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Slab-Coupled Optical Fiber Sensors for Electric Field Sensing Applications

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Slab Coupled Optical Fiber Sensors for Electric Field Sensing Applications

Richard Scott Gibson

A dissertation submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

Slab Coupled Optical Fiber Sensors for Electric Field Sensing Applications

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This dissertation presents the creation of slab coupled optical sensors (SCOS) for electric field sensing applications. SCOS devices utilize the benefits of an optical fiber system for high bandwidth and low electromagnetic interference. These sensors are fabricated by means of mode coupling between a small section of D-shaped optical fiber (D-fiber) with a multi-mode electro-optic slab waveguide. Electric field detection is accomplished by monitoring the behavior of the resonances, seen as transmission dips in the D-fiber transmission, as they shift with electric fields.

The novelties of SCOS devices include their small compact nature, potential for sensor multiplexing and a dielectric structure allowing low electromagnetic interference. The SCOS developed in this work been used to measure fields as low as 30 V/m with 1 kHz resolution bandwidth and a high degree of linearity. Due to their compact size they are capable of placement within devices to measure interior electric fields immeasurable by other sensors that are either too large for internal placement or disruptive of the internal fields due to metallic structure. Wavelength multiplexing allows multiple sensors to be placed on a single fiber for mapping electric fields at multiple instances. As an extension, SCOS multiplexing allows the potential for 3-d field sensing by use of multiple electro-optic crystals having orthogonal orientations of the electro-optic axis.

This work performs a thorough analysis of SCOS design in order to optimize sensor efficiency for its various applications. Furthermore, the straightforward fabrication process for these sensors is outlined for the development of future uses of these sensors.

Keywords: Optics, Fiber Optics, Optical Fiber Sensors, Electric Field Sensors, EOS, D-fiber
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1 INTRODUCTION

Slab coupled optical fiber sensors (SCOS) offer a unique method to measure electric fields in difficult to reach environments with minimal field perturbation. The use of electro-optic sampling (EOS) in the SCOS technology offers promising performance characteristics over traditional electronic measurement techniques. Figure 1-1 shows the relatively large structure of a state of the art D-dot sensor. Its size and metallic composition disrupt the electric fields in its vicinity making it difficult to place within many electronics devices [1]. Though they are highly sensitive to electric fields, their imposing size and perturbing metallic construction are too disruptive for low-impact testing in small or sensitive environments.

![Figure 1-1: Metallic D-dot sensor for measuring electric fields.](image)

EOS currently offers sensors built with all-dielectric composition for minimal field perturbation [2-4], high bandwidth [4-6] and the potential for fiber-based interrogation [7-9]. The purpose of SCOS technology is to provide an effective electric-field sensor for applications
requiring minimal electromagnetic interference and high portability for placement in difficult to reach locations [10]. A typical SCOS sensor is shown in Figure 1-3 compared in size with a standard 1/4 watt resistor. In terms of dimensions, it is virtually the same size as the optical fiber and it also features an all-dielectric composition.

![Figure 1-2: SCOS sensor compared in size with a standard 1/4 watt resistor](image)

1.1 The need for optical fiber based electric field sensors

One important application for electric field sensing is the safeguarding of electronics. High powered microwave (HPM) and electromagnetic pulse (EMP) weapons pose severe concerns on the safety and reliability of electronic equipment [11-14]. These weapons are engineered to generate short, high-powered, high-frequency pulses capable of coupling with conductive lines in electronics and inducing large transient currents to destroy sensitive circuitry and semiconductor devices. An attack from such weapons can quickly disable communications systems, databases, control systems, guidance systems, etc. and reduce a targeted military or civic region of all modern electronic equipment and technologies.

In order to protect electronics from HPM and EMP weapons, metallic shielding has been developed. However, general shielding techniques add significant cost and weight. To better
understand the effectiveness of HPM and EMP weapons on shielded electronic circuitry as well as the efficacy of shielding, sensors are needed to measure high-frequency, high-energy pulses in close proximity to the circuitry within the shielding without affecting the electronics, the shielding, or significantly altering the electric fields within the target. Furthermore, the non-uniform distribution of the electric field within the shielding requires the measurement system to have the capability of sensing the field at multiple points within the target.

In order for EOS to meet the requirements for measuring electric fields within shielding it is necessary to have a small, flexible device that can be threaded within electronic components and circuitry. The use of a D-dot sensor or even a bulk optics system for EOS would not be feasible in this circumstance due to disruption of fields and the difficulty of placement in the device under test [15]. However, SCOS technology satisfies this requirement by allowing the sensor to be placed anywhere that is accessible by an optical fiber as illustrated in Figure 1-3. Furthermore, this fiber-based solution also allows EOS sensor multiplexing in order to map multiple instances of an electric field within the device under test [16].

![Figure 1-3: Illustration of HPM weapon aimed at a device with interior SCOS sensor](image-url)
1.2 An overview of EO sensors

Sensors made by combining the electro-optic effect within an optical fiber system give the promise of minimized electromagnetic interference, small dimensions, high portability and high bandwidth. Electro-optic sensors have already found many applications. In RF links, electro-optic sensors can perform as RF antennas with ultra-high bandwidth while inducing minimal perturbation of the field under measurement [4]. Imaging and mapping systems have also benefited from the development of EOS [7, 15, 17, 18]. It is likewise desirable to use EOS devices in monitoring the effects of electric fields in space-restrictive environments such as a high-powered electromagnetic fields targeted at electronic circuitry.

The main groups of fiber-based sensors used in EOS applications utilize either interferometry based intensity/phase modulation [2, 4, 19-21], or evanescent coupling from the fiber core into an electro-optic microcavity resonator [3, 5, 9], such as in the slab coupled optical sensor (SCOS) approach with an external slab waveguide [22]. While interferometry based devices such as the Mach-Zehnder can provide high levels of sensitivity [4], they prohibit wavelength multiplexing, are often bulky and suffer from insertion loss and the complexity of coupling between optical fibers and electro-optic materials. Fiber sensors based on evanescent mode coupling avoid issues with insertion loss while taking advantage of the naturally high bandwidth of optical fibers for multiplexing. The compact size and wavelength selectivity of SCOS technology offers superb portability and allows wavelength multiplexing for the placement of multiple devices on a single fiber.
1.3 Contributions

Contributions toward SCOS technology have been published in six peer reviewed journals and presented at four technical conferences. Various entities have also contributed funding for the development of this technology for use in the defense industry. The main contributions of this work are given as follows:

- I have developed a new sensing platform based on coupling between a D-fiber and a slab waveguide called slab coupled optical fiber sensing (SCOS).
- I have developed a high-yield fabrication process for SCOS sensors
- I have demonstrated temperature sensing using the SCOS technology.
- I have pioneered the application of SCOS to electric field detection.
• I have developed a detailed theoretical model of the SCOS.
  

• I have used the theoretical model to optimize the various SCOS design parameters.
  

• I have developed a highly linear SCOS electric field sensor capable of measuring fields as low as 15.8 V/m with 1 kHz resolution bandwidth.
  
  o R. Gibson, J. D. Luo, R. Selfridge, and S. Schultz, “Highly sensitive SCOS sensor using AJL8/APC slab waveguide,” *In preparation*

• I have developed, fabricated, and tested an array of SCOS electric field sensors on a single optical fiber.
  
  

• I have designed a multi-axial electric field sensor for monitoring 3-D fields.

• I have demonstrated the potential for internal cavity sensing by mapping the electric field of the TE_{10} mode in an X-Band waveguide.
  
  o R. Gibson, R. Selfridge, and S. Schultz, “Non-intrusive electric field mapping in an X-Band waveguide using SCOS optical fiber electric-field sensor,” *In preparation*
1.4 Dissertation outline

This dissertation is outlined as follows. Chapter 2 includes the background for optical sensing including an overview on mode coupling, fiber couplers and the operation of SCOS sensors. The fabrication of SCOS devices is covered in Chapter 3 which introduces optical D-fibers and birefringent etching and culminates in the different packaging techniques for finished SCOS sensors. Chapter 4 introduces measurement techniques to retrieve desired information from the optical signal from the SCOS transmission. It also mentions ways to improve signal strength. An analysis of the electro-optic slab waveguides used by SCOS for electric field measurement is included in Chapter 5. Chapter 6 investigates methods for optimizing SCOS electric-field sensor performance by analyzing various parameters in the fabrication process. Guidelines for optimal design are included for reference. Additional consideration for improving SCOS performance is given in Chapter 7 regarding the reduction of optical losses in SCOS devices. The fabrication and testing of an array of SCOS sensors is introduced in Chapter 8. Chapter 9 gives an outline for creating multi-axial sensors with SCOS technology for the purpose of obtaining 3-D electric-field measurements. In Chapter 10 a SCOS is used to map the fields inside an X-Band waveguide in order to demonstrate its effectiveness as a sensor in interior cavities. Appendices are also included that offer detailed fabrication steps, references for EO materials mentioned in this work and code for understanding the nature of mode coupling losses with optically thick slabs.
2 BACKGROUND

The SCOS is essentially an asymmetric directional coupler with a high-index multi-mode slab coupled to a short evanescently-exposed section of single mode optical D-fiber as shown in Figure 2-1. The SCOS technology shares similarities with many side-polished fiber (SPF) devices that use standard optical fiber (SMF-28) coupled to an external waveguide. While this coupling has been compared to the coupling in an equivalent waveguide structure, several in-depth analyses exist that make considerations into the asymmetry of the waveguides and the subtleties of evanescent coupling from an optical fiber to external non-fiber waveguides. This chapter begins with a short primer on optical mode coupling followed by an analysis of directional fiber couplers leading into an overview of SCOS operation.

2.1 Optical mode coupling

Optical mode coupling is analogous with the concept of resonant tunneling between quantum wells. In quantum mechanics, two quantum wells isolated by a strong potential barrier behave as defined by their individual eigenstates independently from each other. However, if the potentially barrier is sufficiently thin, eigenstates localized to one well can interact by quantum mechanical tunneling with states in the other well [23]. The resulting thin-barrier structure has delocalized eigenstates with specific eigenenergies where particles may exist in either well. Similarly, if two optical waveguides are in close enough proximity to each other that their
evanescent fields can overlap with the other waveguide, light in one waveguide may couple into the guiding structure of the other waveguide.

In order to understand mode coupling, a rigorous study of coupled waveguide structures involves defining Maxwell’s equations for the system and using boundary conditions to determine modal solutions. For simplicity, if weak coupling is assumed between waveguides it is appropriate to solve the system with coupled-mode theory [24]. In this regime it is assumed that only the amplitudes of the fields in a waveguide are affected by the presence of another waveguide and mode coupling involves scattering light from the mode of one waveguide into the mode of another waveguide. In order for significant power transfer to take place between the two waveguides, the propagation constants of the individual modal solutions must be close enough to allow sufficient phase matching.

2.2 Fiber optic directional coupler analysis

While mode coupling is readily understood between identical lossless waveguides, many useful devices based on mode coupling require considerations beyond canonical solutions. Several analyses exist on the topic of coupling between an optical fiber and a slab waveguide. Marcuse investigated the coupling between a fiber and infinite slab using coupled wave equations for a single mode fiber having lateral confinement and a multimode slab lacking lateral confinement [25]. His coupled-mode analysis focused on light transfer between fiber and slab in relation to their respective propagation constants and treated the lateral modes in the slab waveguide as a source of optical loss in the system. In the case of interest where the slab index is significantly higher than the fiber mode, the slab acts as a sink to coupled modes, creating resonant dips in the transmission of the fiber.
Andreev and Panajatov furthered Marcuse’s analysis by using the coupled mode technique and considering the distributed coupling associated with side-polished fibers due to the variance in coupling strength along the evanescent region of the polished fiber as shown in the top diagram of Figure 2-1 [26-29]. Finding strong agreement with their analysis and experimental results, Panajatov and Andreev conclude that the wavelength of coupling can be controlled predictably by the thickness of the waveguide and that the values of the minimum transmission and corresponding half-width depend strongly on the separation distance (coupling strength) between the fiber and planar waveguide.

Figure 2-1: Side-polished fiber coupled with slab waveguide showing variable separation distance (Top). Etched D-fiber coupled with slab waveguide showing uniform separation (Bottom).

Using insight from these detailed analyses, Hamilton focused on developing an understanding of the lineshape of the resonant modes in the fiber transmission using a simplified coupled mode theory [6]. In his analysis, Hamilton treated the fiber as a lossless waveguide. The multimode slab was modeled with distributed loss to compensate for the radiation of lateral
modes away from the presence of the fiber. Assuming full coupling when the propagation constants of the waveguides are matched, \((\beta_{\text{fiber}} = \beta_{\text{slab}})\), the solutions of his simplified technique analyzed the resonant mode lineshape (example in Figure 2-3) versus phase mismatch \((\Delta \beta = |\beta_{\text{fiber}} - \beta_{\text{slab}}|)\) in order to account for the asymmetric waveguide dispersion of fiber and slab modes. The solutions accommodate optical loss, coupling length and coupling strength in an effort to maximize the linearity of the resonant mode lineshape. This work also provides insight into how these same parameters affect the total transmitted power from one waveguide to another as well as the linewidth of a resonant mode.

While similar to various sensors based on side-polished fiber (SPF) techniques [30-36], the use of D-fiber offers unique characteristics and advantages. The coupling structure for the SPF structure studied by the previous authors is differentiated from SCOS by the curvature of the fiber and resulting variance in coupling strength along the coupling region. The bottom diagram in Figure 2-1 shows a SCOS structure utilizing D-fiber where the separation distance between fiber core and slab waveguide is constant, leading to a uniform coupling strength across the coupling region. This coupling structure allows simplification in the analysis and more closely follows the models proposed by Marcuse and Hamilton where a uniform coupling strength is assumed along the coupling region of the device.

