds to the input acoustic signal.

Section 2.1 discusses the partitioning of the optical microphone system to provide a logical framework for the system design and the packaging. An equivalent electrical circuit for the optical microphone is developed to provide a system level understanding of the optical microphone. Sections 2-2, 2.3, and 2-4 explain the mechanical, optical, and electrical design of the optical microphone system along with a theoretical formulation for the performance metrics such as sensitivity, linearity, and frequency response. Sections 2-5 describes the overall system performance in terms of the system sensitivity, linearity, frequency response, and minimum detectable signal and provides theoretical formulations for the same. This chapter concludes with Section 2-7, which summarizes the design of the optical microphone system.

2.1 System Partitioning

The optical microphone system is a multi energy domain system. The interaction of the acoustic signal and the mechanical and optical, and electrical energy domains may be considered as follows. The input to this system is a time varying pressure signal in the form of acoustic waves. These waves impinge on the membrane and cause it to vibrate thus transducing the pressure signal into mechanical vibrations of the membrane. This is known as *acousto-mechanical* transduction. A set of transmit and receive fiber are placed in front of the membrane. Light directed onto the vibrating membrane from the transmit fiber is reflected and modulated in intensity, resulting in *mechano-optical* transduction.
The intensity modulated optical signal is then converted to an electrical signal using a photodetector via \textit{opto-electrical} transduction. Thus, the conversion of the input acoustic signal into an electrical signal is achieved in three distinct stages and goes through the mechanical, optical, and electrical energy domains. Figure 2-2 shows the various transduction stages involved in the conversion of the input acoustic signal to an amplitude modulated voltage signal.

To subdivide the system into parts, the design process is partitioned into three transduction stages: (1) acousto-mechanical, (2) mechano-optical, and (3) opto-electrical transduction stages respectively. As mentioned by Prof. Senturia [31], the device, system, and package design must be done concurrently in the design of a MEMS product. This is because the proper functioning of a MEMS product is highly dependent on the package. Furthermore, testing and calibration of the device is also dependent on the packaging. Thus, the mechanical, optical, and electrical design were done concurrently with the final package in mind.

Figure 2-2 Block diagram of the transduction mechanisms involved in an optical microphone system.

\textbf{2.2 Acousto Mechanical Transduction}

This section details the design of the acousto mechanical transduction stage of the optical microphone system. Theoretical formulations for the sensitivity, linearity, frequency response, and noise mechanisms are developed along with an equivalent circuit for the acousto mechanical transduction stage.
2.2.1 Mechanical Design

The mechanical design involves the selection of the material for the sensing membrane and the design of the dimensions of the sensing membrane and sensor chip to achieve high acousto mechanical sensitivity, large bandwidth and dynamic range, and linear operation in the given range of interest. To meet the performance criteria specified in Table 1-2, each of the three transduction stages must meet or exceed the specifications in terms of sensitivity, linearity, bandwidth, and dynamic range.

2.2.1.1 Selection of Membrane Material

The sensor consists of a circular silicon nitride membrane with a thin coating of aluminum stretched with residual tensile stress on top of a cavity etched in the bulk silicon substrate. Figure 2-3a and Figure 2-3b shows the top view, and cross sectional view respectively of the MEMS sensor.

![Figure 2-3 Optical microphone chip](image)

Figure 2-3 Optical microphone chip (a) Top view and (b) cross section of optical microphone along AA’. The origin of the dimension will be discussed in Section 2.2.2.

A silicon nitride membrane was selected because of its low in-plane residual stress and the ability to deposit nitride layers of precise thickness during the fabrication
process. The low residual stress of nitride is important because, as will be shown later, for a given aspect ratio (i.e. the ratio of radius \( a \) of the membrane and thickness \( h \)), the acousto mechanical sensitivity of the membrane decreases with increasing residual stress.

To form a nitride membrane on top of a cavity in silicon, the silicon substrate is thermally oxidized to form a thin layer 7000\( \text{A} \) oxide layer followed by the deposition of a 1\( \mu \text{m} \) thick silicon nitride layer. Next, the front side (membrane side) is protected by a photoresist layer, and the backside is then patterned using a photoresist mask to define the cavity. The cavity is etched using a deep reactive ion etch (DRIE) through the opening in the photoresist and oxide layer. The oxide acts as the etch stop for the DRIE process. The oxide is then removed using a buffered oxide etch (BOE), thus releasing the nitride membrane. Using this process sequence, one can obtain a nitride membrane of precise thickness on top of a cavity in silicon. The exact details of the fabrication process are discussed in Chapter 3.

2.2.1.2 Design of Diaphragm Dimensions

The design of the dimensions of the sensing diaphragm is based on the work by Sheplak et al. [30] and Saini et al. [32, 33]. To design the diaphragm dimensions, the mechanics of the diaphragm is first analyzed using small and large plate deflection theory. The silicon nitride diaphragm formed on the bulk silicon substrate is modeled as a clamped circular plate. Using small deflection theory, the deflection of the clamped circular diaphragm, \( w(r) \), with inplane tensile stress \( \sigma_o \), as a function of radius, \( r \), is given by [30]
where $a$ is the radius of the diaphragm, $E$ is the Young’s modulus, $h$ is the thickness of the diaphragm, $p$ is the applied pressure, and $I_0$ and $I_1$ are the modified Bessel functions.

The stiffness parameter $k$ is given by

$$k = \frac{a}{h} \sqrt{\frac{12(1-\nu^2)\sigma_0}{E}}, \quad (2.2)$$

where $\nu$ is the Poisson’s ratio. It can be seen that the diaphragm deflection is a linear function of the applied pressure $p$. The stiffness parameter is a function of the process dependent residual stress. The acousto-mechanical sensitivity is defined as the change in the deflection of the diaphragm for unit change in input pressure, i.e.

$$S_{am}(r) = \frac{dw(r)}{dp}. \quad (2.3)$$

Using Equation (2.1) and Equation (2.3), the acousto-mechanical sensitivity is given by the expression

$$S_{am}(r) = \frac{dw(r)}{dp} = 2.78a^4 \frac{2 \left( I_0 \left( \frac{k}{a} \frac{r}{a} \right) - I_1(k) \right)}{Eh^3} + \frac{1 - \left( \frac{r}{a} \right)^2}{k^2 \left( I_1(k) \right)}.$$

For a given material, the acousto-mechanical sensitivity scales directly as the cube of the aspect ratio and inversely to the square of the stiffness parameter. The decrease in sensitivity due to an increase in residual stress can be offset by increasing the aspect ratio. However, the aspect ratio cannot be indefinitely increased, and the limit is set by the
maximum tensile stress of the material or the bounds of the small deflection theory, usually the latter.

Beyond the bounds of the small deflection theory, the mechanics of the diaphragm may be analyzed using the large deflection theory by solving the governing equations for large deflection numerically. The numerical solution provides information regarding the maximum load that can be applied such that the diaphragm deflection varies linearly with respect to applied pressure. It also shows that an increase in residual stress delays the onset of non-linearity, but, at the same time, reduces the acousto-mechanical sensitivity. This effect can be described by Equation (2.5) relating the maximum non-dimensionalised loading that will produce a 3% departure from linearity in the center deflection as a function of the tension parameter $k$ [32, 33].

$$\frac{P_{\text{max}}}{E} \left( \frac{a}{h} \right)^4 \approx 2.3 + 0.02k^3. \quad (2.5)$$

Therefore, for a given material and maximum pressure, increasing the aspect ratio can recapture the loss in sensitivity due to in-plane residual stress.

Using the information provided by the small and large deflection theory, the dimensions of the diaphragm were designed. The specification of the diaphragm listed in Chapter 1 states the maximum pressure amplitude for which the diaphragm deflection should be linear is 2000 Pa. For the silicon nitride membrane with a Poisson’s ratio of 0.27, Young’s modulus of 270 GPa, an in-plane residual stress of 65 MPa, and an aspect ratio of 500, we obtain linear behavior beyond 2000 Pa with less than 2% nonlinearity in the center deflection at 2000 Pa [32]. This corresponds to a stiffness parameter of 26 that implies membrane behavior. Membrane behavior implies a larger deflection for a unit-applied pressure as compared to plate behavior, which translates to a higher acousto
mechanical sensitivity. Thus, a radius of 500 um and thickness of 1 um giving an aspect ratio of 500 was chosen as the dimensions for the sensing membrane.

The depth of the cavity of the microphone is a function of the distance of the end face of the fiber bundle to the membrane. This distance is designed to maximize the mechano-optical sensitivity, the details of which are presented in the Section 2.3.1.4 and 2.3.1.6. Based on the results presented in the next section, the theoretical cavity depth is 272um when the transmit fiber is single mode and 156um when the transmit fiber is multimode.

2.2.2 Acousto-Mechanical Sensitivity \( (S_{am}) \)

As discussed in the previous section, the acousto-mechanical sensitivity is defined as the change in the deflection of the membrane for unit change in input pressure i.e.

\[
S_{am}(r) = \frac{dw(r)}{dp}
\]

\[
S_{am}(r) = \frac{2.78a^4}{Eh^3} \left[ \frac{2\left(I_0\left(\frac{k}{a}\right) - I_1(k)\right)}{k^3I_1(k)} + \frac{1 - \left(\frac{r}{a}\right)^2}{k^2} \right]
\]

Equation (2.7) shows that the sensitivity of the membrane varies with distance along the radius of the membrane. The radius of the multimode fiber illuminated by the beam is less than 50um for the worst case. Thus, the illuminated radius is less than 10% of the overall radius of the diaphragm. Therefore, the radius under consideration can be approximated to be \( r \approx 0 \). This approximation leads to an error of less than 1% in the range of interest for the acousto mechanical sensitivity. Equation (2.7) can thus be approximated to
For the microphone under consideration, \( a = 5.0 \times 10^2 \text{um} \), \( E = 2.7 \times 10^2 \text{GPa} \), \( h = 1.0 \text{um} \), and \( \nu = 2.7 \times 10^{-1} \) [34]. The value of \( k \) as calculated from Equation (2.2) using the above dimensions is 26. Since the value of \( k \) is greater than 20, the diaphragm can be approximated to a membrane for analysis [30]. Using this value of \( k \) and the dimensions listed above, the acousto-mechanical sensitivity as calculated using Equation (2.8) is

\[
S_{am} = 1.0 \text{nmPa}^{-1}
\]  

(2-9)

2.2.3 Linearity of Acousto-Mechanical Transduction

The input to the acousto mechanical stage is the pressure signal. The output of this stage is the deflection of the membrane. Based on the work by Saini et al., the output is linear for the input pressure range of 0-2000Pa [32]. The displacement is linear within 3% non-linearity using both the linear theory and non-linear theory for modeling the displacement of the membrane.

2.2.4 Equivalent Circuit for the Acoustical to Mechanical Transduction

The acousto-mechanical stage converts the input acoustic pressure to a mechanical deflection of the membrane. This stage consists of the sensing membrane that is exposed to the acoustic waves and the acoustic cavity. The sensing membrane consists of a circular silicon nitride diaphragm fabricated on top of a cavity in the bulk silicon substrate. Figure 2-4(a) shows the schematic of the OM device chip. The mechanical deflection of the diaphragm for an applied pressure is analyzed using a lumped element model (LEM) and plate theory. LEM is based on the assumption that the device scale of
interest is much smaller than the characteristic length of the physical phenomenon, in this case the acoustic wavelength, $\lambda$.

![Silicon Nitride Membrane](image1)

(a) (b)

Figure 2-4 Modeling of acousto-mechanical stage. (a) Schematic of sensor head (b) Lumped element model/equivalent electrical circuit of the acousto-mechanical stage.

Figure 2-4(b) shows the equivalent lumped element circuit. The distributed kinetic energy of the membrane is modeled as lumped kinetic energy corresponding to an effective mass $M_{\text{mea}}$ at $r = 0$. Similarly, the distributed potential energy is approximated as a lumped potential energy corresponding to an effective compliance $C_{\text{mea}}$. The effective mass of the air particles moving with the membrane is modeled by radiation mass $M_{\text{rad}}$. The cavity impedes the motion of the diaphragm by storing potential energy and is modeled as an effective compliance $C_a$. The terminals marked across $C_{\text{mea}}$ in the equivalent circuit representation do not have physical significance. Based on the work by Sheplak and Seiner [35] and Saini et al. [32, 33], the LEM parameters is given in Table 2-1 in terms of the structural parameters for the acoustic domain.
Table 2-1 Lumped element model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{\text{mea}} )</td>
<td>( \frac{\rho_n h}{3\pi a^2} )</td>
<td>( M_{\text{rad}} )</td>
<td>( \frac{\rho_a}{3\pi a^2} )</td>
</tr>
<tr>
<td>( C_{\text{mea}} )</td>
<td>( \frac{\pi a^4}{2\sigma_o h} )</td>
<td>( C_a )</td>
<td>( \frac{\pi a^2 h_{\text{cav}}}{\rho_a c} )</td>
</tr>
<tr>
<td>( f_{\text{res}} )</td>
<td>( 0.39 \frac{\sqrt{\sigma_o h}}{a \sqrt{\rho}} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

where \( \rho_n \) is the density of nitride, \( \sigma_o \) is the in-plane stress, \( \rho_a \) is the density of air, \( h_{\text{cav}} \) is the depth of the cavity, and \( c \) is the velocity of sound in air. The pressure acting on the membrane is \( p(t) \), the volumetric flow rate is \( q(t) \), and the displacement of the membrane is \( x(t) \). The relation between the displacement of the membrane as a function of radial distance and time, \( w(r,t) \) and the center \( (r=0) \) displacement of the membrane as a function of time \( x(t) \) is given by Equation (2.10)

\[
x(t) = w(r,t)
\]

(2.10)

In the acousto electrical analogy, the pressure applied is equivalent to a voltage source and the volume velocity to the current. Hence, elements that share the same pressure are connected in parallel and elements that share the same volume velocity are connected in series. From Figure 2-4(a) we can see that the radiation mass, membrane mass, membrane compliance and the cavity compliance all share the same volume velocity. Hence, they are connected in series in the equivalent electrical circuit. The input to the acousto-mechanical stage is the pressure signal \( p(t) \), and the output is the volume velocity \( q(t) \), integrated to give the membrane displacement \( x(t) \), which forms the input.
to the mechano-optical stage. The magnitude of the transfer coefficient from the acoustic to mechanical domain is the acousto mechanical sensitivity, denoted by $S_{am}$.

2.2.5 Frequency Response of Acousto Mechanical Transduction ($H_{am}(s)$)

The frequency response of the acousto-mechanical stage is obtained from the lumped element model of the acoustic circuit developed in the previous section. The model parameters developed in terms of the structural parameters are evaluated and listed in Table 2-2.

### Table 2-2 Lumped element model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{mea}$</td>
<td>$\frac{\rho_a h}{3\pi a^2}$</td>
<td>$1.188 \cdot 10^3 \frac{kg}{m^4}$</td>
</tr>
<tr>
<td>$C_{mea}$</td>
<td>$\frac{\pi a^4}{2\sigma_o h}$</td>
<td>$1.15 \cdot 10^{-15} \frac{m^3}{Pa}$</td>
</tr>
<tr>
<td>$M_{rad}$</td>
<td>$\frac{\rho_a}{3\pi a^2}$</td>
<td>$661.965 \frac{kg}{m^4}$</td>
</tr>
<tr>
<td>$C_a$</td>
<td>$\frac{\pi a^2 h_{cav}}{\rho_a c}$</td>
<td>$1.764 \cdot 10^{-15} \frac{m^3}{Pa}$</td>
</tr>
<tr>
<td>$f_{res}$</td>
<td>$\frac{0.39}{a} \sqrt{\frac{\sigma_o h}{\rho_n}}$</td>
<td>$118kHz$</td>
</tr>
</tbody>
</table>

In this table, $\rho_n$ is the density of nitride ($\rho_n = 0.028 \frac{kg}{cm^3}$), $\sigma_o$ is the in-plane stress ($\sigma_o = 65MPa$), $\rho_a$ is the density of air ($\rho_a = 1.225 \frac{kg}{m^3}$), $h_{cav}$ is the depth of the cavity ($h_{cav} = 500\mu m$ (approximate value depends on fiber placement)) and $c$ is the velocity of
sound in air \( c = 340 \frac{m}{s} \). All the lumped element model parameters are in the acoustic domain. The unnormalized acousto-mechanical transfer function is defined as

\[
H_{am\_unnormalized}(s) = \frac{X(s)}{P(s)} = \frac{1}{(1/3)s(\pi a^2)} \cdot \frac{Q(s)}{P(s)} 
\]  

(2-11)

\[
H_{am\_unnormalized}(s) = \frac{1}{(1/3)s(\pi a^2)} \cdot \frac{1}{1 + s\left(\frac{M_{mea} + M_{rad}}{s \cdot \frac{C_a C_{mea}}{C_a + C_{mea}}}ight)}
\]  

(2-12)

Equation (2-12) can be simplified to Equation (2.13)

\[
H_{am\_unnormalized}(s) = \frac{C_{eff}}{(1/3)\pi a^2 (1 + M_{eff} C_{eff} s^2)}
\]  

(2.13)

where \( C_{eff} = \frac{C_a C_{mea}}{C_a + C_{mea}} \) and \( M_{eff} = M_a + M_{mea} \).

The normalized transfer function \( H_{am}(s) \) is obtained by dividing Equation (2.13) by the response at \( s = 0 \) i.e.

\[
H_{am}(s) = \frac{H_{am\_unnormalized}(s)}{H_{am\_unnormalized}(j \times 2\pi \times 0\text{Hz})},
\]  

(2.14)

and \( H_{am}(s) = \frac{1}{(1 + M_{eff} C_{eff} s^2)} \).  

(2.15)

The magnitude of the frequency response of the acousto mechanical stage after normalization based on Equation (2.15) is shown in Figure 2-5. The resonant frequency is 118kHz as observed from the graph.
2.2.6 Noise Associated with the Acoustical to Mechanical Transduction

The random motion of air particles over the diaphragm, known as Brownian motion, is the major source of noise in the acoustical to mechanical transduction stage. The random motion of the air particles is due to inherent thermal energy and is present in any acoustic system for temperatures above 0 K. The input pressure noise due to Brownian motion is given by the expression in Equation (2.16) [36]

\[
< p, >^2 = \alpha \sqrt{\frac{32kT}{\pi}} \frac{\left(\sqrt{m_1P_1} + \sqrt{m_2P_2}\right)}{a^2} \Delta f.
\]

where \( < p, >^2 \) is the mean square value of the pressure fluctuations in \( Pa^2 \), \( m_1 \) and \( m_2 \) are the masses of the gas molecules, \( P_1 \) and \( P_2 \) are the mean gas pressures on the two sides of the diaphragm, \( k \) is the Stefan-Boltzmann’s constant, \( T \) is the temperature in Kelvin, \( a \) is
the radius of the diaphragm, and \( \Delta f \) is the bandwidth of measurement. Evaluating Equation (2.16) using \( m_1 = m_2 = 4.78 \times 10^{-26} \text{ kg} \), \( T = 300 \text{ K} \), \( a = 500 \text{ um} \)
\[
P_1 = P_2 = 101.4 \text{ kPa} \text{, } k = 1.38 \times 10^{-23} J K^{-1} \text{ and } \alpha = 1 \text{ (approximately) we get}
\]
\[
< p_r >^2 = 3.6 \times 10^{-11} (Pa)^2 \Delta f .
\]

(2.17)

2.3 Mechano-Optical Transduction

This section details the design of the mechano-optical transduction stage of the optical microphone system. Theoretical formulations for the sensitivity, linearity, frequency response, and noise mechanisms are developed along with an equivalent circuit for the mechano optical transduction stage.

2.3.1 Optical Design

![Block diagram of optical system.](image)

Figure 2-6 Block diagram of optical system.

The block diagram of the mechano-optical transduction stage is shown in Figure 2-6. The optical design involves the selection of the optical source, the wavelength of operation, the power of the light source, the coupling of the light source to a fiber, and the determination of the operating distance. To meet the performance criteria specified in Table 1-2, each of the three transduction stages must meet or exceed the specifications in terms of sensitivity, linearity, bandwidth, and dynamic range.
2.3.1.1 Light Source

The wavelength of operation chosen initially was in the 780nm–850nm range. Laser diodes at this wavelength are commonly used in CD-ROMs. Hence, relatively high power (~10mW) diode lasers are available in this wavelength range at a low cost. A key consideration is laser output fluctuations due to unwanted reflections. Commercial devices that operate at this wavelength such as walkmans, CD-ROMs, and CD-RWs use free space optics for their operation. Hence, cavity lasers incur output power instability when the output power is reflected back into the cavity and amplified [37]. In these devices, the problem of back reflection is eliminated by using two polarizers and a quarter wave plate. The OM system uses optical fibers for its operation. Since optical fibers that support circularly polarized light are not available, the polarizer quarter wave plate approach is not feasible. Integrated pigtailed optical isolators using polarizers and Faraday rotators are not readily available at this wavelength. Optical fiber components are “pigtailed”, in other words, the optical fiber is permanently coupled to the optical component by the manufacturer to ensure maximum power coupling from the fiber into the device. Fiber pigtailed components allow the assembling of fiber optical systems similar to electrical systems wherein different electrical components are electrically connected using electrical wires with appropriate terminations such as BNC, banana plugs, alligator clips, etc. Fiber pigtailed components can be optically connected to each other using special connectors eliminating the need for alignment. However, up to –3dB power attenuation may occur at each connector.