A basic understanding of SCOS operation does not require a full understanding of the coupling between the D-fiber and slab waveguide. However, in order to optimize SCOS performance, further considerations into the coupling analysis of SCOS devices are addressed in Section 6.2. This chapter treats SCOS operation based on the weak coupling condition. In this regime, resonances are analyzed by the eigenvalue equation for the slab waveguide modes,
assuming phase matching with the fiber mode which remains unchanged across the wavelength range of the SCOS transmission spectrum [37].

2.3 SCOS operation as an electric field sensor

This section aims at understanding how the SCOS works as an electric-field sensor. Figure 2-2 shows that the basic SCOS device consists of an electro-optic (EO) slab waveguide of thickness, \( t \), in close proximity to the core of an optical fiber. Resonant mode coupling between the EO slab waveguide and D-shaped optical fiber (KVH Industries, Inc.) form the basis for SCOS sensing. Full resonant transfer of optical power takes place for slab modes at wavelengths where the slab mode index equals the mode index of the fiber and there is adequate evanescent coupling.

![Cross section diagram of the SCOS sensor](image)

*Figure 2-2: Cross section diagram of the SCOS sensor*

The transmission spectrum of a SCOS consists of a periodic set of transmission dips corresponding to wavelengths where the light is resonantly coupled from the optical fiber to a mode in the multi-mode slab waveguide. Figure 2-3 shows a SCOS where modes coupled from
the fiber are dispersed in the slab waveguide and the corresponding resonant dips are seen in the transmission spectrum.

![Diagram](image)

Figure 2-3: SCOS showing optical input into the D-fiber and a coupled slab waveguide where modes are scattered (Top). SCOS transmission from D-fiber output shows resonant modes (Bottom). The free spectral range (FSR) is the spacing between subsequent modes.

As mentioned earlier, these resonant modes occur at wavelengths where the effective index of the fiber mode matches one of the modes in the slab waveguide. The effective index of the \( m^{th} \) slab mode matches that of the fiber when the wavelength is given by [37]

\[
\lambda_m = \frac{2t\pi}{m\pi + \phi_1 + \phi_2} \sqrt{n_o^2 - N_f^2},
\]

(2-1)

where \( t \) and \( n_o \) are respectively the thickness and refractive index of the overlay material, \( N_f \) is the mode index of the fiber (1.451 for D-fiber at \( \lambda=1550 \) nm), \( m \) is the mode number, \( \phi_1 \) and \( \phi_2 \) are phase shifts from the evanescent field according to
\[ \phi_{i=1,2} = \tan^{-1} \xi \left( \frac{N_f^2 - n_i^2}{n_0^2 - N_f^2} \right)^{1/2}, \]  

(2-2)

where \( n_1 \) is the cladding index between the fiber core and slab waveguide, \( n_2 \) is the index of the material above of the slab waveguide and \( \xi \) is a polarization dependant term (1 for TE fields and \( n_o^2/n_i^2 \) for TM fields). For thick slab waveguides, the phase terms \( \phi_1 \) and \( \phi_2 \) can be neglected when considering higher order modes.

The spacing between subsequent modes is given by the free spectral range (FSR) which is conveniently approximated for higher order modes at a chosen wavelength as,

\[ FSR \approx \frac{\lambda^2}{2t \sqrt{n_0^2 - N_f^2}}. \]  

(2-3)

For a slab waveguide material of determined index, \( n_o \), the FSR is determined by the thickness of the slab waveguide. In general, the waveguide is chosen thick enough so that the FSR is less than the operable range of the laser source.

Using EO materials for the slab waveguide allows the SCOS to operate as an electric field sensor. The incident electric field changes the refractive index of the slab, \( n_o \), shifting the spectral position of the transmission dips. Detecting high frequency electric fields with the sensor requires monitoring the corresponding changes in transmitted power at a mid-resonant wavelength. This involves probing at a mid-resonant wavelength where the coupling slope is large as shown by the regions within \( \Delta \lambda \) and \( \Delta T \) in Figure 2-4. When an electric field causes a shift of \( \Delta \lambda \) in the transmission spectrum the output at a mid-resonant wavelength changes by \( \Delta T \). Because the magnitude of \( \Delta T \) ultimately depends on the strength of the electric field, the SCOS works as an effective electric field sensor. The signal, \( \Delta T \), is extrapolated from the SCOS.
transmission by first converting the optical signal to an electrical signal with an optical detector and then reading the frequency content with either an oscilloscope or spectrum analyzer.

![Graph](image)

Figure 2-4: A small shift in wavelength generates an appreciable shift in the transmission output for a SCOS sensor.

### 2.4 Summary

Electric field measurements with SCOS technology takes advantage of the highly sensitive nature of mode coupling in order to monitor small index changes in the slab material from the electro-optic effect. However, the slab index varies with other factors including temperature, pressure and strain [38]. As appropriate, these environmental variables should be taken into consideration wherever a SCOS is used. Electric fields are typically isolated from other physical phenomena by a large margin in the frequency domain. Changes in temperature, pressure and strain occur at relatively slow rates and packaging techniques may be used to further isolate a SCOS device from these factors. The following chapter on fabrication includes several packaging techniques currently employed for SCOS devices.
3 FABRICATION

The geometry of the D-fiber provides a convenient platform for fabricating devices that involve mode coupling – the mechanism where evanescent fields from one waveguide overlap with another waveguide and transfer optical power. Figure 3-1 shows that the fiber’s elliptical core resides in close proximity to the flat surface of the D-fiber. Only a small portion of the cladding needs be removed in order to expose the evanescent portion of the fiber mode, leaving the fiber structurally sound and without significantly increasing its brittleness.

![Diagram of D-fiber](image)

**Figure 3-1:** A 125 µm D-fiber with a 2 µm x 4 µm elliptical core located 13 µm from the flat surface.

Figure 3-2 shows the fabrication for SCOS devices in three main steps. (1) The D-fiber is thoroughly cleaned in preparation for wet etching. (2) The fiber is placed in a bath of hydrofluoric acid to etch down the cladding layer above the core. (3) A slab waveguide is coupled to the etched section of the D-fiber with an index matching adhesive.
Figure 3-2: The SCOS fabrication process follows three steps: 1) cleaning a stripped section of D-fiber, 2) hydrofluoric acid etching to expose evanescent fields, 3) slab waveguide application for coupling to D-fiber.

For SCOS, the following fabrication process using D-fiber enables full control over the evanescent coupling length and the corresponding coupling strength between fiber and slab waveguide [22]. As mentioned previously, the coupling strength remains uniform along the coupling region for D-fibers due to this process. Individual control over both the coupling length and strength are unique to the SCOS. In the remainder of the chapter the three fabrication steps are examined and explained in detail.

### 3.1 Initial cleaning of the D-fiber

Throughout fabrication, cleanliness of the fiber is paramount in order to produce a successful SCOS. Because cleanliness is so important, great care is taken during this first step to ensure that any dust particles, films, or jacket fragments are completely removed before the wet etching process.
The first step is to remove ~2 cm of the protective polymer jacket from the section of the fiber that will be etched. The jacket removal can be done by using a mechanical stripper, a heat stripper, a solvent such as dichloromethane, or acid such as sulfuric acid. All four methods can be used and yield a successful SCOS. Several articles are written on the mechanical integrity of an optical fiber after stripping and the advantages and disadvantages to each method [39-41]. Throughout this work, most of the fibers are stripped using a heat stripper for convenience and ease of use.

Once the jacket is removed the fiber is placed in the fiber holder, flat side facing up as shown in Figure 3-3. Even though the jacket strippers work well at removing the polymer jacket, they leave behind jacket fragments that need to be removed. To remove these jacket fragments and any other contaminants the fiber is placed in a bath of isopropyl alcohol (IPA) in an ultrasonic cleaner. The IPA and ultrasonic cleaner work together to remove any remaining jacket fragments and fiber surface contaminants. After ultrasonic cleaning in IPA, the flat side of the D-fiber surface is visibly shiny from reflected light. Any spots or dull areas on the flat surface indicate that further cleaning is required.

Figure 3-3: The fiber holder uses padded magnetic fasteners to hold onto the fiber at the ends. When the fasteners are slid towards the center of the holder, the D-fiber bends in a direction perpendicular to its flat face. When the fiber is properly oriented with the flat side facing up it will bend downwards allowing it to be placed into a liquid holding container for cleaning and etching.
As an optional final cleaning step, the fiber can be soaked in a bath of DeContam for more than five minutes. DeContam is a cleansing agent used to remove any contamination and film that is left on the fiber after the IPA bath. After soaking the fiber, DeContam is rinsed off using de-ionized (DI) water.

### 3.2 Hydrofluoric acid etching

In order for SCOS technology to work, the evanescent field of the stripped D-fiber section must be exposed by removing part of the fiber cladding as received from the manufacturer. The fiber core is approximately 13 μm from the flat surface of the fiber necessitating the removal of the cladding above the core to enable the mode overlap with the slab waveguide.

In the cladding etch process, a single looped section of D-fiber is placed in a solution of 25% by volume hydrofluoric acid (HF) such that a fixed length is submerged (~1.5 cm). The HF etches the silica in the looped section at a controlled rate, maintaining a smooth layer of silica above the fiber core. Although etching typically takes ~30 minutes, etch time is dependent on temperature, humidity, fiber bend radius and other factors. Therefore, the remaining silica cladding thickness above the core is controlled by using in-situ monitoring of the fiber birefringence between the two polarizations along the major and minor axis of the fiber. Because birefringence changes predictably as an increasing portion of the fiber’s evanescent field is exposed to the acid’s lower index of refraction, it is possible to remove the desired amount of cladding and obtain a uniform waveguide separation, $d$ [42, 43].
Figure 3-4: The fiber holder is used to hold the D-fiber in hydrofluoric acid for etching. The input polarizer and output analyzer are used to monitor the changing birefringence of the D-fiber during the etch.

Figure 3-4 shows the etch setup in which a Teflon etch frame holds the fiber so that the ~1.5 cm section of the fiber is immersed in HF. 1550 nm light is launched into the fiber through a polarizer at a 45° angle relative to the major axis of the elliptical core of the fiber. Launching the light at this angle allows equal amounts of light to be coupled into each of the two polarization modes. One mode is polarized along the major axis of the ellipse (horizontal mode), and the other along the minor axis (vertical mode) as shown in Figure 3-5. An analyzer is placed at the output of the fiber, at a -45° degree angle with respect to the major axis of the ellipse, and a detector measures the transmitted power.

Figure 3-5: Vertical and horizontal fiber modes with mode indices of \( n_x \) and \( n_y \).
3.2.1 Birefringence monitoring during the etch

The total light in the elliptical core D-fiber can be thought of as the sum of two orthogonally polarized electric fields with different propagation constants, $\beta^x_z$ and $\beta^y_z$, relating to the indices of the orthogonal modes by,

$$\beta^{x,y}_z = \frac{2\pi}{\lambda_0} n_{x,y},$$  \hspace{1cm} (3-1)

where $\lambda_0$ is the free space wavelength of light launched into the fiber and $n_x$ and $n_y$ are the effective indices of refraction for the two modes. As etching starts to remove the silica close to the core region, the guiding geometry of the orthogonal modes changes. The difference in boundary conditions for the modes with orthogonal polarizations leads to an asymmetrical change in their respective indices. As a result, the birefringence, $B$, of the D-fiber changes as given by

$$B = \beta^x_z - \beta^y_z,$$  \hspace{1cm} (3-2)

which increases as the etch progresses.

The change in birefringence of the fiber during the etch can be related to the output intensity by

$$I = I_0 \sin^2 \frac{\Delta \phi}{2},$$  \hspace{1cm} (3-3)

where
\[ \Delta \phi = \frac{2\pi}{\lambda_0} \Delta B z, \] 

(3-4)

\( z \) is the length of fiber being etched and \( \Delta B \) is the difference between the birefringence after having etched a certain distance and the initial birefringence of the unetched fiber.

Using BeamPROP, the effective refractive indices of the two polarization states are found for different etch depths. Once the indices are found, Equation (3-3) can be used to calculate the output intensity of light for different core-to-flat distances. The core to flat distance is defined as the distance from the top of the core to the flat surface of the D-shape. Figure 3-6 shows the birefringence as a function of core-to-flat distance. As evident by the figure, the birefringence starts to experience significant change once the core-to-flat distance has been reduced to about one wavelength (~1.5 \( \mu \)m).

Figure 3-7 shows the simulated output intensity using the simulated birefringence data and Equation (3-3). As the cladding layer above the core is reduced, the oscillations in the intensity increase in frequency because the birefringence begins to change more rapidly. Once the cladding layer is completely etched from above the core of the D-fiber the acid begins to etch the core of the fiber. Because the core of the D-fiber etches much quicker than the cladding, power is quickly lost from the fiber once the etch breaches the core. For this reason, it is important to closely monitor the oscillations and make sure the fiber is removed from the hydrofluoric acid before all of the cladding has been removed.
Figure 3-6: Birefringence vs. core–to–flat distance.

Figure 3-7: Output power vs. core-to-flat distance.
3.2.2 Etching results

Figure 7 shows a scanning electron microscope image of an etched D-fiber where the distance between the core and placement of the slab waveguide is $d = 1.5 \, \mu m$. In reference to the previous etch data, the distance between the core and the top of the cladding is $\sim 0.7 \, \mu m$. Due to the depressed cladding structure of the D-fiber, the region around the core etches faster than the rest of the cladding and a small trough is left above the core, leaving a space between the fiber and slab waveguide. The spacing above the core that is inherently created during the etch requires that almost all of the cladding be removed from above the core. For this reason it is important to calibrate the desired etch length to the number of oscillations very carefully in order to avoid removing part of the core during the etch. The air-gap created by this space necessitates the use of an index matching material to properly facilitate coupling between waveguides.