Due to the greater availability of optical fiber components, the wavelength of operation was thus changed to 1550nm, which is the wavelength at which optical
communication systems using fiber optics is carried out. Fiber pigtailed optical isolators that reduce back reflections are readily available at this wavelength.

Based on these requirements, a Thorlabs fiber pigtailed laser diode LPS-SMF28-1550-FC module was selected. The Thorlabs fiber pigtailed laser diode module uses a Mitsubishi ML976H6F laser diode. It operates at 1550nm, requires a threshold current of 11.2mA, and has a maximum power output of 2.23mW at an input current of 30mA. The diode laser is coupled to a single mode fiber with a core diameter of 9um and cladding diameter of 125um, terminating in a FC connector. The diode laser is driven using a Keithley 2400 constant current source. A Newport fiber pigtailed optical isolator ISS-1550-50-20-50 operating at 1550nm was chosen to reduce the problem of back reflections. The isolator is fiber pigtailed with FC terminations and provides 52dB of attenuation to back reflected light.

Fiber coupled LED sources were also investigated since they do not exhibit feedback instability. However, the light output at the end of the fiber pigtailed LED are on the order of a few microwatts, which is not sufficient for the operation of the optical microphone. Hence, the light source chosen for the optical microphone was a cavity diode laser operating at 1550nm.

2.3.1.2 Fiber Arrangement

The design of the arrangement of transmit and receive fibers is based on the work by He, Hu, Zuckerwar and Cuomo [21, 22]. Figure 2-7 shows the schematic of a lever type optical microphone using a single transmit fiber and multiple receive fibers that will be used in this research.

The transmit and receive fiber are placed perpendicular to the reflecting membrane. Placing the fiber bundle perpendicular to the membrane makes it easier to
align the bundle with respect to the membrane as compared to placing the bundle at some arbitrary angle.

Figure 2-7 Schematic of optical lever showing single receive fibers and multiple receive fibers.

Two different types of fibers are used for the transmit waveguide. In one case, the transmit fiber is a single model (SM) fiber and the receive fibers are multimode (MM) and is denoted by SMTMMR (SM Transmit MM Receive). In the other case, a multimode (MM) fiber is used for both transmitting and receiving and is denoted by MMTMMR (MM Transmit MM Receive). The advantage of using multimode fibers for the receive fibers is that they have a larger core radius ($25\mu m$), and this allows the collection of more light as compared to using a single mode fiber ($2\mu m$ core radius).
Figure 2-8 Schematic of fiber end face. (a) SMTMMR (b) MMTMMR

Figure 2-8 shows the schematic of the end face of the fiber bundle in the SMTMMR and MMTMMR case. The fiber bundles were custom built by Romack Optical Inc. The single mode fibers are 3M™ Standard Single Mode Fiber – SN Series to be ordered are designed for operation at $1550\text{nm} \pm 30\text{nm}$ and has a core radius ($R_{\text{core SMFR}}$) of $2\text{um}$ and a cladding radius of ($R_{\text{cladding SMFR}}$) of $62.5\text{um}$. The multi mode fibers used in the experiments are 3M™ Standard Multi Mode Fiber –MN Series designed for operation from $700\text{nm}$ to $2000\text{nm}$ and have a core radius ($R_{\text{core MMFR}}$) of $25\text{um}$ and a cladding radius ($R_{\text{cladding MMFR}}$) of $27.5\text{um}$. The entire assembly consisting of the bare transmit and receive fibers are packed inside a stainless steel tube $45\text{mm}$ long with an outer diameter of $907\text{um}$. The stainless steel tube with the fiber bundle is open to free space on one end. At the other end, the transmit and receive fibers run through the stainless steel tube and a
Kevlar jacket assembly and terminate on separate FC connectors. The outer diameter of the fiber bundle encased in the stainless steel tube (907um) allows the placement of the fiber bundle at any distance inside the 1000um diameter cavity in the sensor chip.

2.3.1.3 Design of Operating Distance for SMTMMR Case

The most important design parameter in the optical design of the microphone is the optimal distance from the fiber end face to the membrane. The optimal distance is the gap distance g between the fiber end face and the membrane at which the rate of change of power coupled is maximum per change in gap distance. The rate of change of output optical power normalized to the input power with change in distance is called the mechanical to optical sensitivity (S_{mo}). It is obtained by differentiating the coupling efficiency curve, which is given by the ratio of output power (P_{optical,out}) to input power (P_{optical,in}), with respect to gap distance.

\[ S_{mo}(g) = \frac{d\eta(z)}{dg} \]  \hspace{1cm} (2.18)

The longitudinal distance traveled by the optical beam is related to the gap distance by Equation (2.19)

\[ z = 2g \] \hspace{1cm} (2.19)

The optimal distance is a function of the core and the cladding diameters, wavelength of light used, and the refractive index of the fiber core.
Figure 2-9 shows a schematic of the fiber arrangement in the SMTMMR case with one receive fiber and the path traced by the outermost ray of light. In the following analysis, the curvature of the membrane has been neglected. To obtain the optical power of the light coupled into the receive fiber, the areal power density for light emanating from an optical fiber end face must be known. The areal power density is commonly known as irradiance. The coupling of the reflected light depends on the location and area of the receive fiber. The ring of receive fiber is approximated by an annular ring with an inner radius $R_{\text{inner}}$ and outer radius $R_{\text{outer}}$ given by

$$R_{\text{inner}} = R_{\text{clad\_SMF}} + R_{\text{clad\_MMF}} - R_{\text{core\_MMF}}, \quad (2-20)$$

$$R_{\text{outer}} = R_{\text{cladding\_SMF}} - R_{\text{core\_SMF}} + R_{\text{cladding\_MMF}} + R_{\text{core\_MMF}}. \quad (2-21)$$

This approximation results in an overestimation of the light power collected.

The irradiance $I(r, z)$ of light emanating from a single mode fiber as a function of the longitudinal distance $(z)$ traveled by the light beam along the fiber axis and the radial
distance \( r \) from the longitudinal axis can be approximated by a Gaussian [38] and is given by the expression

\[
I(r, z) = \frac{n w_0^2 E_0^2}{2 w^2(z) Z_0} e^{-\frac{-2r^2}{w^2(z)}},
\]

(2-22)

where \( n \) is the refractive index of air, \( w_o \) is the beam waist diameter at the fiber end face edge, \( w(z) \) is the beam waist diameter at a distance \( z \) from the fiber endface, \( Z_0 \) is the characteristic impedance of free space \( \left( Z_0 = \sqrt{\mu_0 / \varepsilon_0} = 377 \Omega \right) \), and \( E_0 \) is the magnitude of the electric field vector at fiber end face edge.

The variation of beam waist along the fiber axis \( w(z) \) is given by the expression

\[
w(z) = w_0 \sqrt{1 + \left( \frac{z}{Z_R} \right)^2},
\]

(2-23)

where \( w_o \) is the radius of the beam at the fiber end face, and \( Z_R \) is the Raleigh distance given by the expression

\[
Z_R = \frac{\pi n w_0^2}{\lambda},
\]

(2-24)

where \( \lambda \) is the wavelength of the light used. Thus at \( z = Z_R \), \( w(z) = \sqrt{2}w_o \).

The infinitesimal power transmitted through an infinitesimally thin ring is given by the expression

\[
dP_{optical, out}(r, z) = \frac{1}{2} \frac{n w_0^2 E_0^2}{2 w^2(z) Z_0} e^{-\frac{-2r^2}{w^2(z)}} 2\pi rdr.
\]

(2-25)
The total power in the ring with inner and outer radius given by Equations (2-20) and Equation (2-21) is obtained by integrating Equation (2-25) from the limits $R_{inner}$ to $R_{outer}$.

\[ P_{\text{optical, out}}(z) = \int_{R_{inner}}^{R_{outer}} \frac{1}{2} \frac{nw_0^2 E_0^2}{Z_0} e^{\left[ \frac{-2r^2}{w^2(z)} \right]} 2\pi rdr, \quad (2-26) \]

and

\[ P_{\text{optical, out}}(z) = \frac{nw_0^2 E_0^2}{4Z_0} \left( e^{\left[ \frac{-R_{outer}^2}{w^2(z)} \right]} - e^{\left[ \frac{-R_{inner}^2}{w^2(z)} \right]} \right) \]. \quad (2-27) \]

The power at the center of the end face of the fiber ($r = 0, z = 0$) is the approximate power incident on the membrane and is denoted by $P_{\text{optical, in}}$. It has been assumed that the power variation across the beam waist at the fiber end face is negligible, i.e. the light emanating from the end of a SM fiber is approximated by an ideal point source

\[ P_{\text{optical, in}} = \int_{0}^{\infty} I(r, z) 2\pi rdr = \int_{0}^{\infty} \frac{nw_0^2 E_0^2}{2w^2(z)Z_0} e^{\left[ \frac{-2r^2}{w^2(z)} \right]} 2\pi rdr. \quad (2-28) \]

The coupling efficiency $\eta(z)$ is given by

\[ \eta(z) = \frac{P_{\text{optical, out}}}{P_{\text{optical, in}}}. \quad (2-29) \]

A plot of the coupling coefficient and sensitivity as a function of gap distance respectively based on Equations (2.18), (2-27), (2-28), and (2-29) is shown in Figure 2-10 and Figure 2-11. From the sensitivity plot, the optimal distance of operation for the SMMTMMR case is 272um, which is the location of maximum sensitivity for the fiber parameters given above.
Figure 2-10 Plot of power coupling efficiency vs. gap distance for SMTMMR case.

Figure 2-11 Plot of sensitivity vs. gap distance for SMTMMR case.
2.3.1.4 Design of Operating Distance for MMTMMR Case

The analysis of the mechano-optical sensitivity for a multi mode transmit fiber is considerably more complex due to the propagation of various modes in the multimode optical fiber. In the following analysis, the curvature of the membrane has been neglected. Figure 2-12 shows a diagram of the fiber bundle in the MMTMMR case. The power coupled and the sensitivity of the membrane in the case of a MMTMMR fiber bundle is based on the analysis of He and Cuomo [21].

When the fiber is illuminated with a light source, all the light rays with an angle less than the critical angle given by \( \theta_c = \sin^{-1}\left(\frac{NA}{n}\right) \) will be coupled into the fiber where \( NA \) is the numerical aperture of the fiber and \( n \) is the refractive index of air. It is assumed that the light rays exiting the fiber will leave with the same angle with which they enter. The light rays leave the fiber end face and reflect off the reflecting plane and enter the receiving plane. The distance between the receiving plane and reflector plane is denoted by the gap distance \( g \). The image plane is an imaginary plane located at a distance of \( g \) from the reflector plane. The irradiance \( I_k \), at a given gap distance \( g \) from the fiber endface for different normalized radii \( k \) in Equations (2.30) is given by He and Cuomo [21].
Figure 2-12 Schematic of fiber arrangement in SMTMMR case with the center single mode transmit fiber and one outer multimode receive fiber [21].

\[
I_k = \begin{cases} 
\frac{AI_0}{(1 - A^2)\theta_c} \left\{ \tan^{-1}(k_c - 1) - A \tan^{-1}\left[A(k_c - 1)\right] \right\} & 1 \leq k_c < 2, 0 \leq k \leq 2 - k \\
\frac{AI_0}{(1 - A^2)\theta_c} \left\{ \tan^{-1}(k_c - 1) - A \tan^{-1}\left[A(k_c - 1)\right] + \tan^{-1}(1 - k) - A \tan^{-1}\left[A(k - 1)\right] \right\} & 1 \leq k_c < 2, 2 - k < k \leq 1 \\
\frac{AI_0}{2(1 - A^2)\theta_c} \left\{ \frac{\pi}{4} - A \tan^{-1}\left[A(1 - k)\right] - A \tan^{-1}\left[A(1 - k)\right] \right\} & k_c \geq 2, 0 \leq k \leq 1, k - k_c \leq 2 \\
+ \frac{AI_0}{8\theta_c} \ln \left(\frac{(k_c - 1)^2}{1 + A^2(k_c - 1)^2} \right) & \end{cases}
\]
\[
I_k = \begin{cases} 
\frac{A L_o}{2(1-A^2)} \left\{ \frac{\pi}{4} - A \tan^{-1} A + \tan^{-1} (1-k) - A \tan^{-1} \left[ A(1-k) \right] \right\} \\
+ \frac{A L_o}{8 \theta_c} \ln \left[ \frac{(k_c-1)^2 + A^2}{1 + A^2 (k_c-1)^2} \right] \\
\frac{A L_o}{2(1-A^2)} \left\{ \frac{\pi}{4} - A \tan^{-1} A + \tan^{-1} (1-k) - A \tan^{-1} \left[ A(1-k) \right] \right\} \\
+ \frac{A L_o}{8 \theta_c} \ln \left[ \frac{(k+1)^2 + A^2}{1 + A^2 (k+1)^2} \right] \\
\frac{A L_o}{2(1-A^2)} \left\{ \tan^{-1} (k_c-1) - \tan^{-1} (k-1) \right\} \\
+ A \tan^{-1} \left[ A(k-1) \right] + A \tan^{-1} \left[ A(k_c-1) \right] \right\} \\
\frac{A L_o}{2(1-A^2)} \left\{ \frac{\pi}{4} - A \tan^{-1} A - \tan^{-1} (k-1) + A \tan^{-1} \left[ A(k-1) \right] \right\} \\
+ \frac{A L_o}{8 \theta_c} \ln \left[ \frac{(k_c-1)^2(1+A^2)}{1 + A^2 (k_c-1)^2} \right] \\
\frac{A L_o}{2(1-A^2)} \left\{ \frac{\pi}{4} - A \tan^{-1} A - \tan^{-1} (k-1) + A \tan^{-1} \left[ A(k-1) \right] \right\} \\
+ \frac{A L_o}{8 \theta_c} \ln \left[ \frac{(k+1)^2(1+A^2)}{1 + A^2 (k+1)^2} \right] \\
\frac{A L_o}{8 \theta_c} \ln \left[ \frac{(k_c-1)^2(1+A^2)}{(k-1)^2 + A^2 (k_c-1)^2} \right] \\
\frac{A L_o}{8 \theta_c} \ln \left[ \frac{(k+1)^2(1+A^2)}{(k-1)^2 + A^2 (k+1)^2} \right] \\
\end{cases}
\]
Here \( g \) is the distance between the light source and the reflector plane, \( k \) is the radial distance of a point in the image plane normalized with respect to the radius of the core \( R_{\text{core\_MMF}} \) of the multi mode fiber, \( A = \frac{R_{\text{core\_MMF}}}{2g} \), and \( k_c \) is the maximum radial distance in the image plane that the outermost beam can reach normalized with respect to the radius of the core of the multi mode fiber.

To obtain the optical power of the light coupled into the receive fiber, the areal power density for light emanating from the transmit optical fiber end face must be known. The coupling of the reflected light depends on the locations and area of the receive fiber. The ring of the receive fibers is approximated by an annular ring with an inner radius \( R_{\text{inner}} \) and outer radius \( R_{\text{outer}} \).

\[
R_{\text{inner}} = R_{\text{clad\_MMF}} + R_{\text{clad\_MMF}} - R_{\text{core\_MMF}} \quad (2.31)
\]

\[
R_{\text{outer}} = R_{\text{cladding\_MMF}} - R_{\text{core\_MMF}} + R_{\text{cladding\_MMF}} + R_{\text{core\_MMF}} \quad (2.32)
\]

The normalized subtended power is given by [21]

\[
\eta(k) = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{2}{\pi} \int_{m-1}^{b} I_k \sigma dk , \quad (2.33)
\]

where \( \sigma = \cos^{-1}\left(\frac{k^2 + m^2 - 1}{2km}\right) \) and \( m = 2 + \frac{R_{\text{cladding\_MMF}} - R_{\text{core\_MMF}}}{R_{\text{core\_MMF}}} \) and \( b = k_c \) if \( k_c \leq m + 1 \) and \( b = m + 1 \) if \( k_c > m + 1 \). Equation (2.33) gives the coupling efficiency as a function of gap distance and is plotted in Figure 2-13.
Figure 2-13 Plot of power coupling efficiency vs. gap distance for MMTMMR case.

Figure 2-14 Plot of sensitivity vs. gap distance for MMTMMR case.
2.3.2 Mechano-Optical Sensitivity \( S_{mo} \)

The mechanical to optical sensitivity for the MMTMMR case is given by

\[
S_{mo}(g) = \frac{d\eta(z)}{dg}
\]  

(2.34)

A plot of Equation (2.34) is shown in Figure 2-14. From the sensitivity plot, the optimal distance of operation for the MMTMMR case is predicted to be 56um, which is the location of maximum sensitivity. Based on the formulations given above, the theoretical mechano-optical sensitivity for the SMTMMR and MMTMMR case are as follows:

\[
S_{mo} = 0.93 \times 10^{-3} \frac{mW}{mW \cdot um}
\]  

(2.35)

\[
S_{mo} = 3.1 \times 10^{-3} \frac{mW}{mW \cdot um}
\]  

(2.36)

2.3.3 Linearity of Mechano-Optical Transduction

The input to the mechano-optical stage is the deflection of the membrane. The output of this stage is the optical output power. The linearity for this transduction stage is obtained by identifying the range of gap distances for which the output power is within 3% of the linear value. For the SMTMMR case, this corresponds to a distance of 248um to 298um. The maximum sensitivity is \( 0.95mW / mW / Pa \) and is obtained at a distance of 272um. Similarly for the MMTMMR case, this corresponds to a distance of 49um to 66um. The maximum sensitivity is \( 3.15mW / mW / Pa \) and is obtained at a distance of 56um. Therefore, for the sensor to be linear, the fiber bundle has to be placed within the linear region. The maximum deflection of the membrane for \( p_{max} = 2000Pa \) is 2.07um.
Therefore, the mechano-optical transduction is linear for the maximum range of membrane deflection.

### 2.3.4 Equivalent Circuit for the Mechanical to Optical Transduction

The mechano-optical stage converts the input mechanical deflection of the membrane into an intensity modulated optical signal. Thus, the input to the mechano-optical stage is the membrane center deflection at $r = 0, x(t)$, and the output is the reflected and collected output optical power, $P_{optical, out}$. The membrane deflection results in a change in the gap distance, $d_g = -x(t)$. The magnitude of the transfer coefficient from the mechanical to optical domain is the mechano optical sensitivity and is denoted by $S_{mo}$. Therefore, the output optical power $P_{optical, out}$ is given by the product of the nominal mechano optical sensitivity, the input optical power, and the membrane deflection i.e.

$$P_{optical, out} = S_{mo} |_{g} \times P_{optical, in} \times x(t) \quad (2.37)$$

This transduction stage can be represented in the form of an equivalent electrical circuit as shown in Figure 2-15.

![Figure 2-15 Electrical equivalent circuit of mechano optical stage.](image-url)
The optical output power, $P_{\text{optical, out}}(t)$, is denoted by a dependent current source whose magnitude is linearly dependent on the mechanical deflection of the membrane. A theoretical formulation for the mechano-optical sensitivity was discussed in Section 2.3.1 on optical design.

2.3.5 Frequency Response of Mechano-Optical Transduction ($H_{mo}(s)$)

The transduction of the mechanical deflection into an intensity modulated optical signal occurs instantaneously in the frequency range of interest ($0 \text{ Hz} - 20\text{kHz}$) i.e. there is no phase lag or lead between the input mechanical deflection and the modulation via reflection of the output optical signal. This can be attributed to the absence of optical energy storing elements, which are responsible for phase variation between the input and output signal, in the mechano-optical transduction. Thus, the mechano-optical transduction is modeled as a constant over all acoustic frequencies. Therefore, the frequency response of the mechano-optical sensitivity normalized to the ($s = 0$) mechano optical sensitivity is constant given by Equation (2-38)

$$H_{mo}(s) = 1.$$ (2-38)

The magnitude of the normalized frequency response of the mechano-optical transduction stage based on Equation (2-38) is shown in Figure 2-16.
2.3.5 Noise Associated with the Mechanical to Optical Transduction

The main source of noise in the mechanical to optical transduction stage is the variation in optical power of the reference light source. When the input light signal used is a light emitting diode (LED), the noise is due to the shot noise associated with the direct current flowing in the pn junction. In the case of a cavity diode laser, in addition to the shot noise, output power fluctuation due to feedback-induced instability is also a source of noise.

Shot noise is present in a device that has a potential barrier with a direct current overcoming the barrier. This is present in a reverse biased pn junction. The current through the diode is composed of discrete particles (electrons and holes) that cross the potential barrier at the pn junction. The passage of the carriers across the junction is a random process composed of a large number of random independent current pulses. A
formulation for the power spectral density of shot noise $<I_{mo}>^2$ in a junction is given by \cite{39}

$$<I_{mo}>^2 = 2eI_D\Delta f,$$ \hspace{1cm} (2.39)

where $e$ is the electronic charge, and $I_D$ is the current flowing through the diode. The expression in Equation (2.39) is converted to an equivalent power fluctuation $<P_{mo}>^2$ by multiplying the expression by the square of the current to power conversion coefficient $\psi$ of the laser diode i.e.

$$<P_{mo}>^2 = 2eI_D\psi^2\Delta f.$$ \hspace{1cm} (2.40)

The ThorLabs laser diode was driven with a current of 18mA and has a current to power conversion coefficient of 0.0743mW/mA. Using this value in Equation (2.40), the noise associated with the mechano optical stage is given by

$$<P_{mo}>^2 = 3.18\times10^{-22}\Delta f.$$ \hspace{1cm} (2.41)

The performance of a laser diode is affected by optical feedback occurring due to an external cavity formed between the laser and some external reflecting surface. The stability of the laser is dependent on the fraction of output power reflected back into the laser cavity. The amount of external feedback necessary to cause feedback-induced instability can be roughly estimated using the relation \cite{37}

$$f_{ext} \gg \left(\frac{R_{sp}\tau_L}{P}\right)^2,$$ \hspace{1cm} (2.42)

where $f_{ext}$ is the fraction of output power reflected back into the laser cavity, $\tau_L$ is the laser cavity round trip time, $R_{sp}$ is the rate of emission of spontaneous photons and $P$ is
the steady state laser power \cite{37}. A 40dB attenuation of the back reflected light is recommended to avoid feedback-induced instability \cite{37}.