![SEM image of the D-fiber core region after etching in hydrofluoric acid](image)

Figure 3-8: SEM image of the D-fiber core region after etching in hydrofluoric acid. The fiber core resides $\sim 0.7 \, \mu m$ from the surface after $\sim 12.3 \, \mu m$ are removed by HF etching. The distance, $d$, between the core and the placement of the slab waveguide is labeled.
3.3 Slab waveguide application

After removing the desired thickness of silica cladding along the etched region, the fiber is cleaned again in the ultrasonic IPA bath to ensure good adhesion with the slab waveguide. To promote better adhesion a one hour dehydration bake at 100\(^\circ\) C may be used to drive out any moisture absorbed by the fiber during the etch process.

After cleaning, an EO slab waveguide is attached to the etched region of fiber with a UV-cure polymer epoxy that is index matched with the fiber cladding (MY Polymers Ltd.). A pipette is used to apply a drop of the epoxy onto one side of the slab. Due to the small size and mass of the EO slabs used, surface tension alone is required to hold the slab in place on the fiber until the adhesive is cured.

3.3.1 In-situ slab placement

With a broadband amplified stimulated emission source (ASE) coupled to the input of the fiber, an Optical Spectrum Analyzer (OSA) is used to view the SCOS output as the slab is positioned on the fiber as shown in Figure 3-9. This in-situ monitoring is used to observe the expected mode resonances between fiber and slab to ensure proper placement, separation and positioning before permanent attachment. Because contaminants between the fiber and slab can interfere with coupling, in-situ monitoring is vital to ensure both high product yield from the fabrication process and high performance from the sensor. Otherwise, unseen contaminants can induce optical losses or create a wedge that increases waveguide separation. Furthermore, the layer of adhesive between the fiber and slab must be quite thin for proper coupling and sliding the slab along the fiber helps disperse and spread excess adhesive until the layer is thin enough to
develop the proper coupling between waveguides. The adhesive is ready for curing when the OSA shows deep, low-loss resonances with narrow linewidths being transmitted from the SCOS.

In addition to ensuring clean placement, manipulating the slab position on the fiber can be used as a means to fine tune the coupling parameters. For example the effective coupling length can be reduced by positioning the slab along the transition region of the etched portion of fiber. The portion of the slab extending into the transition region couples weakly with the fiber and any portion far enough along the transition region will not couple at all due to the increased waveguide separation.

Sometimes a particular slab waveguide is too long, too short or otherwise does not provide good coupling conditions with the D-fiber. In this case the slab waveguide is discarded and replaced with a more suitable sample that obtains desirable coupling.

Because the index of UV cure epoxy typically increases as it is cured, the evanescent fields from the fiber will extend further into the slab waveguide after the adhesive is set. In essence, the coupling strength increases and this effect can be accommodated for beforehand by
fine tuning the coupling before initiating curing. This is accomplished by first finding the optimal coupling spectrum for the SCOS on the OSA and then reducing the coupling strength between the fiber and slab so that the mode extinction is ~10 dB less. After backing off the coupling strength, the adhesive is exposed by a UV lamp to initiate curing and the resonances return to suitable extinction after curing is complete.

3.4 The completed SCOS

An SEM image of a finished sensor is shown in Figure 3-10 after having been cleaved. The image shows a 61 μm thick AJL8/APC polymer slab separated from the D-fiber core by ~1.6 μm. A thin layer of epoxy is evident between the D-fiber core and slab with an estimated thickness of ~0.5 μm. Figure 3-10 also shows an optical image of an AJL8/APC polymer SCOS with the slab width about 2.5X that of the D-fiber.

The optical transmission for the polymer SCOS in the top of Figure 3-10 is displayed in Figure 3-11 with sequential modes separated by a free spectral range (FSR) of ~19 nm. With a maximum transmission of -7dB and resonant modes as deep as -22 dB, the dynamic range is 15 dB. An important design parameter in the fabrication process requires ensuring that the FSR of the SCOS falls within the range of the tunable laser to be used. For a given material, the FSR decreases with slab thickness.
Figure 3-10: SEM image of the cross section of a polymer SCOS sensor (Top). Optical image of the top-down view on a polymer SCOS sensor (Bottom).

Figure 3-11: SCOS transmission for AJL8/APC SCOS
3.5 Packaging, fusion splicing and connectorizing

In the final product, the D-fiber SCOS is often placed in protective packaging and either connectorized or fusion spliced with a standard fiber type to allow integration with systems using common fiber types. Packaging not only provides protection for the SCOS from breaking, but also isolates it from contamination. Figure 3-12 shows a polymer SCOS before and after it is placed inside sealed Teflon tubing. The transparent tubing allows the SCOS orientation to be visible.

Figure 3-12: An AJL8/APC polymer SCOS compared with 1/4 watt resistor (Top). The same SCOS is placed in protective Teflon tubing for protection and durability (Bottom).

Packaging can also provide a convenient way to designate SCOS orientation. Figure 3-13 shows a KTP SCOS mounted onto a glass slide with a low index epoxy. The slide mounted sensor is oriented so that the field-sensitive optic axis of the slab waveguide is normal to the face of the slide. The low index epoxy provides a protective cladding layer over the etched portion of the D-fiber not coupled with the slab waveguide.
Figure 3-13: A KTP SCOS is glued to a glass slide with its EO axis oriented normal to the face of the slide.

Fusion splicing has been developed as the most common technique for integrating a D-fiber device with a fiber system utilizing other types of fibers. The D-fiber fusion splicing process ensures a relatively low insertion loss and helps keep the polarization maintaining properties of the D-fiber [44]. Using an in-situ fusion splicing process, the SCOS output can be monitored to minimize both optical losses and cross-talk between polarization modes.

3.6 Summary

The highlight of the fabrication process is the high yield output of fabricated devices. Through in-situ etching, the D-fiber can be prepared with an ideal amount of coupling strength for SCOS devices. Furthermore, in-situ slab placement allows knowledge of the final SCOS transmission during the fabrication process and guarantees a successful device so long as an appropriate slab waveguide is used.
At a system level view, a tunable laser is tuned to a mid-resonance wavelength of the SCOS transmission. The transmitted power from the SCOS is received by an optical receiver to convert it into an electrical signal which is then read by a spectrum analyzer (or oscilloscope) in order to discern the frequency content and signal strength of electric fields incident on the SCOS. Figure 4-1 shows the system level view of the detection setup and includes a diagram of the SCOS transmission at a mid-resonance wavelength.

Figure 4-1: SCOS measurement setup system (Top). Diagram of SCOS transmission function (Bottom).
4.1 SCOS signal analysis

The signal received by the optical receiver is governed by the transmission function of the SCOS device, illustrated in Figure 4-1, and given by,

\[ T = T_0 + \Delta T. \]  

(4-1)

\( T_0 \) relates to the portion of the transmitted signal acting as the bias point, or d.c. component and \( \Delta T \) represents the EO signal at that bias point given by

\[ \Delta T = \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E, \]  

(4-2)

where the first term in parentheses is the slope of the transmission function and the second term in parentheses represents the spectral shift of the mode resonance due to the electric field, \( E \). In full, the transmission function of the SCOS becomes,

\[ T = T_0 + \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E. \]  

(4-3)

With a bias power of \( P_0 \), the transmitted power from the SCOS at a biased wavelength into the optical receiver is

\[ P_{in} = P_0 T_0 + P_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E, \]  

(4-4)

and the signal portion of the output at the optical receiver, \( P_s \), becomes
showing that the signal power increases linearly by three factors: (1) the optical input power, (2) the slope of the SCOS resonance at the bias point and (3) the spectral shift of the mode resonance due to $E$. In demonstration of the first factor, Figure 4-2 shows data taken from a SCOS probed at a fixed wavelength as the optical power is varied from a tunable laser source.

\[
   P_s = P_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E, \tag{4-5}
\]

As expected, the signal strength from the SCOS increases linearly with the optical power. The remaining two factors that increase the signal strength are directly related to the SCOS fabrication and a detailed analysis on how to optimize these factors is addressed in Chapter 6. Assuming that a SCOS has a fixed resonant slope and a constant rate of spectral shift from

![Figure 4-2: FFT signal of SCOS electric field sensor as a function of transmitted optical power. The data points (circles) are mapped against a linear fit (solid line) showing that performance is linear ($R^2=0.9995$) with optical power and that device sensitivity increases with higher optical power.](image)
electric fields, the remainder of this chapter focuses on determining the minimum detectable electric field for a SCOS as the input optical power is allowed to vary.

### 4.2 Improving SNR

When measuring small signals the limitations on measurement are given by competing noise signals. The two sources of noise at the optical receiver are the thermal noise, $I_{th}^2$, and shot noise, $I_{shot}^2$.

The thermal noise is given by

$$I_{th}^2 = \frac{4k_B T}{R_L} F_n \Delta f,$$  \hspace{1cm} (4-6)

and by substituting the noise equivalent power,

$$NEP = \sqrt{\frac{4k_B T F_n}{R_L R^2}},$$  \hspace{1cm} (4-7)

we arrive at

$$I_{th}^2 = (R \ NEP)^2 \Delta f.$$  \hspace{1cm} (4-8)

In these equations $k_B$ is Boltzmann’s constant, $T$ is the absolute temperature, $R_L$ is the load resistor, $F_n$ is the amplifier noise figure, $R$ is the responsivity of the detector, $\Delta f$ is the effective noise bandwidth of the receiver and $NEP$ is noise equivalent power.
The shot noise is given by

\[ I_{\text{shot}}^2 = 2qRP_{\text{in}} \Delta f, \]

\[ = 2qRP_0 T_0 \Delta f, \]  \hspace{1cm} (4-9)

where \( q \) is the charge of an electron. The corresponding SNR of the signal from the optical receiver becomes

\[
SNR = \frac{I_s^2}{I_{\text{shot}}^2 + I_{\text{th}}^2},
\]

\[
= \frac{(RP_s)^2}{[2qRP_0 T_0 + (R \text{ NEP})^2] \Delta f},
\]

\[
= \frac{\left[ P_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E \right]^2}{\left[ \frac{2qP_0 T_0}{R} + (\text{NEP})^2 \right] \Delta f}.
\]  \hspace{1cm} (4-10)

4.2.1 Thermal noise limit

If the noise signal from the system is dominated by thermal noise, the SNR reduces to,

\[
SNR_{\text{th}} = \frac{\left[ P_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E \right]^2}{(\text{NEP})^2 \Delta f},
\]  \hspace{1cm} (4-11)

which increases quadratically with input power \( P_0 \).
"4.2.2 Shot noise limit

With enough optical power, the system becomes shot noise limited and the SNR becomes

\[ SNR_{shot} = \frac{(RP_0) \left[ \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E \right]^2}{2qT_0\Delta f}. \] (4-12)

Equation (4-12) indicates that while shot noise limited we can continue increasing the SNR linearly by increasing input power to the SCOS. In addition, choosing a bias wavelength that minimizes \( T_0 \) while maintaining sufficient coupling slope \( \frac{\Delta T}{\Delta \lambda} \) will also increase the SNR while shot noise limited.

Figure 4-3 shows a LiTaO\(_3\) SCOS resonance used to collect data for comparing the SNR for varying levels of \( T_0 \) in the presence of an E-field with an amplitude of 7kV/m and a frequency of 40 MHz. The SCOS resonance was probed at the wavelengths shown in the top plot of Figure 4-4 while the input power was adjusted through an Erbium Doped Fiber Amplifier (EDFA) to maintain a constant level of received power from the SCOS.

The bottom plot of Figure 4-4 shows the SNR of the received signal as a constant power level of 20 \( \mu \)W was maintained for each reading. The SNR is measured with a 3 dB confidence level and shows that the SNR increases with a decreasing \( T_0 \). However, as the resonant slope begins to decrease at the bottom of the SCOS resonance, the SNR no longer improves with a lower \( T_0 \). It is important to note that while the SNR improves linearly with a decreasing \( T_0 \) it improves with the square of the resonant slope.
Figure 4-3: Transmission spectrum of LiTaO$_3$ SCOS.

Figure 4-4: LiTaO$_3$ SCOS transmission, $T_\theta$, versus wavelength (Top). SNR for $T_\theta$ of LiTaO$_3$ SCOS (Bottom).
4.3 Minimum detectable field

With knowledge of how to maximize the SNR, the next step is to determine the minimum detectable electric field, $E_{\text{min}}$. The ultimate sensitivity of a SCOS device is given by the electric field that gives $\text{SNR}=1$, signifying that the signal from the SCOS is equal to the noise level at the optical receiver.

\[
1 = \left[ \frac{P_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right) E_{\text{min}}}{2qP_0T_0 \frac{\Delta f}{R} + (\text{NEP})^2} \right]^2.
\] (4-13)

Solving for $E_{\text{min}}$ in the thermal noise limit,

\[
E_{\text{min,th}} = \frac{\text{NEP}\sqrt{\Delta f}}{P_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right)}.
\] (4-14)

Equation (4-12) shows that SCOS sensitivity improves linearly with $P_0$ while monitoring the minimum detectable electric field in the thermal noise limit. Similarly, solving for $E_{\text{min}}$ in the shot noise limit gives,

\[
E_{\text{min,shot}} = \frac{\sqrt{2qT_0\Delta f}}{\sqrt{RP_0 \left( \frac{\Delta T}{\Delta \lambda} \right) \left( \frac{\Delta \lambda}{E} \right)}}.
\] (4-15)

Equation (4-15) shows that in the shot noise limit SCOS sensitivity improves with the square root of $P_0$ as $P_0$ increases and it also improves with the square root of $T_0$ as $T_0$ decreases.
4.4 Summary

While the SNR of a SCOS signal improves quadratically with $P_0$ when thermal noise limited and linearly with $P_0$ and $T_0$ when shot noise limited, the minimum detectable field, $E_{\text{min}}$, scales differently. Instead, $E_{\text{min}}$ improves linearly with $P_0$ when thermal noise limited and by the square root of $P_0$ when shot noise limited. Likewise, $E_{\text{min}}$ improves by the square root of a reducing $T_0$ so long as the wavelength of SCOS operation remains in a linear portion of the resonant slope. For additional improvements in SCOS sensitivity, Chapter 6 addresses how to increase the resonant slope ($\Delta T / \Delta \lambda$) and spectral shift ($\Delta \lambda / E$) of SCOS resonances and Chapter 0 addresses how to further maximize SCOS transmission by reducing optical losses.
5 ELECTRO-OPTIC SLAB WAVEGUIDES

The electro-optic slab waveguide is a key component of a SCOS E-field sensor and acts as the transducer for the electric fields. This chapter analyzes the key features of EO slab waveguides used in fabricating SCOS. Crystals and polymers are typically used as EO materials due to their ability to exhibit linear EO dependence.