In the optical microphone designed in this thesis, two techniques have been implemented to reduce the effects of the optical power in the laser diode. To reduce the feedback-induced instability formed from an external cavity, an optical isolator is connected in series with the laser source as shown in the Figure 2-8. The optical isolator reduces the amount of back reflection reaching the laser by 52dB \cite{40}.

To reduce the variation in laser power associated with variation in the laser diode current, the output optical power has been referenced to the unmodulated reference input optical power. To achieve this, the optical beam passing through the isolator is split into two equal power beams using a Newport F-CPL-50-20-50 1x2 splitter. Half of the input optical power is routed to a reference photodetector, and the other half is incident on the reflecting membrane. The collected reflected output power (modulated by the acoustic signal) is measured by a second photodetector. The voltage output of the two photodetectors is divided using an analog divide circuit based on the AD734 IC. The referenced output signal is then measured using the Bruel and Kjaer PULSE data acquisition system for further processing.

2.4 Opto-Electrical Transduction

This section details the design of the opto electrical transduction stage of the optical microphone system. Theoretical formulations for the sensitivity, linearity, frequency response, and noise mechanism are developed along with an equivalent circuit for the opto-electrical stage.
2.4.1 Electrical Design

The electrical design involves the selection of the photodetector and the design of an analog divide circuitry to reference the intensity-modulated output with the unmodulated reference signal. Figure 2-17 shows the block diagram of the electrical components used in the optical microphone system.

![Block diagram of electrical system](image)

Figure 2-17 Block diagram of electrical system.

2.4.1.1 Photodetector

The various factors to be considered in the selection of the photodetector (PD) are the detector bandwidth, sensitivity, noise equivalent power, and maximum power that the detector can handle without saturating. The detector bandwidth must be large enough to respond to the highest signal frequency of interest and must have a high optical to electrical responsivity \( r_\phi \equiv i_{\text{diode}} / P_{\text{optical}} \) at the wavelength of interest. Other desirable features of a detector are a built-in low noise amplifier (LNA) to amplify the electrical signal and filters to select the signals only at the frequencies of interest. Based on the criteria discussed, the Thorlabs PDA 400 switchable gain, amplified InGaAs detector was chosen. The ThorLabs PD consists of a photodiode integrated with a high speed, LNA based on the Analog Devices IC, AD829. This PD-LNA combination has a maximum bandwidth in of 50kHz at a maximum transimpedance gain of 1.5x10^6 and an output...
voltage of $0V$ to $10V$ when biased with $\pm 12V$ power supply [41, 42]. Figure 2-18 shows a plot of the opto-electrical responsivity of the ThorLabs photodetector as a function of wavelength. It has an opto electrical responsivity of $0.95A/W$ at $1550nm$. The maximum power that the photodetector can measure without saturation is $10mW$ at the wavelength of operation.

![PDA400 Responsivity](image)

Figure 2-18 Responsivity of ThorLabs photo detector as a function of wavelength [41].

2.4.1.2 Design of Analog Divide Circuitry

The analog divide circuitry used to reference the intensity modulated output signal to the unmodulated signal is based on the Analog Devices AD734 IC. This IC was chosen because it requires only two external capacitors for operation. The AD734 IC shown in the circuit in Figure 2-19 is a four quadrant analog multiplier/divider and provides the general transfer function $W = \frac{XY}{Z}$ where $X$, $Y$ and $Z$ are the input signals, and $W$ is the output signal. It has a bandwidth of $100MHz$ with an output voltage swing of $20V_{pk-pk}$. The analog divide circuit has 0deg phase delay up to $100kHz$ which is the
frequency range of operation of the analog divide circuit in the optical microphone system. When wired as a divider as shown in Figure 2-23, it provides the transfer function given in Equation (2.43)

$$W = 10 \left( \frac{Z_2 - Z_1}{X_1 - X_2} \right) + Y_1.$$

(2.43)

It has an input swing of $-12V$ to $+12V$. The differential input to the numerator channel can have either polarity and is applied to pins labeled $Z_1$ and $Z_2$, whereas the differential input to the denominator channel must be positive and greater than $100mV$ and is applied to the pins labeled $X_1$ and $X_2$. The intensity-modulated signal is applied to input $Z_2$, and the unmodulated reference signal is applied to $X_1$ with $Z_1$, $X_2$, and $Y_1$ grounded.

![Figure 2-19 AD734 based analog divide circuit.](image)
The output voltage corresponding to the referenced intensity modulated signal is available at pin 10 with respect to ground, which is used for further processing via the PULSE multi-analyzer system.

2.4.2 Opto-Electrical Sensitivity ($S_{oe}$)

The opto-electrical sensitivity is defined as the change in the output voltage of the photodetector for unit change in optical power i.e.

$$S_{oe} = \frac{dV}{dP_{optical}} = r_\phi R_f,$$  \hspace{1cm} (2-44)

where $V$ is the output voltage of the detector, $P_{optical}$ is the optical power incident on the photodetector, $r_\phi$ is the responsivity, and $R_f$ is the transimpedance gain (feedback resistance). For the Thorlabs photodetector PDA 400, at $1.55\times10^2 \text{mm}$, $r_\phi = 0.95 \text{mA/W}$ and, the maximum transimpedance gain is $1.50\times10^6 \text{mm}$ \cite{41}. Using Equation (2-44), the maximum opto-electrical sensitivity is given in Equation (2.45)

$$S_{oe} = 1.43 V/\text{mW}.$$ \hspace{1cm} (2.45)

The bandwidth at maximum opto-electrical sensitivity is $50kHz$ \cite{41}.

2.4.3 Linearity of Opto Electrical Transduction

The input to the opto-electrical stage is the coupled modulated optical power. The output of this stage is the variation in electrical voltage of the photodetector. The linearity of this stage is governed by the linearity of the PD-LNA combination.

To determine the linearity of the opto-electrical stage, the maximum optical power incident on the PD is estimated. The laser diode is driven by a current of $18mA$. This corresponds to a power level of $1.34mW$ \cite{43}. Since a $1\times2$ equal power splitter is used, the actual nominal power incident on the membrane is only $670\mu W$. Thus,
the maximum power that can be coupled into the receive fiber is $670 \mu W$. Using Equation (2.45) this corresponds to a maximum output voltage of $0.955 V$. The PD-LNA has a maximum linear output swing of $0V-10V$. Hence, the opto-electrical transduction stage is linear in the region of interest.

2.4.4 Equivalent Circuit for the Optical to Electrical Transduction Stage

The opto-electrical stage converts the modulated optical output power into a corresponding time varying voltage signal using a photodiode. A photodiode consists of a reverse biased pn junction diode that produces a current ($i_{electrical}(t)$) proportional to the magnitude of optical power incident on the active area of the diode. This current produced by the photodiode is converted to a corresponding voltage signal $v_o(t)$ by a transimpedance amplifier with a transimpedance gain of $R_f$. Therefore, the output of the opto-electrical stage is modeled as a current source whose magnitude is given by the product of the optical power and the opto-electrical responsivity, which is amplified by a transimpedance amplifier with a transimpedance gain (feedback resistance $R_f$).

![Figure 2-20 Electrical equivalent circuit of opto-electrical stage.](image)

The input to the opto electrical stage is the optical power and the output is the voltage of the transimpedance amplifier. The transfer coefficient from the optical to
electrical domain is called the opto-electrical sensitivity and is denoted by $S_{oe}$ which is given by Equation (2-44).

This transduction stage can be represented in the form of an equivalent electrical circuit as shown in Figure 2-20. The theoretical formulation for the opto-electrical sensitivity was discussed in the previous section.

2.4.5 Frequency Response of Opto-Electrical Transduction ($H_{mo}(s)$)

The frequency response of the optical to electrical transduction is limited by the bandwidth of the integrated amplifier in the ThorLabs photodetector. Based on the information in [44], the photodetector acts as a low pass filter with a $-3dB$ cut off frequency, $f_{cut\,off}$, at $50kHz$. Therefore, the frequency response of the optical to electrical transduction stage is modeled as a single pole system with a time constant corresponding to $50kHz$. The frequency response of the opto-electrical stage normalized to the output of the opto electrical sensitivity at $s = 0$ is given by

$$H_{oe}(s) = \frac{1}{s} \frac{1}{\frac{2\pi f_{cut\,off}}{\pi} + 1}.$$  \hspace{1cm} (2-46)

The magnitude of the frequency response of the acousto-mechanical stage based on Equation (2-46) is shown in Figure 2-21.
2.4.5 Noise Associated with the Optical to Electrical Transduction

The two main noise mechanisms associated with the optical to electrical transduction are the thermal noise mechanism and the shot noise mechanism. Thermal noise due to the random fluctuations are present in any device that dissipates energy due to thermal vibration. It is present at operating temperatures above 0 K and is independent of bias or input conditions. Thermal noise is directly proportional to temperature because an increase in temperature increases the random thermal vibration. The power spectral density of electrical thermal noise $<V_{oe\_thermal}>^2$ is given by

$$<V_{oe\_thermal}>^2 = 4kTR_f \Delta f,$$  \hspace{1cm} (2.47)

where $R_f$ is the electrical resistance of the feedback resistance of the transimpedance amplifier. Substituting the value of the feedback resistance at the maximum gain setting as $1.5M\Omega$ [41] in Equation (2.47), we obtain

Figure 2-21 Frequency response of opto electrical transduction stage.
\[ <V_{oe\_thermal}>^2 = 2.49 \times 10^{-14} \Delta f. \] (2.48)

The other important source of noise in the opto-electrical transduction stage is the shot noise associated with the bias current in the photodetector. An expression for the shot noise in a photodetector is given in [24]

\[ <V_{oe\_shot}>^2 = R^2 \left( 2e r \phi \right) \Delta f, \] (2.49)

where \( e \) is the electronic charge, \( \Delta f \) is the detector bandwidth, \( r \phi \) is the responsivity of a photodetector expressed in \( A/W \), and \( P_{optical} \) is the optical power incident on the photodetector. For the Thorlabs photodetector \( r \phi \) is \( 0.95 A/W \) at \( 1550nm \), and the maximum power incident on the photodetector is \( 670uW \), resulting in a shot noise of

\[ <V_{oe\_shot}>^2 = 4.78 \times 10^{-10} \Delta f V^2/Hz. \] (2.50)

The power spectral density of the total noise in the opto-electronic stage is given by the sum of the power spectral density of the shot noise and the thermal noise.

\[ <V_{oe}>^2 = <V_{oe\_thermal}>^2 + <V_{oe\_shot}>^2 \] (2.51)

\[ <V_{oe}>^2 = 4.78 \times 10^{-10} \Delta f V^2/Hz. \] (2.52)

### 2.5 System Performance Metrics

This section details the theoretical formulations for the various system performance metrics, namely: sensitivity, linearity, and frequency response for the overall OM systems including all transduction stages.