5.1 The linear electro-optic effect

The linear electro-optic effect was first discovered in 1893 by Friedrich Carl Alwin Pockels (1865 – 1913). As a result it is often referred to as the Pockel’s effect and the material coefficients describing its strength are often referred to as Pockel’s coefficients. Pockels noticed that by applying an electric field to a birefringent material, it changed the refractive indices of the material in proportion to the strength of the applied electric field.

The linear electro-optic effect is a second order non-linear optical process which requires that the electro-optic material exhibit non-centro-symmetry, or long range order. Because the non-linear electro-optic effect requires non-centro-symmetry, it is often found in crystals such as lithium niobate (LiNbO$_3$) where the crystalline structure provides long range symmetry and the non-centro symmetric structure succumbs to asymmetric deformation under electric-field induced stresses on the molecular structure. Other crystals and materials such as polymers exhibit non-centro symmetry and likewise produce significant electro-optic response. Many
crystals have significant Pockel’s coefficients and birefringent properties. In polymers, the alignment of chromophores with large hyperpolarizabilities can produce electro-optic coefficients in the 100 pm/V range, about three times greater than found in LinbO$_3$. This alignment is induced by heating the host polymer to its glass transition temperature and applying a large electric field in order to orient the chromophores along the direction of the field. Chromophore alignment is retained by reducing the temperature of the host polymer under the continued electric field.

The electric field dependent bulk index of refraction of an electro-optic material can be expressed as

\[ n(E) = n + a_1 E + a_2 E^2 + \ldots. \] (5-1)

However, it is more common to use the impermeability of the material

\[ \eta(E) = \eta_0 + r E + s E^2 + \ldots, \] (5-2)

where \( \eta = \frac{1}{n^2} \), \( r \) are the Pockels coefficients of the linear electro-optic effect and \( s \) are the Kerr coefficients for the quadratic electro-optic effect. In most cases \( rE \gg sE^2 \) and all other higher order terms. The first term is called the linear electro-optic effect. With only the linear electro-optic effect being considered the impermeability can be expressed in matrix form as

\[
\begin{bmatrix}
\Delta \eta_1 \\
\Delta \eta_2 \\
\Delta \eta_3 \\
\Delta \eta_4 \\
\Delta \eta_5 \\
\Delta \eta_6 \\
\end{bmatrix} =
\begin{bmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33} \\
r_{41} & r_{42} & r_{43} \\
r_{51} & r_{52} & r_{53} \\
r_{61} & r_{62} & r_{63} \\
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y \\
E_z \\
\end{bmatrix}.
\] (5-3)
5.2 Electro-optic polymers

For some time there has been great interest in electro-optic (EO) polymers due to their high electro-optic coefficients, relatively low cost, low material dispersion, and straightforward processing [45]. EO polymers also exhibit minimal phase mismatch between microwave signals and optical signals, allowing for EO modulation/detection at frequencies in the terahertz regime [46].

In general EO polymers are classified as a guest-host system. The host polymer offers the main structure of the material while guest chromophores induce the electro-optic sensitivity [47, 48]. Before the polymer can exhibit EO qualities, it must first be poled such that the polarized chromophore molecules distributed within the host polymer matrix are aligned to form an EO axis. Once the chromophores are aligned, the presence of an electric field causes the chromophores to produce a directional stress on the host polymer, changing its optical properties. Without chromophore alignment, random orientation cannot produce an EO effect.

5.2.1 AJL8/APC

The preferred EO guest/host polymer used in this work is AJL8/amorphous polycarbonate (AJL8/APC) [49]. While DR1/PMMA is commonly used as an EO polymer because it is inexpensive, DR1 yields a relatively weak Pockel’s coefficient around 4 pm/V. Furthermore, the relatively soft host, PMMA, allows chromophore orientation to relax over time due to its low glass transition temperature ($T_g=100^\circ$C). The chromophore AJL8, shown in Figure 5-1, was designed and synthesized at the University of Washington for its high hyperpolarizability allowing it to obtain large EO coefficients on the order of ~100 pm/V.
Owing to the high glass transition temperature of APC \((T_g=140^\circ\text{C})\), the guest/host system AJL8/APC shows temporal stability when heated to 85°C for over 500 hours. Various devices have already been fabricated using AJL8/APC including ring resonators and Mach-Zehnder modulators [50, 51].

![Molecular structure of AJL8](image)

**Figure 5-1: Illustration of the molecular structure for AJL8**

### 5.2.2 EO polymer slab fabrication

AJL8/APC polymer slabs are fabricated by first mixing the guest/host polymer in a 20/80 wt% ratio with a compatible organic solvent. The liquid polymer solution is then spin coated on a smooth planar surface. For the uncommonly thick polymer slabs used for SCOS devices (30 – 70 \(\mu\text{m}\)), a hot embossing technique was developed at the University of Washington using heat and pressure to melt multiple thin layers of polymer into one thick layer with uniform properties and good parallelism. Poling is accomplished by sandwiching the film between two electrodes
in a nitrogen environment as they are heated to the glass transition temperature of the APC and a large electric field is applied (~100 MV/m) for about 5 minutes [49].

After poling, the EO guest/host polymer’s electro-optic tensor takes on the form [52]

$$r = \begin{bmatrix}
0 & 0 & r_{13} \\
0 & 0 & r_{13} \\
0 & 0 & r_{33} \\
r_{13} & 0 & 0 \\
r_{13} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix},$$  
(5-4)

where the $\hat{z}$ direction is the assumed EO axis of the polymer (direction of poling). In general, if the applied electric field is in the $\hat{z}$ direction (poled axis of polymer), the index ellipsoid becomes

$$\left(\frac{1}{n_0^2} + r_{13}E_z\right)x^2 + \left(\frac{1}{n_0^2} + r_{13}E_z\right)y^2 + \left(\frac{1}{n_0^2} + r_{33}E_z\right)z^2 = 1,$$  
(5-5)

where

$$\left(\frac{1}{n_0^2} + r_{13}E_z\right)x^2 = \frac{1}{n_x^2},$$
$$\left(\frac{1}{n_0^2} + r_{13}E_z\right)y^2 = \frac{1}{n_y^2},$$  
(5-6)

$$\left(\frac{1}{n_0^2} + r_{33}E_z\right)z^2 = \frac{1}{n_z^2},$$

and

$$\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} = 1.$$  
(5-7)
The material indices under the presence of a \( \hat{z} \) oriented electric field become,

\[
\begin{align*}
    n_x &= n_o - \frac{1}{2} n_o^3 r_{13} E_z, \\
    n_y &= n_o - \frac{1}{2} n_o^3 r_{13} E_z, \\
    n_z &= n_o - \frac{1}{2} n_o^3 r_{33} E_z,
\end{align*}
\]  

and the index of the EO polymer responds linearly with an applied electric field in proportion with the Pockels coefficients.

The benefits of EO polymer slabs include the variability of index and slab thickness in the fabrication process, high EO coefficients and the relatively low dielectric constant. Drawbacks for polymers include thermal expansion, thermo-optic dependence and the restriction on the direction of the EO axis from the limitation of poling normal to the surface of the polymer.

5.3 EO crystals

The EO properties of crystals are owed to a non-uniform redistribution of charges within the crystal lattice under an applied electric field. This non-uniform charge redistribution incurs slight deformations in the crystal lattice structure which results in alterations to the dielectric tensor. Several commercially available crystals exhibit EO properties that can be used in the fabrication of SCOS devices. The crystals used in this work include lithium niobate (\( \text{LiNbO}_3 \)), lithium tantalite (\( \text{LiTaO}_3 \)) and potassium titanyl phosphate (KTP).
Both LiNbO$_3$ and LiTaO$_3$ have trigonal 3m symmetry [53] with the EO tensor,

$$
\mathbf{r} = \begin{bmatrix}
0 & -r_{22} & r_{13} \\
0 & r_{22} & r_{13} \\
0 & 0 & r_{33} \\
0 & r_{51} & 0 \\
r_{51} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}, 
$$

(5-9)

while KTP has an orthorhombic 2mm symmetry [54] with EO tensor,

$$
\mathbf{r} = \begin{bmatrix}
0 & 0 & r_{13} \\
0 & 0 & r_{23} \\
0 & 0 & r_{33} \\
0 & r_{42} & 0 \\
r_{51} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}, 
$$

(5-10)

In the case of these EO crystals, the change in indices from a \( \hat{x} \) directed E-field will yield similar results as with EO polymers but with their own respective Pockels coefficients and optical indices. Typically, only the EO response from \( \hat{x} \) directed E-fields are considered for SCOS, however the development of multi-axial E-field sensing does require knowledge of the EO behavior from cross fields which can cause axial rotations of the dielectric tensor due to off-axis terms such as \( r_{42} \) and \( r_{51} \) [53]. Section 9.3 includes an analysis on the use of KTP in multi-axial sensing.

Crystals are purchased from the manufacturer with the desired thickness, crystal orientation and polish quality. The benefits of using crystals for the EO slab waveguide include a lower coefficient of thermal expansion compared with polymers as well as a lower thermo-optic coefficient. Additionally, crystals can be cut to any desired orientation to allow a SCOS to measure electric fields oriented other than perpendicular to the face of the slab. With this
freedom, it becomes possible to monitor several electric field orientations with the use of multiple crystals having their EO axes orthogonal to each other. Appendix B lists the properties of the EO materials considered and used in this work.

5.4 Considerations for anisotropic waveguides

Resonant coupling from the D-fiber to a polymer or crystal slab overlay exhibits polarization dependent behaviors that affect SCOS performance. EO materials in general are anisotropic in nature and knowledge of mode behavior in an anisotropic waveguide is necessary to properly understand the behavior and performance of a SCOS device. In the general case, ordinary and extraordinary modes are coupled in an anisotropic waveguide, leading to the possibility of degenerate modes and or changes in polarization [55-57]. However, pure TE and TM modes can exist within uniaxial and biaxial materials in a decoupled state if the optic axis of the waveguide is either parallel with the electric field of the TE mode or else in the plane of the possible electric field orientations for the TM mode [55]. For both mode types the boundary conditions are satisfied for uncoupled mode propagation.

Without the proper axial alignment, TE and TM modes couple to each other from reflections at boundary interfaces. For simplicity and proper SCOS function, slab waveguides should be chosen so the material axes are aligned with the waveguide axes of the slab and D-fiber. Under these conditions, a SCOS device will work predictably based on the orientation of the EO axis and the input polarization of light.
5.4.1 Polarization analysis for coupled anisotropic waveguides

Figure 5-2 diagrams a SCOS device showing a fiber mode represented as a ray propagating straight down the longitudinal axis of the fiber. The low index contrast of the weakly guiding fiber gives rise to TEM like modes such that polarized light remains orthogonal to the direction of propagation. These TEM modes can be classified as either vertically polarized TM modes (E-field in the plane of the page) or horizontally polarized TE modes (E-field out of page).

![Diagram of the coupling structure for a SCOS device. Ray tracing shows the relationship between the polarization angle of the electric field for TE modes (E-field out of page) and TM modes (E-field in the plane of the page).](image)

In contrast, rays representing modes in the crystal slab waveguide travel at relatively large angles compared to the direction of longitudinal propagation. This is due to the high index contrast of the slab waveguide and the angle of propagation can be approximated by the critical angle for modes close to cutoff (as is the case for the coupled modes in a SCOS device). In the case of LiTaO$_3$ the angle of the phase fronts with respect to the normal of the slab surface for a mode close to cutoff is $\theta_c = \sin^{-1}(1.441/2.1208) = 42.7^\circ$. This disparity between the index
contrast of the D-fiber modes and slab modes infers that the polarization of light launched into the D-fiber will not necessarily align with the crystal axes once coupled into the slab waveguide.

In Figure 5-2 the orientation of the electric field for the horizontally polarized TE mode (E-field coming out of the page) remains unchanged between fiber and slab modes as the angle of propagation changes. For this case, the slab index to which the fiber couples is simply the material index of the slab axis that is parallel with the global y axis of the waveguide. After coupling to the slab waveguide, the vertically polarized TM mode (E-field in the plane of the page) changes the orientation of its electric field to an angle in the xz plane. For TM modes, the bulk slab index, \( n_o \), in the xz plane is given by [58],

\[
    n_o = \frac{n_x n_z}{\sqrt{n_x^2 \sin^2 \theta + n_z^2 \cos^2 \theta}} \tag{5-11}
\]

where \( n_x \) and \( n_z \) are the material slab indices aligned with the global x and z axes of the SCOS waveguide structure and \( \theta \) is the effective propagation angle of the light in the slab waveguide as given by \( \theta = \sin^{-1}(N_f/n_o) \). The slab index seen by vertically polarized TM modes is a mean between the two slab indices and the EO response is likewise a mean between the EO responses of the two axes, \( r_{eff} \), given by,

\[
    r_{eff} = \frac{r_{13} r_{33}}{\sqrt{r_{13}^2 \sin^2 \theta + r_{33}^2 \cos^2 \theta}} \tag{5-12}
\]

where \( r_{13} \) is the EO coefficient corresponding to \( n_x \).