#### 2.5.1 System Sensitivity (S)

Sensitivity of a transducer is defined as the change in output signal for a unit change in input signal. For the optical microphone, the system output is a voltage that
tracks the system input which is a pressure fluctuation corresponding to the acoustic signal. The optical microphone is a multi energy domain system where the transduction of the input acoustic signal to the output electrical signal is accomplished in three stages. Each transduction stage has an associated sensitivity. The overall sensitivity of the optical microphone system is the product of the sensitivities of the individual stages. The first stage consists of the transduction of the acoustic signal to a mechanical signal associated with the pressure induced deflection of the membrane. The sensitivity associated with this stage is the acousto-mechanical sensitivity ($S_{am}$). The second stage consists of the transduction of the deflection of the membrane to intensity variations of the reference optical signal using the optical lever principle. The sensitivity associated with this stage is the mechano-optical sensitivity ($S_{mo}$). The third and final stage consists of transduction of the intensity modulated optical signal to an electrical signal. The sensitivity associated with this stage is called the opto-electrical sensitivity ($S_{oe}$). The overall sensitivity $S$ is given by the product of the individual sensitivities, i.e.

$$S = S_{am} S_{mo} S_{oe}$$  \hspace{1cm} (2-53)

The overall sensitivity of the optical microphone system is a measure of the total output voltage for a unit input pressure. The product of the sensitivities of the individual stages gives the overall sensitivity of the optical microphone system. For the SMTMMR and MMTMMR fiber bundle arrangement, the overall theoretical sensitivity is obtained by substituting the appropriate values for the individual sensitivities in Equation (2-53). Therefore the magnitude of the overall sensitivity for the SMTMMR and MMTMMR case assuming an input optical power of 700$\mu$W is given by Equation (2-54) and (2.55)
\[
SMTMMR \quad S = 961\frac{\mu V}{Pa} \quad (2-54)
\]
\[
MMTMMR \quad S = 2748\frac{\mu V}{Pa} \quad (2.55)
\]

2.5.2 System Linearity

Linearity is a measure of the closeness of the output-input calibration curve to a straight line. The linearity range of a system is defined as the range of input signals for which the output signal deviates less than 3% from the linear value. The linearity of the overall system is dependent on the linearity of the individual transduction stages. Since the individual stages are linear in the region of operation, the overall microphone system is linear in the required range.

2.5.3 System Equivalent Circuit

The electrical equivalent circuit for the overall optical microphone system is obtained by cascading the equivalent electrical circuits developed for the three individual transduction stages. From the block diagram of the overall microphone system shown in Figure 2-1, the input to the optical microphone system is an acoustic signal, \( p(t) \), and the output is a voltage signal \( v_o(t) \). Figure 2-22 shows the equivalent circuit for the overall optical microphone.

![Figure 2-22 Electrical equivalent circuit of optical microphone system.](image-url)
2.5.4 System Frequency Response \( (H(s)) \)

The overall frequency response of the optical microphone is governed by the frequency response of the individual transduction stages. The overall frequency response of the optical microphone \( H(s) \) is given by the product of the frequency response of the acousto-mechanical stage \( H_{am}(s) \), mechano-optical stage \( H_{mo}(s) \), and opto-electrical stage \( H_{oe}(s) \).

\[
H(s) = H_{am}(s) \cdot H_{mo}(s) \cdot H_{oe}(s)
\]  
(2-56)

The overall normalized frequency response is thus obtained by substituting Equations (2-12), (2-38), and (2-46) in Equation (2-56). It is given by

\[
H(s) = \left\{ \frac{1}{1 + s^2 C_{eff} M_{eff}} \right\} \cdot \left\{ \frac{1}{s + \frac{1}{2\pi f_{cut \ eff}}} \right\}
\]  
(2-57)

The magnitude frequency response and phase response of the overall optical microphone system based on Equation (2-57) is shown in Figure 2-23 and Figure 2-24. From the figure, the -3dB frequency is 52kHz. The bandwidth of operation from DC to 52kHz, is greater than the desired specification of 50kHz.

2.5.6 Minimum Detectable Signal (MDS)

The analysis of noise in the optical microphone consists of identifying and quantifying the noise sources in the three transduction mechanisms involved in the operation of the optical microphone. The main noise source in the acousto-mechanical stage is due to random motion of air particles impinging on the diaphragm. The main noise source in the mechano-optical stage is due to the random variation in the power of the light source and shot noise.
Overall Frequency Response

Figure 2-23 Overall normalized magnitude frequency response of the optical microphones system.

Phase Response

Figure 2-24 Overall phase frequency response of the optical microphones system.
The minimum detectable signal for the optical microphone system is a function of the noise generated in each of the transduction stages. For a 1Hz bandwidth, it is given by the expression

\[
MDS = \sqrt{<p^2_r> + \left(\frac{<P_{mo}>}{S_{am}S_{mo}}\right)^2 + \left(\frac{<V_{oe}>}{S}\right)^2}
\]  

(2-58)

where \( S \) is the overall sensitivity of the optical microphone expressed in \( V/Pa \).

Substituting the values from Equation (2.17), (2.41), and (2.52) in Equation (2-58), we get the minimum detectable signal for 1Hz bandwidth for the optical microphone as

\[
SMTMMR \quad MDS \equiv 61dB SPL
\]  

(2.59)

\[
MMTMMR \quad MDS \equiv 52dB SPL.
\]  

(2.60)

It can be noticed from Equations (2.17), (2.41), and (2.52) that the MDS of the optical microphone system is dominated by the shot noise of the detector.

2.6 Packaging

Figure 2-25 shows the packaging scheme used in the optical microphone The sensitivity of the device is highly dependent on the placement of the optical transmit and receive fibers at the optimum distance from the membrane.

The overall OM package consists of a MEMS device chip encompassing the reflective membrane, an open cavity, and an optical fiber guide chip. The proposed optical fiber guide chip is a Pyrex chip which has the same areal dimensions as the sensor, 5\( mm \times 5\( mm \) but is 1000\( um \) thick. To avoid confusion between the device chip and the Pyrex chip, the Pyrex chip is denoted as the handle chip. The handle chip has a 1\( mm \) diameter hole in the center, which is the same dimension as that of the cavity.
Figure 2-25 Packaging scheme for optical microphone.

A stainless steel tube containing the optical fiber bundle is inserted into the handle chip and protrudes through the hole such that the fiber end face is at the optimal distance from the sensing membrane. The handle chip is then glued onto the stainless steel tube using epoxy. The stainless steel tube with the handle chip is carefully inserted into the sensor chip. A thin layer of epoxy holds the sensor chip and handle chip together. Thus, the handle chip effectively guides and places the optical fiber end face at the appropriate distance.

Figure 2-26 shows the mechanical plug used to mount the device chip. It consists of a structure made of aluminum that has a recess 5.00 mm long 5.00 mm wide and 0.50 mm deep on one side. It has a $9.15 \times 10^2 \mu m^2$ diameter hole running through the entire length of the structure through which the stainless steel tube is inserted. Seven setscrews are positioned along the length of the through hole to securely hold the stainless steel
needle such that the fiber endface is at the optimal distance from the reflecting membrane.

Figure 2-26 Aluminum plug for holding device chip. (a) Front view (b) Side view (c) Back view.

This structure is then mounted inside the normal incidence plane wave tube for characterization. The details of the experimental setup used for the characterization of the OM are discussed in Chapter 4.

2.7 Summary

This chapter described the design of the optical microphone system. An electrical equivalent circuit for the overall optical microphone system was developed. Theoretical formulations were developed for the system performance metrics such as sensitivity, linearity, frequency response, and minimum detectable signal. Based on the dimensions designed in Section 2.2.1, the fabrication of the optical microphone chip has been initiated at the MIT Microsystems Technology Laboratory. The process flow for the
fabrication of the optical microphone chip, and the proposed process flow for the package are discussed in Chapter 3.
CHAPTER 3
FABRICATION OF OPTICAL MICROPHONE

This chapter discusses the fabrication of the optical microphone. As discussed in Chapter 2, the goal of the MEMS OM is to fabricate a low stress silicon nitride membrane with reflecting layer on top of a cavity with a means to control the distance between the fiber and the membrane. A wafer-bonded approach was developed with the optical fiber held in the handle wafer. In this chapter, the mask is described, and the procedure for fabrication is outlined.

3.1 Mask Description

The mask is used in the fabrication process to define the microphone cavity. The dark field mask consists of a 25x25 array of 1mm diameter circles to expose 625 microphones on a 5” x 5” soda lime glass plate. Figure 3-1 shows a part of the mask. The circular blue structures represent the pattern to define the cavity.

Figure 3-1 Section of the dark field mask “Mask1” used for creating microphone cavity. The blue dots represent the area where the holes will be created.
3.2 Process Flow

The optical microphone device consists of the sensor chip and the handle chip. The sensor chip consists of a sensing diaphragm made of silicon nitride that performs the acousto-mechanical transduction. The proposed handle chip, machined from a Pyrex wafer, will be used to position the fiber endface from the membrane accurately. It also provides mechanical support for the device wafer and the fiber bundle. The sensor chip and the proposed handle chip will be bonded together using epoxy. The process flow for the fabrication of the optical microphone device is divided into the fabrication of the sensor chip and the proposed process flow for the fabrication of the handle chip.

3.2.1 Sensor Chip

The structure of the sensor chip to be fabricated was shown in the Section 2.1 on mechanical design and is repeated in Figure 3-2. The fabrication of the optical microphone begins by growing a thin layer of oxide on both sides of a silicon wafer. The thin oxide layer acts as the etch stop in the deep reactive ion etch process to be performed later. Low stress nitride of 10400A thickness is then deposited on the oxide. After etching away the nitride and oxide on the back side of the wafer using a plasma etch followed by a buffered oxide etch respectively, a thick layer of photoresist is spun on the backside.

![Figure 3-2 Schematic of structure of optical microphone.](image-url)
The photoresist layer is patterned and exposed using the mask described in the previous section. A deep reactive ion etch process is then carried out to form the cavity, stopping on the oxide layer. The oxide layer is then removed using a buffered oxide etch (BOE) releasing the silicon nitride membrane on top of a cavity in bulk silicon. A thin layer of aluminum is then deposited on the top surface of the nitride membrane to make it reflective at 1550nm. Table 3-1 lists the process flow for the fabrication of the device wafer. Figure 3-3 shows the cross sections at the various key steps during the fabrication of the device wafer.
1. Grow Thin Oxide

2. Deposit Low Stress Nitride

3. Plasma etch nitride on back side followed Spinning of thick photo resist

4. Pattern using Mask1

5. Plasma etch to remove nitride followed by BOE to remove oxide

6. DRIE upto the oxide layer

7. Ash Photoresist

8. BOE to release membrane followed by Aluminum deposition

**Figure 3-3** Cross-section at various key steps during the fabrication of the optical microphone.
Table 3-1 Process flow for optical microphone.