The maximum sensitivity from a SCOS device comes from operating in the TE mode. In this mode of operation, the EO axis of the slab waveguide is transverse (\( y \)-oriented) with the flat of the D-fiber surface. Only in this case is the electric field of the mode parallel with the optic
axis for a complete realization of the EO effect. For a SCOS operated in the TE mode, care must
be taken to ensure accurate orientation of the slab with the D-fiber.

Figure 5-3 shows the transmission spectra of a 2-cut LiTaO$_3$ (optic axis normal to
waveguide) SCOS with both vertically polarized and horizontally polarized light. The full index
profile for LiTaO$_3$ at $\lambda=1550$ nm is $n_x = n_y = 2.1208$ and $n_z = 2.1253$ (the $\hat{z}$ axis is the EO axis of
the crystal). In the top spectrum, the vertically polarized TM mode shows a strong resonance at
1554 nm corresponding with the slab index of the xz-axis of the crystal with $\theta=42.7^\circ$. A
relatively weak resonance from the more confined TE mode at 1552 nm corresponding with the
$\hat{y}$-axis index of the crystal is seen in the lower plot. Light couples more strongly from the TM
mode because it is less confined than the TE mode and overlaps more with the slab waveguide.
Because of the difference in coupling strength between fiber modes, a single SCOS can only
work optimally for either vertically or horizontally polarized light due to the difference in mode overlap and coupling strength for these two polarization modes [59].

5.5 Summary

Principles from this chapter can help determine the best slab material for a particular application. For accurate field measurements, optimum alignment is obtained by using a SCOS in the TM mode and the optic axis normal to the flat surface of the fiber. With this configuration fields are measured normal to the face of the slab waveguide with an accuracy determined by the slab manufacturing process (typically within 0.5% of a degree). Otherwise, in the case of TE mode operation the optic axis orientation is determined by manual placement of the EO axis in the longitudinal/transverse plane of the D-fiber. Because the surface normal serves as a ready reference, both crystals and polymers serve as ready candidates for operation in the TM mode.

When designing a SCOS for maximum sensitivity it should operate in the TE mode with the EO axis of the slab aligned transverse to the fiber (parallel with the horizontal polarization of the TE mode). Otherwise, in TM mode operation the overall EO effect is reduced. Although only crystal slabs can operate in the TE mode, it might be highly desirable to use an EO polymer in the TM mode if it has a much higher $r_{33}$. In addition to the potential for a high $r_{33}$, an additional reason to consider the use of a polymer is the typically lower dielectric constant of polymer slabs. A lower dielectric constant allows a larger presence of the electric field in the slab material than for materials with higher dielectric constant. This concept is discussed in further detail in section 6.6. The following chapter on optimization includes additional detail on slab waveguide parameters that affect SCOS performance.
6 OPTIMIZATION

There are many aspects of the SCOS design that affect its sensitivity. These aspects are covered individually in a modular approach. Afterwards, a panoramic view of each design concept involved in SCOS fabrication indicates which parameters of the SCOS design should be addressed for optimizing sensor performance.

6.1 Equation for signal maximization

The received power, $P_{rec}$, from a SCOS device is given by

$$P_{rec} = P_0 \left( T_o + \frac{\Delta T}{E} E \right),$$

(6-1)

where $P_0$ is the transmission power of the laser, $T_o$ is the transmission coefficient without an applied electric field and $\Delta T$ is the change in the transmission coefficient with an applied electric field causing a shift of $\Delta \lambda$ as diagrammed in Figure 6-1. The received signal essentially consists of the bias power, $P_0 T_o$, and an E-field dependent modulation. Maximizing SCOS sensitivity requires optimizing the change in SCOS transmission via the term, $\Delta T/E$, which is broken up into multiple components.
Figure 6-1: Sample transmission spectrum of a SCOS device.

The two primary components that contribute to the change in transmission coefficient for a given applied electric field are (1) the slope of the edge of the resonance ($\Delta T/\Delta \lambda$), and (2) the shift in the resonant wavelength with applied electric field ($\Delta \lambda/E$). These two terms can be further subdivided into five terms as given by the modular equation used for maximizing the SCOS signal,

$$\frac{\Delta T}{E} = \left(\frac{\Delta T}{\Delta N}\right) \left(\frac{\Delta N}{\Delta \lambda}\right) \left(\frac{\Delta n_o}{E_{slab}}\right) \left(\frac{E_{slab}}{E_{inc}}\right).$$

In Equation (6-2), $(\Delta T / \Delta N)$ gives the effect of the coupling strength between the D-fiber and slab waveguide on the slope of the resonant mode. In general, reducing coupling strength likewise reduces off-resonant coupling and narrows the linewidth of resonant modes for steeper coupling slopes. The second term, $(\Delta N / \Delta \lambda)$, gives the effect of slab index and thickness on the slope of the resonant mode. In essence, dissimilarities between the fiber and slab
waveguide reduce the range of wavelengths that efficient coupling can take place, also allowing for narrower and steeper resonant slopes. The linewidth of the resonant mode can be reduced by both the coupling parameters between the D-fiber and slab waveguide and by the properties of the slab waveguide itself in order to achieve resonances with steeper slopes.

The third term of Equation (6-2), \( \Delta \lambda / \Delta n_o \), is solely a function of the slab waveguide properties and tells how much of a spectral shift is expected for changes in the slab index. The fourth term in Equation (6-2) is the change in the refractive index of the EO slab from an applied electric field and relies both on the slab index and the electro-optic coefficient. The final term in Equation (6-2) indicates the strength of the E-field in the slab in relation to the incident field and depends on the shape and dielectric properties of the material.

Overall, maximizing \( \Delta T \) from SCOS transmission requires knowledge of and control over the necessary design parameters in the fabrication process including the properties of the slab waveguide and the coupling parameters between the D-fiber and slab waveguide. This chapter will analyze elements of the design and fabrication process that affect these parameters beginning with coupling properties and leading to slab properties. In addition, considerations are made into the method for extracting the signal, \( \Delta T \), from the SCOS transmission for additional improvements in the general sensitivity.

6.2 Coupling strength

At resonance, the coupling strength between the fiber and slab waveguide is one of the key parameters in obtaining a narrow linewidth. In the analysis by Hamilton [6], sharper resonances were modeled with waveguides having lower loss and the appropriate coupling
strength to match the coupling length ($\kappa L = \pi/2$). In this analysis an additional step is taken to observe how the relationship between $\kappa$ and $L$ affects the resonant slope. For simplification, this analysis begins by considering coupling between lossless parallel waveguides in order to illustrate this effect. It is assumed that optical power is launched into an initial waveguide (analogous to the D-fiber) and evanescently coupled into an external waveguide (analogous to the slab waveguide in the SCOS). For parallel waveguide directional couplers, the maximum power transfer, $T$, of the initial waveguide has the relationship given by [60]

$$T = 1 - \frac{\kappa^2}{\kappa^2 + \Delta\beta^2/4},$$  \hspace{1cm} (6-3)

where the coupling coefficient, $\kappa$, is assumed to be identical between both waveguides and $\Delta\beta = \Delta N k_0 = (N_{eo} - N_f)k_0$ is the difference in propagation constants, $k_0 = 2\pi/\lambda$ is the wavenumber of free space, and $N_{eo}$ and $N_f$ are respectively the effective indices of the modes in the EO slab and the D-fiber. The difference between mode indices, $\Delta N = (N_{eo} - N_f)$, is specified at each wavelength, $\lambda$, according to the difference in waveguide dispersion and $\Delta N = 0$ at the resonant wavelength where mode indices are matched. Because the fiber mode index is relatively constant across the typically narrow range of wavelengths in interest, $\Delta N$ is dominated by slab waveguide dispersion. For mathematical simplicity, $\Delta N$ will be treated as the index of the slab mode relative to the index at resonant wavelength.

In accordance with Equation (6-3), Figure 6-2 illustrates the effect of coupling strength on resonant width and resonant slope for two coupling strengths. Although high mode extinction is possible at the resonant wavelength for both coupling strengths, steeper resonant slopes come from weaker coupling coefficients where off resonant coupling is lower.
In relation to the SCOS transmission, $\Delta N = 0$ at a mode resonance where the mode indices of the fiber and slab waveguide match and $\Delta N$ increases for wavelengths further from resonance due to waveguide asymmetry and modal dispersion. The curves in Figure 6-2 indicate that as $\Delta N$ increases in magnitude with off-resonant wavelength for a SCOS device, weaker coupling between the D-fiber and slab waveguide will give narrower resonances and steeper resonant slopes for higher SCOS sensitivity.

In this analysis the coupling slope is found by taking the derivative of Equation (6-3) with respect to $N$,

$$
\frac{\partial T}{\partial N} = \frac{\partial}{\partial N} \left( 1 - \frac{\kappa^2}{\kappa^2 + \Delta \beta^2 / 4} \right),
$$

(6-4)
By continuing the derivation and assuming a linear slope in the region of interest the desired expression becomes,

\[ \frac{\Delta T}{\Delta N} = \frac{2\kappa \left( \frac{\pi}{\lambda} \right)^2 \Delta N}{\left[ \kappa^2 + \left( \frac{\pi}{\lambda} \right)^2 \Delta N^2 \right]^2}, \tag{6-6} \]

having the form needed for Equation (6-2) and showing dependency on the coupling coefficient, \( \kappa \).

Figure 6-3 compares the coupling slope between two waveguides with coupling coefficients, \( \kappa = 100 \) and \( \kappa = 1000 \) respectively. For completeness, the \( \Delta N \) vs. \( \lambda \) relationship from a 1.999 \( \mu \)m thick LiNbO\(_3\) SCOS (shown in Figure 6-9) is used in these plots. The top plot of Figure 6-3 shows a maximum slope many times greater for a coupling coefficient of \( \kappa = 100 \) compared with \( \kappa = 1000 \) for the lower plot.

The maximum value of \( \Delta T/\Delta N \) is calculated from Equation (6-6) to give

\[ \left( \frac{\Delta T}{\Delta N} \right)_{\text{max}} = \frac{8}{9 \sqrt{2}} \left( \frac{\pi}{\lambda} \right) \left( \frac{1}{\kappa} \right). \tag{6-7} \]

In order to better visualize the effect of the coupling strength, the maximum coupling slope was determined for a wide range of coupling coefficients. The trend is depicted in Figure 6-4 showing a large increase in the maximum coupling slope for smaller coupling coefficients.
This data suggests that SCOS sensitivity is improved by utilizing weak coupling between the D-fiber and slab waveguide.

Figure 6-3: Coupling slope for resonances of two different coupling strengths and full resonant transfer.

Figure 6-4: Maximum coupling slope versus coupling coefficient strength, $\kappa$. 

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Applied to the fabrication process, weaker coupling requires increased waveguide separation. As two coupled waveguides are placed further apart, the field overlap between the waveguides decreases and the coupling strength is reduced. The coupling length required for maximum power transfer, $L_c$, is given by [60]

$$L_c = \frac{\pi}{2\kappa},$$  (6-8)

therefore a larger separation between waveguides decreases the coupling coefficient but requires a longer interaction length for full power transfer. Luckily, the SCOS fabrication method gives precise control in separately obtaining both a uniform separation between fiber core and waveguide overlay and a desired coupling length. In the case of SPF devices, the curvature of the fiber places limits on the coupling strength and coupling length.

### 6.2.1 Effects of coupling loss

As a limitation in the design process, it is necessary to assume the degree of optical losses in the second waveguide when modeling a SCOS device. These losses typically arise as the slab waveguide disperses a portion of light laterally away from the region of the fiber core. Additional losses can include absorption and scattering depending on the material and finish quality of the waveguide surfaces. As a result of these losses, the mode resonances widen in relation to the strength of the loss as shown by Hamilton. In addition to widening the resonant mode, these losses also restrict how weak the coupling strength can be between the D-fiber and slab waveguide. In general, the coupling coefficient should be comparable to the strength of the loss coefficient.
The design process for a SCOS partially depends on the degree of optical losses in the slab waveguide which can be separated into two regimes. In the low-loss regime, coupling length is critical for obtaining mode resonance with good extinction. If coupling length is shorter, not enough power is built up in the slab waveguide and if coupling length is longer, power couples back into the fiber. However, with a high loss waveguide, good mode extinction can be obtained with a wide range of coupling lengths because the majority of power coupled into the slab is lost and cannot return to the fiber. Figure 6-5 shows the minimum transmission power at resonance for a LiNbO$_3$ SCOS modeled with loss coefficient, $\alpha = 500$ (dashed line) and $\alpha = 5000$ (solid line), in relation to the length of coupling between the D-fiber and slab waveguide. The coupling strengths, $\kappa = 1725$ and $\kappa = 3450$ respectively, are chosen to set the first resonance at a coupling length of 1 mm.

![Figure 6-5](image_url)

Figure 6-5: Minimum SCOS transmission at resonance versus coupling length for different loss coefficients.
For a low loss SCOS ($\alpha=500 \text{ m}^{-1}$), mode extinction in excess of 20 dB (demarcated by the dotted line) occurs with a coupling length in a range of ~.15 mm centered about 1 mm. Mode extinction in excess of 20 dB for the high-loss SCOS will occur for any coupling length above ~0.8 mm. Figure 6-6 shows a comparison between the simulated resonances for a low-loss and a high-loss LiNbO$_3$ slab SCOS with coupling length chosen so that both have 20 dB mode extinction. The low-loss slab with weaker coupling and longer interaction length has a much sharper mode resonance than the high-loss slab with the same mode extinction.

![Simulated resonances for high-loss and low-loss LiNbO$_3$ SCOS.](image)

While the high-loss slab gives freedom in choosing coupling length for obtaining high mode extinction, excessive coupling length incurs higher overall loss while further increasing the mode linewidth and decreasing the resonant slope. Figure 6-7 shows simulated mode resonances for the high-loss LiNbO$_3$ slab for coupling lengths of $L_c=0.91 \text{ mm}$ (dashed line) and $L_c=1.50 \text{ mm}$
(solid line), both having 30 dB extinction. The SCOS with the same coupling strength but higher incurred losses shows a noticeable decrease in slope along the mode resonance.

![Figure 6-7: Simulated resonances for high-loss LiNbO₃ SCOS with same coupling and loss coefficients but different coupling lengths.](image)

In general, SCOS devices have narrower, steeper resonances with weaker coupling and lower losses. Depending on the application and the slab waveguide used, knowledge of the approximate loss figure in the slab waveguide aids the choice of design parameters for an ideal SCOS device. High loss slabs simply require a coupling length above a minimum value in order to obtain high extinction. Low loss slabs require considerations for obtaining the proper coupling length for high mode extinction but are highly desirable for obtaining higher sensitivity devices. This need is especially important when multiplexing several SCOS devices on a single fiber where overall loss becomes a concern and the finesse limits the number of unique devices that fit within a usable transmission spectrum.
6.3 EO slab waveguide dispersion ($\Delta N/\Delta \lambda$)

In a highly asymmetric waveguide coupler, such as the case with SCOS, the dispersion ($\Delta N/\Delta \lambda$) is dramatically different between the two coupled waveguides. Since the mode indices of the waveguides need to be matched for resonant coupling, the dispersion differential causes the resonance to be highly wavelength sensitive. This mismatch in waveguide dispersion is the basis for SCOS operation. A larger difference in the dispersion between the two waveguides will cause the resonance to be steeper and thus the SCOS will be more sensitive. For illustration, Figure 6-8 shows the numerically calculated mode index vs. wavelength of the first several modes in a 522 nm thick LiNbO$_3$ slab waveguide with index contrast, $n = 1.44 - 2.15$. After cutoff, the index of each slab mode begins in the index range of the D-fiber (demarcated by the dashed horizontal lines). However, the rate of slab dispersion shows the mode indices quickly increasing beyond the range of the fiber mode as the wavelength decreases. Though asymptotic, subsequently higher order modes show even larger dispersion rates.

The mode index of the D-fiber is fixed for all SCOS and calculated using BEAMPROP to be $N_f=1.451$ at 1555 nm and its dispersion $\Delta N_f/\Delta \lambda=1.25x10^4$ nm$^{-1}$ (the dispersion in the D-fiber mode is often insignificant compared to that of the multimode slab waveguide and thereby neglected). However, the dispersion of the slab waveguide varies with both index and thickness and is determined by calculating the mode index as a function of wavelength as shown in Figure 6-8. After finding the mode indices, the dispersion is calculated by determining its slope at 1550 nm.
6.3.1 Optimizing slab waveguide thickness

Dispersion versus slab thickness is studied for a SCOS waveguide of a set index. This analysis assumes use of a LiNbO$_3$ crystal with an index of $n=2.15$ having a cladding layer matched to the index of the D-fiber ($n=1.441$). Slab thicknesses are chosen such that we can observe a mode resonance at 1555 nm. Figure 6-9 shows the comparison of mode index curves for modes 1 and 4 in a LiNbO$_3$ SCOS of appropriate thickness. The solid lines depict mode indices for slab modes while the dashed line depicts the D-fiber mode. The intersection of mode indices indicates the resonant wavelength for the SCOS. While the first slab mode has a dispersion of $\Delta N_{eo}/\Delta \lambda = 1.7 \times 10^5$ nm$^{-1}$, the fourth mode has a dispersion of $\Delta N_{eo}/\Delta \lambda = 4.5 \times 10^5$ nm$^{-1}$ in comparison with the fiber dispersion of $\Delta N_f/\Delta \lambda = 1.25 \times 10^4$ nm$^{-1}$. Based on these slopes, the fourth mode is roughly three times more selective than the first mode of the LiNbO$_3$ SCOS.
Figure 6-9: Mode index versus wavelength comparison for modes one and four of LiNbO₃ SCOS.

To extend an understanding of the thickness versus dispersion trend, the curves in Figure 6-10 show that dispersion continues to increase with waveguide thickness for multiple slab indices, including LiNbO₃. This data highlights the asymptotic increase of the slab dispersion with higher order modes as mentioned with regards to Figure 6-8. For all indices shown, a large change in dispersion exists for waveguides between 0.5 μm and 20 μm thick; however, the rate at which the dispersion increases saturates at about 20 μm. Although this slope continually increases with waveguide thickness, the asymptotic nature reduces the efficacy of increasing waveguide thickness [9].

Crystal slab waveguides are readily and commercially available in larger thicknesses seeing how they are typically grown in a boule and then sliced and polished to the desired thickness. Polymer slab waveguides however are typically spin coated which yields relatively thin waveguides. Thicker polymer waveguides require special processing considerations in order to maintain thickness uniformity.
6.3.2 Optimizing slab waveguide index

As expected, higher slab indices also increase waveguide dispersion as is evident in Figure 6-10 [61]. In order to more completely analyze the dispersion relation to slab index, Figure 6-11 shows the dispersion at 1555 nm for 100 μm thick waveguides ranging in index from $n=1.475$ to $n=2.5$. The data follows a quadratic fit for indices above the fiber mode index,

$$\frac{\Delta N_{eo}}{\Delta \lambda} = 4.3 \times 10^5 \ n^2 + 915n - 9.07 \times 10^5.$$  

(6-9)

In designing a SCOS sensor, even though the efficacy of selecting an arbitrarily thick slab waveguide is limited asymptotically, this analysis shows that larger index waveguides do not hold similar limitations. However, practicality does limit the index of slab waveguides to those available in commercial materials such as crystals and polymers. Nevertheless, this
analysis suggests wisdom in choosing thicker, higher index waveguides in order to improve the resonant mode slope of SCOS devices.

6.4 Mode shifting

The second term of Equation (6-2), $(\Delta \lambda / \Delta n_o)$, tells how much spectral shift is expected as the index of the slab waveguide changes. Spectral shift with index change is the underlying principle of how SCOS sensors measure environmental variables. When an external force, such as an electric field, alters the optical index of the slab waveguide in a SCOS device, the coupling properties between the fiber and slab are slightly altered. This effect is seen in the transmission spectrum as a resonant shift. On the large scale this is a non-linear effect. However, the slab index changes are quite small, allowing a linear approximation with excellent agreement.
6.4.1 Mode shift vs. slab index

To analyze the shift in transmission spectrum with index, we perform the following derivative,

\[
\frac{\partial \lambda_m}{\partial n_o} \left( \frac{2t}{m} \sqrt{n_o^2 - N_f^2} \right) = \frac{2t/m}{\sqrt{n_o^2 - N_f^2}} n_o.
\]

(6-10)

Then if we make the following substitution,

\[
\frac{2t}{m} = \frac{\lambda_m}{\sqrt{n_o^2 - N_f^2}},
\]

(6-11)

we arrive at,

\[
\frac{\partial \lambda}{\partial n} = \frac{\lambda_o n_o}{n_o^2 - N_f^2},
\]

(6-12)

where \( \lambda_o \) has been substituted for \( \lambda_m \) to reflect that the resulting expression is irrespective of the mode number. Because of the limited range for index changes, we can substitute \( \partial \lambda/\partial n \) with \( \Delta \lambda/\Delta n \) for the final result,

\[
\frac{\Delta \lambda}{\Delta n} = \frac{\lambda_o n_o}{n_o^2 - N_f^2}.
\]

(6-13)

Figure 6-12: Wavelength shift of resonant mode versus bulk index. shows the values of \( \Delta \lambda/\Delta n \) for a SCOS with \( N_f = 1.451 \). As expected, \( \Delta \lambda/\Delta n \) grows asymptotically to an infinite value as \( n_0 \) approaches \( N_f \), suggesting larger wavelength shifts for slab waveguides with indices
close to the fiber mode index. While this is indeed the case, our analysis breaks down as the waveguide index approaches the index of the fiber mode which would cause full coupling across a wide range of wavelengths and give a transmission spectrum lacking useful features in the band of a tunable laser.

![Graph showing wavelength shift of resonant mode versus bulk index.](image)

**Figure 6-12:** Wavelength shift of resonant mode versus bulk index.

6.5 The linear electro-optic effect

The third term in Equation (6-2) is the change in the refractive index of the EO slab with an applied electric field. The dominant behavior in electro-optic crystals for the optical power levels used in SCOS devices is the Pockel’s effect, or the linear electro-optic effect. The effective EO coefficient, \( r_{\text{eff}} \), (as discussed in section 5.4.1) is used for this analysis. The electro-optic effect gives an overall index change of
\[ \Delta n_0 = \frac{1}{2} n_0^2 r_{eff} E, \]

where \( E \) is the electric field and \( n_0 \) is the index of the EO axis. Irrespective of the EO coefficient, the crystal index change scales cubically with increasing index, suggesting that crystals with higher index will incur a larger wavelength shift in the SCOS spectrum. The electro-optic effect is displayed in Figure 6-13 for an index range of \( n=1.6-2.5 \), to reflect the common index range found in electro-optic materials such as crystals and polymers. The values for the EO effect in this figure are normalized by \( (r_{eff} E) \) to show deference to the dependency on \( n_0 \).

![Graph showing electro-optic effect versus slab index]

**Figure 6-13: Linear electro-optic effect versus slab index.**

### 6.6 RF permittivity

Another material specific parameter of the slab that affects the sensitivity of SCOS devices is the electric dielectric constant. The dielectric constant is a measure of how much the
individual molecules in a material counteract and resist an external field. When a dielectric is present in an external field, the individual molecules are partially polarized opposite to that field and thereby reduce the total field within the material [62]. For a dielectric material in air, the ratio between the incident electric field and that inside of the EO crystal is calculated primarily by applying boundary conditions resulting in [63].

\[
\frac{E_{slab}}{E_{inc}} = \frac{3\varepsilon_0}{\varepsilon_{slab} + 2\varepsilon_0}.
\]

(6-15)

### 6.7 Optimal design

The analysis of Equation (6-2) for optimizing SCOS performance shows dependencies on coupling conditions, slab thickness, slab index and permittivity. Equation (6-2) can be expanded into its integral parts as,

\[
\frac{\Delta T}{E} = \left( \frac{2\kappa \left( \frac{\pi}{\lambda} \right)^2 \Delta N}{\left[ \kappa^2 + \left( \frac{\pi}{\lambda} \right)^2 \Delta N^2 \right]^2} \right) (4.3 \times 10^5 \ n_o^2 + 915 n_o - 9.07 \times 10^5) \left( \frac{\lambda \ n_o}{n_o^2 - N_f^2} \right) \left( \frac{1}{2} \ n_o^3 r_{eff} \right) \left( \frac{3\varepsilon_0}{\varepsilon_{slab} + 2\varepsilon_0} \right),
\]

(6-16)

which is valid for an index range of \(n=1.475\) to \(n=2.5\) given by the fit for \((\Delta N/\Delta \lambda)\).

In review, the first term is dependent on coupling strength where a stronger SCOS signal favors low loss slab waveguides with weaker coupling and longer interaction length. The second term shows that the resonant slope improves quadratically with index and the reference thickness
is chosen at 100 μm due to the preference for thicker waveguides and commercial availability. The third term shows that mode shifting favors lower indices and the fourth term shows the electro-optic effect increasing cubically with index. Finally, the last term shows that the RF permittivity reduces the internal fields of the slab waveguide giving preference to materials with lower permittivities.

To better understand the role index plays in improving SCOS performance, Figure 6-14 shows the combined effect of the index-dependent terms in Equation (6-16). The thickness is set at 100 μm and the coupling parameters are neglected due to their independence from index. It should be independently assumed that the coupling parameters are optimized for each specific SCOS based on the loss and other parameters of the slab waveguide. Although mode shifting favors lower slab indices, Figure 6-14 shows that SCOS devices favor higher indices for improving device sensitivity.

![Graph](image_url)

**Figure 6-14: Effect of index-dependent terms on SCOS performance.**
The EO materials commonly used for slab waveguides include crystals and polymers. For reference, Table 6-1 lists several EO materials with their associated parameters that affect sensitivity. An overview of the data in Table 6-1 shows the best predicted SCOS performance from the high EO coefficient and low dielectric constant of an AJL8/APC polymer slab waveguide. Specialty polymers in general promise good results with potential for high $r_{33}$ coefficients, low dielectric constants and a variable index (depending on the host polymer and doping chromophore doping level). Considerable research efforts are focused on developing the use of high-performance EO polymers.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Angle, $\theta$</th>
<th>Bulk Index, $n_o$</th>
<th>$r_{eff}(pm/V)$</th>
<th>$\varepsilon_r$</th>
<th>$\Delta N/E_{inc}(V/m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO$_3$</td>
<td>42</td>
<td>2.18</td>
<td>11</td>
<td>30</td>
<td>7.9 x 10$^{-12}$</td>
</tr>
<tr>
<td>LiTaO$_3$</td>
<td>43</td>
<td>2.12</td>
<td>10</td>
<td>43</td>
<td>4.5 x 10$^{-12}$</td>
</tr>
<tr>
<td>KTP</td>
<td>53</td>
<td>1.78</td>
<td>14</td>
<td>13</td>
<td>19 x 10$^{-12}$</td>
</tr>
<tr>
<td>SBN</td>
<td>40</td>
<td>2.30</td>
<td>87</td>
<td>3400</td>
<td>0.7 x 10$^{-12}$</td>
</tr>
<tr>
<td>DAST</td>
<td>43</td>
<td>1.79</td>
<td>28</td>
<td>5.2</td>
<td>40 x 10$^{-12}$</td>
</tr>
<tr>
<td>AJL8/APC</td>
<td>56</td>
<td>1.75</td>
<td>37</td>
<td>4.0</td>
<td>58 x 10$^{-12}$</td>
</tr>
</tbody>
</table>

* Data in this table derived from crystal information contained in Appendix B

Amongst crystalline materials, the DAST crystal is the strongest performer due to its high index, high EO coefficient and relatively low dielectric constant [64]. However, as a relatively newer crystal, the fabrication process still carries limitations that ultimately drive costs quite high for obtaining good quality single crystal samples.
While SBN has a relatively large index and a very large EO coefficient, the magnitude of its dielectric constant reduces its internal fields to levels so low that it is outperformed by every other crystal considered. KTP, LiNbO$_3$ and LiTaO$_3$ are the most commonly available crystalline materials, amongst which KTP is favored for E-field sensing in large part due to its smaller dielectric constant [65].