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Step #</th>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0</td>
<td>Start with n-type wafers</td>
</tr>
<tr>
<td>D</td>
<td>1.1</td>
<td>RCA clean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pre-oxidation clean</td>
</tr>
<tr>
<td>D</td>
<td>1.2</td>
<td>Grow oxide - dry oxide for 7000 Å</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Note. 3500 Å of silicon is consumed by dry oxidation</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>Deposit low-stress nitride using PECVD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Note: 10000 Å membrane, $\sigma \sim$ 50 - 80 MPa,</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>Plasma Etch Nitride on one side</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>Spin photoresist on front surface, thick coat (7um) and pattern using contact mask (Mask1)</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>Etch Oxide BOE</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
<td>DRIE silicon down to BOX</td>
</tr>
<tr>
<td>D</td>
<td>7</td>
<td>Ash Photoresist</td>
</tr>
<tr>
<td>D</td>
<td>8</td>
<td>Etch oxide BOE</td>
</tr>
<tr>
<td>D</td>
<td>9</td>
<td>E-beam 800Å of Aluminum</td>
</tr>
</tbody>
</table>

3.2.2. Handle Chip

The structure of the handle chip is shown in Figure 3-4. It consists of a 5mm x 5mm Pyrex chip with a 1mm diameter hole in the center. In the proposed process flow for the handle wafers, an array of 1mm diameter holes are ultrasonically drilled through the center of these chips. The 4” Pyrex wafers are then cut into 5mm x 5mm chips. Bullen Ultrasonics has been selected as the company for the fabrication of the handle chips.
3.3 Limitation of Optical Microphone Structure

There are three main limitations to the process flow discussed in this section for the device wafer. First, there is no provision in the structure of the device itself for positioning the fiber end face from the membrane accurately. This simplifies the device structure considerably. However, the procedure discussed in Section 2.1.12 must be utilized for accurately positioning the sensor. Second, since the high voltage required for anodic bonding may damage the metalized membrane, epoxy will be used to bond the device and handle wafer together. The thickness of the epoxy used to hold the sensor chip and handle chip cannot be estimated accurately. This will cause an error in the distance of the fiber end face from the membrane. Third, the sensor chip structure does not have a vent channel. A vent channel is a structure that equalizes the pressure on both sides of the sensing membrane. Thus, the OM will respond to DC pressure fluctuations.
CHAPTER 4
EXPERIMENTAL SETUP AND RESULTS

The static and dynamic characterization of the optical microphone was done at the Interdisciplinary Microsystems Laboratory at the University of Florida. This chapter discusses the experimental setup and results of the static and dynamic characterization of the optical microphone system.

4.1 Static Calibration

This section describes the experimental setup used for the static calibration and the results of the experiments.

4.1.2 Experimental Setup for Static Calibration

The static calibrations are employed to obtain the coupling efficiency curve and to experimentally determine the distance between the fiber end face and the reflecting membrane for maximum sensitivity. The static calibration was performed only for the mechano-optical stage for the MMTMMR case. The entire experiment is carried out on a Newport 4300 optical table. The block diagram of the experimental setup is shown in Figure 4-1.

The fiber bundles for the SMTMMR and MMTMMR case respectively, are held using a Newport fiber holder FP-01. The fiber holder is attached on to a SP-3 12.7mm Newport post and then mounted onto a Newport ESP100 Universal Actuator/Driver nanopositioner system using a custom interface plate. The interface plate is a 5 cm x 10 cm x 1 cm rectangular aluminum plate with several mounting holes. The plate is then bolted onto the
nanopositioner. The mechanical drawing of the plug and interface plate is shown in Appendix A. The motion of the nanopositioner is computer controlled via the RS232 port using Labview software.

Figure 4-1 Block diagram of experimental setup for static calibration.

The stainless steel tube at the end of the fiber bundle passes through a custom-made alignment structure. The custom-made alignment structure is a 3.5cm diameter and 1 cm thick aluminum disk with a 1mm diameter hole in the center through which the stainless steel tube passes. It is held vertically by a Newport SP-2 12.7mm post that is connected to a Newport RSP-1 rotation stage held by a Newport SP-3 25.4mm post. The reflective surface is simulated using a Newport 100D5420ER.2 2.54cm broadband front polished metallic mirror mounted in a Newport LH-100 lens holder. The mirror lens holder assembly is attached to a Newport RSP-1 rotation stage via a Newport SP-2 12.7mm post. Figure 4-2 shows a picture of the entire setup.
Figure 4-2 Experimental setup for static calibration. The laser source, beam splitter, and isolator are not shown.

A Thorlabs fiber pigtail laser diode LPS-SMF28-1550-FC driven by a Keithley 2400 sourcemeter configured as a constant current source is used as the light source. It is connected to a Newport F-CPL-1x2-OPT-50-11-50 1x2 beam splitter via a Newport ISS-1550 –50-20-50 fiber pigtailed isolator. One of the two outputs of the beam splitter is used as the unmodulated reference power signal and is converted into a voltage signal using a Thorlabs PDA 400 photodetector with its transimpedance gain set to $1.5 \times 10^4 \text{V/A}$. This voltage signal is amplified and fed to the denominator channel of the analog divide circuit.

The second output of the beam splitter is connected to the transmit fiber of the fiber bundle using a FC-FC male adapter. The intensity-modulated reflected light is collected via the receive fibers and is converted into a voltage signal using a second Thorlabs PDA 400 photodetector with a transimpedance gain of $1.5 \times 10^6 \text{V/A}$. The output is fed into the numerator channel of the analog divide circuit. The output of the analog divide circuit is amplified by the internal amplifier of the AD734IC by a fixed gain of 10.
This voltage signal is measured using a Keithley 2000 multimeter controlled by the GPIB interface using LabView software.

The first step in obtaining the coupling efficiency curve is to position the fiber end face perpendicular to the mirror. This is done based on the assumption that at some given distance the power collected by the receive fiber is maximum when the fiber end face is perpendicular to the membrane. To achieve this, the fiber end face is first placed at some distance away from the mirror. The two rotation stages are then iteratively adjusted until the output voltage obtained from the photodetector is maximized.

The fiber bundle is then moved towards the mirror and placed such that the fiber end face is adjacent to the mirror. The fiber bundle is then repeatedly stepped back from the mirror with a step size of 1um using the nanopositioner. At every position, 100 data samples from the output of the analog divide circuit are measured. The average is recorded along with the distance of the fiber end face from the mirror.

4.2.2 Results of Static Calibration

The static calibration was performed for the MMTMMR case only. The power coupling efficiency for the MMTMMR case is shown in Figure 4-3. The power coupling efficiency curve is linear from 503um to 1050um. The position of maximum sensitivity i.e. the distance at which the end face of the fiber bundle must be placed with respect to the membrane, is at a distance of 776um, which is the midpoint of the linear range. This does not agree well with the theoretical value of 56um obtained in Section 2.3.3. This could be attributed to the improper arrangement of the transmit and receive fibers inside the stainless steel tube which holds the fibers. The ideal arrangement of fibers in the stainless steel tube is shown in Figure 2-8. Figure 4-4 shows a digital camera picture of the actual end face of the MMTMMR fiber at 20X magnification using an Olympus BX-
30 microscope. The transmit and receive fibers can be seen clearly.

![Coupling Efficiency Curve](image)

**Figure 4-3** Coupling efficiency curve for MMTMMR using analog divide circuit.

The bright section on the outside is the light reflecting off the stainless steel tube. The diameter of the transmit and receive fibers are different whereas in the analysis it was assumed to be the same. It can also be noticed that the arrangement of fibers in the stainless steel tube is markedly different from the ideal case shown in Figure 2-8. There is considerable gap between the individual receive fibers and between the transmit and receive fibers. This is because the fiber bundle was manufactured by manual assembly of the individual fibers and not machine made which causes a variation in the distance between the individual fibers.
4.2 Dynamic Calibration

This section describes the experimental setup used for the static calibration and the results of the experiments.

4.2.1 Experimental Setup for Dynamic Calibration

The block diagram of the setup used for the dynamic characterization is shown in Figure 4-5. The dynamic response of the optical microphone was characterized using a normal impedance plane wave tube. The plane wave tube consists of a rigid-walled duct that supports planar acoustic waves along the length of the duct. The plane wave tube
used for characterizing the optical microphone consists of a 96 cm long, 2.54 cm x 2.54 cm square duct that permits characterization in a known acoustic field at frequencies up to 6.7 kHz. A JBL 2426 J compression driver is mounted on one end of the plane wave tube. On the other end, a rigid termination is provided which forces the formation of standing waves. The rigid termination has provision for mounting the reference microphone and the optical microphone next to each other. This allows the optical microphone and the reference microphone to experience the same pressure field. The reference microphone used is a 1/8-inch – Bruel and Kjaer (B&K) Type 4138 microphone, which is initially calibrated using a Bruel and Kjaer 4228 pistonphone. The microphone uses a Bruel and Kjaer 2670 preamp that was powered by the PULSE system. The JBL compression driver is excited using a signal generated by the PULSE multi-analyzer system using the LabShop 3.0 software after amplification by a Crown K1 balanced current amplifier. The schematic of the PWT tube is shown in Figure 4-6.

![Schematic of normal incident plane wave tube (PWT)](image)

Figure 4-6 Schematic of normal incident plane wave tube (PWT) [9].

The optical microphone chip is securely seated in a custom plug (Appendix A) as shown in Figure 4-7 using a two part quick dry epoxy. The stainless steel needle is held securely at a given distance in the plug using seven setscrews. The plug is then attached
into the end plate that has provision for mounting the optical microphone and the Bruel & Kjaer reference microphone adjacent to each other.

Figure 4-7 Aluminum plug for plane wave tube to mount optical microphone.

The prototype device used for performing the static and dynamic calibrations is an ultrasonic resonator that consists of a composite plate made of silicon dioxide, silicon nitride, and silicon which is 10um thick on top of a 1000um diameter cavity developed for the MEMS based cavity monitoring system project [45]. Figure 4-8 shows the top view and cross sectional view of the prototype device.

Figure 4-8 Schematic of prototype device. (a) Top view (b) Cross section.
The optical setup is the same as that used for the static calibrations. The output of the analog divide circuit was connected to the Stanford Research Systems (SRS) 785 low noise amplifier using a gain of 10 and the filter banks set as high pass filter with a cut-in frequency of 300Hz. The output of the amplifier was fed to the PULSE multi-analyzer system using LabShop software for data acquisition and processing. Figure 4-9 shows a picture of the dynamic calibration setup.