Because of cost limitations only commonly available crystals (KTP, LiNbO$_3$ and LiTaO$_3$) and AJL8/APC polymer waveguides are used in this work. The future of EO sensing will be greatly enhanced by the continued development of improved EO materials including both high EO performance crystals and polymers.

6.7.1 AJL8/APC SCOS performance

Testing was performed on the AJL8/APC SCOS highlighted in Section 3.4 in order to find its minimum sensitivity to electric fields. Using the signal measurement technique mentioned in Chapter 4, the SCOS was placed between two parallel plate electrodes with a fixed separation and driven by a voltage signal at 10 MHz. With a tunable laser set at 1550 nm, an optical output power of ~100 $\mu$W was received by a detector having a responsivity of $R=0.95$ A/W (Agilent 83434A). The AJL8/APC SCOS was capable of detecting a field strength as low as 15.8 V/m with a spectrum analyzer (HP 8592L) monitoring its signal using a resolution bandwidth of $\Delta f=1$ kHz. A screenshot of the spectrum analyzer reading is shown in Figure 6-15 showing the signal just slightly above the noise.
The theoretical limit for this SCOS is determined by using Equation (4-15) which is given in mathematical simplicity. For convenience, this equation can be restructured for operational use as,

\[ E_{\text{min,shot}} = \frac{\sqrt{2} q P_{\text{out}} \Delta f}{\sqrt{R S_t \left( \frac{\Delta \lambda}{E} \right)}} \]

where \( P_{\text{out}} = P_0 T_0 \) and is the total bias power measured at the output of the SCOS and \( S_t = P_0 (\Delta T / \Delta \lambda) \) which is measured as the transmission slope at the mid-resonance wavelength of the SCOS.

For this SCOS, the transmission slope was measured at \( S_t = 82.3 \ \mu\text{W/nm} \). In addition, the shift with field is obtained from Equations (6-13) and (6-14), recognizing that measurements were performed with no air gap, causing the full field to be present across the polymer slab. Using the data in Table 6-1 the shift with field is calculated as \( (\Delta \lambda / E) = 2.82 \times 10^{-7} \ \text{nm/mV} \) and
$E_{\text{min}}$ is theoretically calculated at 7.9 V/m for this SCOS. Lower levels of sensitivity are expected for this SCOS by using higher optical power or a reduced resolution bandwidth.

### 6.8 EO modulators

The use of SCOS technology for EO modulation is not considered in this work, however its operation is based on similar principles. In the design of a modulator, electrodes to drive an electric field are typically placed on opposing sides of the EO material thereby inducing the full field across the material regardless of dielectric constant. It should be mentioned that while the dielectric constant of the slab waveguide reduces the field measured by SCOS devices, materials with high dielectric constant may still be good candidates for EO modulators. However, care must be taken to ensure phase matching between the electrical signal driving the electric field and the optical fields under modulation. As a modulator, the SCOS in Section 6.7.1 would provide a modulation performance of,

$$A[1 + m \sin(\omega t)] ,$$

where the $A$ is equal to $P_{\text{out}}$ and the degree of modulation is given by $m = S_t / T_0 (\Delta \lambda / E) = 82.3 \mu \text{W/nm} / 100 \mu \text{W} \times 2.82 \times 10^{-7} \text{nm m/V} = 2.32 \times 10^{-7} \text{E (V/m)}$.

### 6.9 Summary

Outlining an optimal recipe for SCOS E-field sensors requires understanding multiple factors whose interdependencies also affect SCOS performance. The SCOS design for E-field sensors offers an excellent platform for achieving optimal low-loss coupling conditions for
highly selective resonances, however further improvements to SCOS design largely depend on slab waveguide choice and the quality of its wave guiding properties. The primary design guidelines for waveguide material choice are high EO coefficient, high bulk index and a low dielectric constant. Secondary guidelines for slab waveguides are the polish quality, parallelism and thickness recognizing that highly selective resonances come from waveguides that more closely approximate the canonical parallel slab waveguide. Because optical losses reduce the overall signal of a SCOS, the following chapter will address the sources of typical losses for SCOS devices and include guidelines for reducing the overall loss figure.
7 REDUCING OPTICAL LOSSES IN SCOS DEVICES

Optical loss reduces the efficiency of SCOS devices on multiple fronts. Generally speaking, the sources of loss can be categorized as absorption, coupling or scattering losses. Optical losses reduce the output power of a SCOS device which limits its efficiency and the power of the output signal, effectively reducing the SNR. Optical losses involved with coupling between the D-fiber and slab waveguide also have the indirect effect of reducing the efficiency of the mode resonance and lowering the Q-factor. These losses broaden the resonant modes of the SCOS which in turn reduces its sensitivity. Understanding the nature and sources of these optical losses is necessary for improving the fabrication of efficient SCOS devices.

7.1 Slab waveguide optical absorption losses

Optical absorption naturally occurs in all materials. Absorption is often minimal in commercial waveguides such as optical fibers and LiNbO₃ where manufacturing processes have been optimized to reduce absorption. However, specialty materials often suffer from design trade-offs in order to achieve special optical qualities and are not necessarily optimized for minimal optical absorption. For example, the use of polymers with a high Pockel’s coefficient typically infers the use of non-linear dyes that are optically absorbent. In the case of polymer or
other specialty waveguides it should be understood that a material that is not optically transparent adds to the overall loss of the system and affects the coupling.

7.2 Slab waveguide radiation losses

Radiation losses are another concern in SCOS fabrication due to the limited control we have over such losses in the fabrication process and device operation. Optical fibers efficiently direct light along a single axial dimension – the core of the fiber. Slab waveguides however only provide confinement in one direction. Therefore, light coupled from a well confined fiber mode into a slab mode will spread laterally into the slab waveguide as shown in Figure 7-1. In this picture an etched D-fiber is coupled to a glass slide that has been roughened on top in order to scatter light from its surface. The shape of the scattering slab mode is seen beginning from a small point where the D-fiber starts coupling with the slide and the lateral modes spread laterally from that point.

Figure 7-1: IR picture of light dispersing and scattering from the slab waveguide of a SCOS.
Coupling between the D-fiber and slab only occurs between the light in the fiber and the light in the slab waveguide that remains within the evanescent region of the fiber. The amount of light that diffracts away from the interaction region of the evanescent fields of the fiber increases the overall loss of the SCOS. Radiation losses in the slab waveguide behave similarly with absorption losses and have been modeled as such [6]. These radiation losses can be minimized by reducing the length of coupling in the SCOS device.

7.3 Slab waveguide scattering losses

Coupling losses generally refer to the optical losses arising from light coupling into undesired modes. Examples of coupling losses include scattering from optically rough surfaces such as in the case of a poorly polished slab waveguide as well as coupling into undesired modes when the slab waveguide thickness is non-uniform. Figure 7-1 demonstrates an extreme example of coupling loss from scattering where the surface has been purposely roughened to demonstrate this effect. A poorly polished waveguide or a poorly etched/polished fiber can have optically rough surfaces that direct portions of light into undesired cladding and free space modes.

Untampered optical fibers offer optically smooth interfaces in the guiding regions as well as the outer surfaces; however fabrication processes can disrupt the surface finish quality. Polishing fibers to expose their evanescent fields can readily add scattering losses as well as introduce contaminants on the fiber surface that increase scattering and absorption. Using careful polishing techniques however can yield optically smooth interfaces for low-loss [35]. However, the SCOS fabrication technique of etching D-fibers in hydrofluoric acid provides a
uniform chemical etch without worry of introducing contaminants. With the proper fabrication process coupling losses from scattering can be largely avoided.

7.4 Coupling losses from waveguide thickness variation

Another concern in optical loss arises from coupling from the fiber into undesired modes due to non-uniformities in the slab waveguide thickness. For example, the 400th mode of a t=196.000 µm thick LiNbO₃ slab couples at a wavelength of 1554.8 nm and the 399th mode couples at 1558.7 nm giving a free spectral range of 3.9 nm. However, if the length of the slab waveguide has a thickness variation of 1/10th of a wavelength (196.155 nm) then some coupling will also want to occur at 1556.0 nm (a slab with parallelism of 1/20th arc second would yield a 194 nm difference in thickness over 2 mm length). Assuming that the thickness variation is distributed along the interaction with the fiber, the dominant thickness relates to the dominant modes of the SCOS while subdominant features are evidence of variations on the dominant thickness in the coupling region between the D-fiber and slab waveguide.

Figure 7-2 shows the normalized transmission spectra from two separate SCOS devices coupling to ~200 µm thick LiNbO₃ with coupling lengths of 6 mm and 2.5 mm. The top plot shows several subdominant modes and has an overall 12 dB coupling loss after placing the LiNbO₃ on the etched fiber. The bottom plot in Figure 7-2 shows a few subdominant modes and has a coupling loss of 10 dB. Notice that the depth and linewidth of the modes are improved with the longer interaction length of the 6 mm LiNbO₃ slab. While the additional coupling length increased the sharpness of the resonant modes, it also introduced 3.5 mm more coupling length and additional thickness variation, increasing mode ambiguity by adding more
subdominant features. The superposition of several sub-modes reduces mode continuity and adds an overall loss to the transmission spectrum of the SCOS.

![Transmission Spectra](image)

**Figure 7-2:** Transmission spectra from two LiNbO₃ SCOS with 6 mm coupling length (Top) and 2.5 mm coupling length (Bottom).

Coupling losses from non-uniform slabs can be approached in several ways: 1) employ improved waveguide processing techniques for higher waveguide uniformity, 2) reduce coupling length and 3) use thinner crystals. Purchasing or manufacturing waveguides with higher uniformity is an obvious solution but can incur a high cost–to–return ratio when employing greater precision in processing techniques. Reducing the coupling length to improve losses has already been discussed and illustrated in Figure 7-2 and is an obvious solution, especially when the slab waveguide surfaces are known to be of poor quality. Using thinner crystals however is a less obvious solution and will be discussed in further detail.
7.5 Reducing coupling losses with thinner waveguides

Thicker waveguides suffer more from imperfections in slab parallelism by increasing mode ambiguity and reducing mode continuity [66]. In explanation, the free spectral range (FSR) of subsequent modes in a SCOS device is largely determined by the waveguide index and thickness. The LiNbO$_3$ mentioned above has a free spectral range of ~3.9 nm. For a non-uniform slab, all subdominant modes (mode ambiguities) are manifest within the 3.9 nm range and readily overlap with each other, causing coupling losses. However, a 50 µm thick slab exhibits a FSR of ~15 nm, allowing subdominant features to spread out more within the transmission spectrum, thereby increasing mode continuity and reducing the overall transmission loss.

A coupling simulation was used to gain insight on the effects of slab thickness on the coupling losses for a slab modeled with non-uniformities. In this analysis, a generic Lorentzian line shape is associated with all dominant and subdominant mode features. The thickness, index and length are set for a specific slab in the SCOS transmission simulation while the thickness variation along the slab length is set at random within the limits of $1/10^{th}$ of a wavelength and parallelism of $1/20^{th}$ arc second. The simulated transmission spectrum is shown in Figure 7-3 for slabs that are 50, 100 and 200 µm thick, all having the same slab thickness variation profile for their respective thicknesses. The simulation shows the dominant mode amidst the subdominant features in each of the plots.

In the bottom plot of Figure 7-3, a 50 µm thick slab is simulated showing subdominant mode features spread out within the ~15nm spectral range of the dominant modes. The larger FSR “thins” the losses by increasing mode continuity. The middle and top plots show
transmission simulations for 100 μm and 200 μm thick slabs, respectively. Transitioning from thinner to thicker slabs, subdominant features representing mode ambiguities are progressively compressed into each other, increasing the overall transmission loss with the reduced FSR.

---

![Simulated transmission spectrum for SCOS utilizing slab waveguides of various thicknesses.](image)

Figure 7-3: Simulated transmission spectrum for SCOS utilizing slab waveguides of various thicknesses.

Though rudimentary, the preceding analysis correctly predicts the effect of waveguide thickness on coupling losses for a slab waveguide with random thickness non-uniformities. Data to support the conclusions of this simulation was collected for multiple SCOS devices shown in Figure 7-4. Each of the SCOS transmission spectra were obtained using the same etched section of D-fiber and crystals with different thicknesses but the same length. The crystals were coupled to the D-fiber with an index matching oil so that they could later be removed and the same fiber used again for subsequent crystals.
Figure 7-4: Transmission spectra for SCOS of three different slab waveguide materials and thicknesses.