4.2.2 Linearity

The linearity of the microphone was tested using a 1kHz sine wave input. The input amplitude was increased from 105 dBSPL to 135 dBSPL corresponding to a pressure of 3Pa to 112Pa. The root mean square output voltage of the analog divide circuit was measured and recorded using the PULSE multianalyzer system by taking a linear average of 8000 samples at each input pressure level. The desired maximum pressure that the optical microphone is to be calibrated is 160dBSPL whereas the prototype device was tested only up to 135dBSPL because of the phenomenon of wave steepening that occurs at high input pressure levels. Figure 4-10 shows the sensor output
as a function of input pressure. The microphone exhibited a linear response for all input pressures measured from an input pressure level of 3Pa to 113Pa which corresponds to 103dB SPL to 135dB SPL re 20uPa. The slope of the curve provides the sensitivity and is equal to 151.65uV/Pa ± 3.67uV/Pa.

![Linearity Graph](image)

**Figure 4-10** Linearity of optical microphone with analog divide circuit.

### 4.2.3 Frequency Response

The frequency response of the optical microphone was tested using a periodic random signal. The transfer function between the optical microphone and the reference Bruel and Kjaer Type 4138 microphone was determined at 800 frequency bins from 1kHz to 7.4kHz using a linear average of 8000 samples with a Hanning window. All the data above 6.4kHz was discarded because of the propagation of higher order modes in the plane wave tube. The frequency response of the optical microphone was measured with and without the analog divide circuit.
The magnitude and phase response of the optical microphone with and without the analog divide circuit for the MMTMMR setup are shown in Figures 4-11 to 4-14. The magnitude response is flat from 1kHz to 6.4kHz. The sensitivity of the optical microphone for the (10um thick diaphragm) MMTMMR case with the analog divide circuit has an average value of 157uV/Pa for the case with the analog divide circuit whereas the theoretical sensitivity for a 1um thick membrane is 2748uV/Pa. The phase response shows a decreasing trend and varies from 10degrees at 1kHz to –41deg at 6.4kHz for the case with analog divide circuit. Similarly, the sensitivity of the optical microphone for the MMTMMR case without the analog divide has an average value of 82uV/Pa. The phase response shows a decreasing trend and varies from 17deg at 1kHz to -40deg at 6.4kHz for the case with the analog divide circuit. The variation in phase with frequency can be attributed to the absence of a vent channel in the optical microphone structure to equalize the pressure on both sides of the membrane. Another cause for the variation in phase may be due to a mounting error in the calibration of the device. A slight axial offset in the position in the PWT of the reference microphone and test microphone will result in a bias in the phase measurement [9].
Figure 4-11 Magnitude frequency response (with analog divide circuit) as measured in the normal incidence PWT.

Figure 4-12 Phase response (with analog divide circuit) as measured in the normal incidence PWT.
Figure 4-13 Magnitude frequency response (without analog divide circuit) as measured in the normal incidence plane wave tube.

Figure 4-14 Phase response (without analog divide circuit) as measured in the normal incidence PWT.
4.2.4 Minimum Detectable Signal

The minimum detectable signal (MDS) and signal to noise ratio (SNR) is measured by initially making a measurement without a true signal (i.e. the input to the JBL compression driver is turned off) to measure the noise floor (noise power spectral density (PSD)). Then the exact same measurement is repeated with the input acoustic signal turned on. The MDS is given by the square root of the PSD at the frequency of interest assuming a frequency bin falls on the frequency of interest i.e.

\[ MDS = 20 \log_{10} \left( \frac{ \sqrt{(\text{noise PSD}) \times (\text{bin width})}}{S} \right) \frac{S}{20\mu Pa} \]  (4.1)

The signal to noise ratio (SNR) at a given frequency, and a specified input pressure level is given by Equation (4.2)

\[ SNR = 10 \log_{10} \left( \frac{\text{coherence} \times \text{signal PSD}}{\text{noise PSD}} \right) \]  (4.2)

To measure the maximum SNR, a 1kHz single tone was input at 135dBSPL was used. The PSD was measured by taking a linear average of 8000 samples of the output. The optical microphone has a measured noise floor of \( 7.35 \times 10^{-9} V^2/Hz \) at 1kHz and a measured sensitivity of \( 73.7uV/Pa \) without the analog divide circuit and \( 13 \times 10^{-9} V^2/Hz \) and a sensitivity of \( 138uV/Pa \) with the analog divide circuit. Using this data, the MDS for the optical microphone with and without the analog divide circuit are computed to be 110dBSPL and 113dBSPL at 1kHz for an 8Hz bin width respectively, i.e.

\[ MDS = 110\text{dBSPL (with analog divide circuit)}, \]  (4.3)

\[ MDS = 113\text{dBSPL (without analog divide circuit)}. \]  (4.4)
The measured signal PSD for the optical microphone system with the analog divide circuit for a single tone sine wave input at 1kHz at 135dBSPL is $28.9 \times 10^{-6} V^2/Hz$ and $7.88 \times 10^{-6} V^2/Hz$ when the analog divide circuit is absent. Using this data and the formulation for SNR discussed in Section 4.2, the measured SNR for 1kHz sine wave at 135dBSPL is 33.24dB and 30.3dB respectively, i.e.

\[ SNR = 33.24dB \text{ (with analog divide circuit),} \quad (4.5) \]
\[ SNR = 30dB \text{ (without analog divide circuit).} \quad (4.6) \]

Comparing Equation (4.3) (113dBSPL) with Equation (2.67) (52dBSPL) the experimentally obtained MDS is higher than the theoretical value. The main reason for the higher experimental value is the order of magnitude thicker membrane, 10um thick, available prototype membrane whereas the OM designed has a thickness of 1um (1um diaphragm is currently being fabricated). The relation between the mechanical sensitivity and membrane thickness assuming a homogenous plate with inplane stress is given by Equation 2.7. Using the expression in Equation 2.7, the final device should have an acousto mechanical sensitivity that is 32 times larger. This corresponds to a theoretical decrease of 30dBSPL in the measured MDS to 80dBSPL.

4.3 Summary

In this section, the summary of the experimental results is presented. Table 4-1 lists the experimentally obtained sensitivity, MDS, and SNR for the prototype device and the predicted results for the actual optical microphone.
Table 4-1 Summary of experimental results.

<table>
<thead>
<tr>
<th></th>
<th>10um membrane</th>
<th>1um membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity at 1kHz</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical</td>
<td>42.6uV/Pa</td>
<td>1.54mV/Pa</td>
</tr>
<tr>
<td>Experimental</td>
<td>7.7uV/Pa</td>
<td>Not Available</td>
</tr>
<tr>
<td><strong>MDS at 1kHz</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical</td>
<td>86dBSPL (1Hz bin)</td>
<td>56dBSPL (1Hz bin)</td>
</tr>
<tr>
<td>Experimental</td>
<td>109dBSPL (8Hz bin)</td>
<td>Not Available</td>
</tr>
</tbody>
</table>
CHAPTER 5
CONCLUSIONS AND FUTURE WORK

This chapter recapitulates the word done in this thesis. Various suggestions for improving the performance of the optical microphone and long term goals are suggested.

5.1 Conclusions

An optical microphone for measurement in the aero acoustic range was designed. An equivalent circuit for the overall optical microphone system was developed. A process flow for the fabrication of the device was developed and has been sent for fabrication. A prototype device was constructed and characterized using a 1000um diameter 10um thick composite membrane (silicon-dioxide, silicon nitride, and silicon). The sensitivity, linearity, frequency response function, and minimum detectable signal were obtained experimentally for the prototype device. The principle of the intensity modulated optical lever was verified at the MEMS scale.

A quantitative deviation did exist from the analytic model and the experimental results. However, the overall qualitative behavior of the optical microphone was well predicted by theory. The prototype optical microphone had a sensitivity of 157 \( \mu V/Pa \) at 1kHz. It has a MDS of 110 dB SPL for a 8Hz bin at 1kHz. The output of the microphone is linear from 103dB SPL to 135dB SPL.

The quantitative differences were believed to be due to several factors. First, the prototype device that was used in the experiments was 10um thick whereas the design recommended a thickness of 1um. This reduced the sensitivity theoretically by a factor of
Secondly, the diaphragm in the prototype device consisted of a composite stack of silicon dioxide, silicon nitride, and bulk silicon whereas the diaphragm was designed to consist of silicon nitride only. Thirdly, the fiber bundle was manually assembled. This caused the relative positioning of the fibers with respect to each other to deviate from the ideal case shown in Figure 2-11 for the SMTMMR and MMTMMR case, causing a variation in the opto-mechanical sensitivity as predicted by theory. Fourthly, the phase response varied from 43\textdegree at 1kHz to 17\textdegree at 6.4kHz. This is attributed to the fact that the current design of the optical microphone has no vent channel to equalize the pressure on both sides of the membrane.

5.2 Future Work

The prototype device was calibrated from 1kHz to 6.4kHz because of propagation of higher order modes in the plane wave tube above this frequency. The device thus needs to be calibrated over the entire frequency range of interest. An uncertainty analysis of the intensity profile of the light at the end of the SM and MM fiber needs to be performed to study the effects of angular misalignment, and radial and axial offset on the mechano-optical sensitivity. The effect of the curvature of the membrane needs to be included in the analysis of the intensity distribution. The measurements need to be repeated for the 1um thick diaphragm OM that is currently being fabricated. The process flow for the fabrication of the device could be modified to include a provision on the device itself for positioning the fiber end face at the optimal distance from the membrane instead of using the packaging scheme discussed in Chapter 2. The process flow could also be modified to include a vent channel.
Other work could focus on using multiple transmit and receive fibers to improve the acousto-mechanical sensitivity. An LED source instead of a laser could be used, which will reduce the cost and prevent the problem of back reflections associated with laser sources. Long-term work could focus on the development of optical microphone based acoustic arrays.
Figure A-1 Schematic of plug for normal incidence plane wave tube.
LIST OF REFERENCES


[41] *PDA-400 Switchable Gain InGaAs Amplified Photodetector Product Data Sheet*. Newton, New Jersey: Thorlabs Inc.


BIOGRAPHICAL SKETCH

Karthik Kadirvel was born on August 30th, 1978, in Chennai, Tamil Nadu, India. He moved to the United Arab Emirates in 1989 and graduated from Our Own English High School in Dubai, United Arab Emirates, in 1996. He went back to India for his bachelor’s degree and obtained his Bachelor of Engineering degree specializing in Electronics and Instrumentation from Annamalai University, Tamil Nadu, India, in May 2000. He is currently pursuing his Master of Science degree in the Department of Electrical and Computer Engineering at the University of Florida. After obtaining his master’s degree he plans to pursue his doctoral degree at the University of Florida. His research interests include the design of analog interface circuitry for MEMS devices and RF circuits for wireless communications.