The top plot in Figure 7-4 shows the transmission from a SCOS made with a 60 μm thick LiTaO₃ slab of 2 mm length. With a FSR of 12 nm, a transmission loss of ~1 dB was observed after placing the LiTaO₃ on the fiber. The middle plot in Figure 7-4 shows the transmission from a SCOS made with a 100 μm thick KTP slab of 2 mm length. With a FSR of 9.5 nm, a transmission loss of ~3 dB was measured after placing the LiTaO₃ on the fiber. Finally, the bottom plot shows the transmission from a SCOS made with a 200 μm thick LiNbO₃ slab of 2 mm length. With a transmission loss of ~8 dB and a FSR of 3.9 nm between subsequent modes, this thick sample shows the drawbacks of using a thick slab waveguide with poor surface qualities as evidenced by the blending of multiple subdominant modes and the high transmission loss.

The KTP and LiTaO₃ crystals used to obtain the transmission spectra in the top and middle plots were commercially ordered and professionally polished with requests for optimal surface quality and parallelism in order to minimize coupling losses and to reduce the number of
mode ambiguities. In agreement with the previous simulation, beyond a certain point, optically thick slabs have higher coupling loss and more sub-dominant features.

7.6 Summary

By considering the physical and optical properties of the slab waveguide, it is possible to minimize the optical losses and help optimize SCOS performance. However, trade-offs in the design process reduce the feasibility of fully minimizing optical losses. Doing so imposes adverse effects on other aspects of SCOS performance. For example, minimizing coupling length reduces both radiation losses and mode ambiguity but requires increasing the coupling strength in order to maintain a full resonant transfer of optical power from the fiber to slab waveguide. Unfortunately, stronger coupling broadens the resonant linewidth of coupled modes and reduces sensitivity. In another example, minimizing waveguide thickness to the limit in order to improve mode continuity in the coupling spectrum and maximize transmission power ultimately widens the linewidth of resonant modes and increases difficulties in fabrication. Furthermore, doing so greatly increases fabrication costs if waveguides must be polished individually to the desired dimensions and thicknesses. Aside from improving signal power from SCOS devices, reducing optical losses also aids the development of SCOS multiplexing where optical losses are compounded with each additional SCOS and cross-talk is minimized with good mode continuity.
8 SCOS ARRAYS

As a wavelength selective fiber-based sensor, SCOS devices allow sensor multiplexing on a single interrogating optical fiber as shown in Figure 8-1. Therefore, not only is a SCOS extremely portable in terms of placement within interior packaging, but multiple sensors may be placed within a device under test only using a single optical fiber. With this convenience, it is possible to map multiple instances of an electric field within a device under test. In addition, multiplexing an array of optical sensors is an essential building block toward the multi-axial SCOS array discussed in section 9.2. This chapter demonstrates an evanescent-coupled electric-field sensor array that performs with a high degree of linearity and is capable of monitoring electric fields at multiple locations in small, hard to reach areas of electronics devices.

Figure 8-1: An array of SCOS sensors on a single optical fiber.
8.1 SCOS multiplexing

In order to operate more than one SCOS correctly on a single fiber it is necessary for the transmission spectrum of each SCOS to multiplex properly. Figure 8-2a and Figure 8-2b both show simulated transmission spectra for SCOS devices with different free spectral ranges (FSR). The FSR (Equation (2-3)), which is defined as $\lambda_m - \lambda_{m+1}$, of the two SCOS devices are differentiated by slab waveguides with different indices and/or thicknesses. Figure 8-2c shows that when both devices are coupled on a single fiber, the resulting transmission spectrum is a superposition of the resonant modes from the constituent SCOS devices. The FSR of each device helps identify the respective transmission dips in the combined spectrum.

![Figure 8-2: A simulation of the transmission spectrum of a fiber coupled with an EO waveguide showing the resonant modes. Two separate SCOS devices with different resonance behavior are shown in (a) and (b) while the transmission when both devices are multiplexed is shown in (c). The dashed portion in (c) indicates the portion of the transmission spectrum where there is significant overlap between the resonances of the two devices.](image-url)
Most regions of the spectrum exhibit isolated resonances because the resonant dips are narrow. This separation of the resonant wavelengths enables each sensing element in this array configuration to function independently. The dashed portion of the transmission spectrum in Figure 8-2c indicates a region where resonances between the two sensing elements overlap. Regions with overlapping resonances are unsuitable to use for sensing because resonant shifting from one or both elements causes power change in the output leading to ambiguity in the output signal. The number of SCOS devices that can be multiplexed on a single fiber is limited by the finesse of the SCOS which is defined as the FSR divided by the full-width half-max of the resonances.

8.2 A KTP/LiNbO$_3$ SCOS array

Lithium Niobate (LiNbO$_3$) and Potassium Titanyl Phosphate (KTP) crystals were chosen as the two slab waveguides for a dual SCOS array. Table 8-1 highlights pertinent information for each individual SCOS based on analysis. Because the coupling strength is likely different between the two SCOS, the transmission slopes of each resonance are measured directly and only the analytical value of $\Delta \lambda/E_{inc}$ is included in the table.

<table>
<thead>
<tr>
<th>$EO$ Slab</th>
<th>$t$ (µm)</th>
<th>$n_o$</th>
<th>FSR (nm)</th>
<th>$\Delta \lambda/E_{inc}$, ( nm m/MV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTP</td>
<td>120</td>
<td>1.729</td>
<td>10.5</td>
<td>6.8 x 10$^{-3}$</td>
</tr>
<tr>
<td>LiNbO$_3$</td>
<td>200</td>
<td>2.138</td>
<td>3.5</td>
<td>20 x 10$^{-3}$</td>
</tr>
</tbody>
</table>
Figure 8-3 shows the individual transmission spectrum of both the SCOS coupled with a LiNbO$_3$ slab and the SCOS coupled with a KTP slab as well as the transmission spectrum of the overall sensory array after both devices are fusion spliced together with a polarization maintaining fusion splicer. In the final product, the D-fiber based sensor array is fusion spliced on its ends with a combination of elliptical core fiber then PANDA fiber for use with standard optical equipment. The splice progression from D-fiber to elliptical core fiber and finally PANDA fiber is necessary to improve mode overlap between the fibers at each splice and minimize the optical losses incurred from splicing D-fiber straight to PANDA fiber [44].

Because crystal thickness and index affects not only the wavelength of resonant modes, but also the FSR, this attribute uniquely identifies the resonant modes associated with each respective crystal. The LiNbO$_3$ SCOS shows resonant transmission dips every 3.5 nm while resonant transmission dips are seen every 10.5 nm in the KTP SCOS. As visible in Figure 8-3 the KTP SCOS has prominent resonances seen at 1544.5 nm and 1555 nm in the sensor array spectrum while the remaining resonances belong to the LiNbO$_3$ SCOS.

One concern in the use of a sensor array is choosing an optimal wavelength to probe each SCOS for maximum sensitivity while not incurring crosstalk between the sensing elements. In essence, a proper mid-resonant wavelength for sensing must not be within one of the regions with resonance overlap as indicated by the dashed sections of the bottom transmission spectrum in Figure 8-3. Furthermore, this mode overlap sets the limit on the number of SCOS that can be placed in an array.
Figure 8-3: (Top) Transmission spectrum of a SCOS with 200 µm thick LiNbO₃ crystal slab resulting in a FSR of 3.5 nm. (Middle) Transmission spectrum of a SCOS with 120 µm thick KTP crystal slab resulting in a FSR of 10.5 nm. (Bottom) Transmission spectrum of the sensor array showing a superposition of the individual resonant behavior with both EO crystals. Regions with overlap are indicated by the dashed sections in the transmission spectrum.

8.3 SCOS array performance and results

Figure 8-4 shows a linear plot of the measured transmission spectrum of the SCOS array consisting of a KTP-slab and a LiNbO₃-slab on different etched sections of a contiguous D-fiber. The power transmission slope is measured directly from the indicated regions on the resonances in this plot. For reference, the primary parameters that affect the sensitivity of the SCOS elements are listed in Table 2. The values for device sensitivity favor the LiNbO₃ SCOS which indicates the achievement of better coupling parameters over the KTP SCOS in the fabrication. The minimum detected field under testing is also indicated.
Figure 8-4: Zoomed transmission spectrum of KTP- and LiNbO$_3$-SCOS array. The mid-resonance wavelengths for the two elements are chosen outside of the resonance overlap region as indicated by the dotted portion of the transmission spectrum with $\lambda_{KTP}=1555.7$ nm and $\lambda_{LiNbO_3}=1557.0$ nm. At the respective mid-resonance wavelengths the slopes are respectively $S_{c}=0.69 \ \mu$W m/MV and $S_{c}=1.6 \ \mu$W m/MV for the KTP- and LiNbO$_3$-SCOS.

Table 8-2: Sensitivity parameters for the electric field sensor array

<table>
<thead>
<tr>
<th></th>
<th>Mid-resonance wavelength, $\lambda_o$</th>
<th>Bias power, $P_0$</th>
<th>Transmission slope, $\Delta P/\Delta \lambda$</th>
<th>Sensitivity, $\Delta P/E$</th>
<th>Minimum Detected Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTP-SCOS</td>
<td>1555.7 nm</td>
<td>1.25 $\mu$W</td>
<td>2.5 $\mu$W/nm</td>
<td>51 nW (m/MV)</td>
<td>$\sim$300 V/m</td>
</tr>
<tr>
<td>LiNbO$_3$-SCOS</td>
<td>1557.0 nm</td>
<td>2.1 $\mu$W</td>
<td>8.1 $\mu$W/nm</td>
<td>55 nW (m/MV)</td>
<td>$\sim$100 V/m</td>
</tr>
</tbody>
</table>

For illustrative purposes, Figure 8-5a shows how two SCOS elements are monitored simultaneously using wavelength division multiplexing. Figure 8-5b shows the configuration used to measure one SCOS element at a time. To switch monitoring between the two elements the laser wavelength is simply changed between 1555.7 nm for the KTP-SCOS to 1557.0 nm for the LiNbO$_3$-SCOS.
To measure sensitivity of this SCOS array, a reference field is applied to the desired SCOS element by placing the SCOS between two copper electrodes and driving the electrodes with an AC voltage with a frequency of 20 kHz and amplitude up to 10V. Using an electrode spacing of 1.3 mm this corresponds to electric field amplitude up to 7.7 kV/m. Figure 8-6 shows the FFT signal strengths for both sensors as a function of the electric field strength. During this test the voltage was only applied to the electrode corresponding to the SCOS element being selected. For example, the solid line in Figure 8-6 corresponds to a voltage being applied to Electrode 1 and the laser tuned to a wavelength of 1555.7 nm. The optical signal was received by a Newport 818-IR large area detector followed by a Stanford Research SR760 spectrum analyzer for the signal analysis using a resolution bandwidth of 48 Hz. Each sensor in the array showed a highly linear response while the minimal detected field was 300 V/m for the KTP-SCOS and 100 V/m for the LiNbO$_3$-SCOS.
In order to ascertain that sensor function was also linear with optical power, Figure 8-7 shows the FFT signal strength of the LiNbO$_3$ sensor as a function of the transmitted optical power with applied electric field strength of 7.7 kV/m. This measurement indicates that the sensitivity of the SCOS array improves by increasing the optical power.

A simple cross-talk measurement was performed by applying the maximum voltage to Electrode 1 (KTP-SCOS) while the laser was tuned to a wavelength of 1557.0 nm corresponding to the mid-resonance wavelength of the LiNbO$_3$-SCOS. The resulting FFT signal was below the noise floor of the measurement demonstrating insignificant cross-talk. A similar cross-talk measurement was also performed for the LiNbO$_3$-SCOS with an identical result.
Figure 8-7: FFT signal of electric field sensor array as a function of transmitted optical power. The data points (circles) are mapped against a linear fit (solid line) showing that performance is linear ($R^2=0.9995$) with optical power and that device sensitivity increases with higher optical power.

8.4 Summary

With an electric field sensor array, one interrogating optical fiber is capable of retrieving data regarding the nature of an electric field at multiple locations. Because the fabrication process still maintains the relative size and the structural integrity of the optical fiber, this sensor array is as suitable for threading into small spaces and cavities as a single SCOS. In addition, the following chapter discusses how multi-axial field measurements are possible with SCOS arrays.
9 MULTI-AXIAL SENSING

One of the benefits of SCOS is the potential for multi-axial sensing. Vectorial measurements of electric fields have been demonstrated using free space coupling with bulk crystals [67, 68]. Additionally, fiber optic based sensors have also been proposed for mapping electric fields [18, 69]. SCOS technology makes 3-vector analysis of an electric field possible while adding the convenience of in-fiber technology. With SCOS technology, a multi-axial E-field sensor can be situated within a device to measure its fields while the light used to probe EO induced behaviors is fed through optical fiber. In this way multi-axial field measurements are possible and the portability of the sensor and measurement system is greatly improved over bulk optic counterparts requiring free-space coupling.

9.1 Spatially oriented multi-axial SCOS

One version of a multi-axial SCOS sensor is implemented by placing three individual SCOS at orthogonal orientations on a probe as shown in Figure 9-1. With this multi-axial sensor configuration, each individual SCOS is fabricated to measure field strengths along the axis normal to its slab waveguide. This design allows flexibility in the use of either polymer slab waveguide or crystal slab waveguides and eliminates the necessity for accurate slab alignment during the SCOS fabrication. The conveniences aside, care must still be taken to ensure proper placement of each individual SCOS on the final probe to ensure orthogonal relations exist.
between the three individual sensors. With this setup, each SCOS in the spatially oriented multi-axial sensor is probed individually to acquire field strength measurements for its respective field orientation. The convenience of mounting sensors to the probe is countered by the increased size of the final sensor. In addition, each SCOS requires its own tunable laser, optical receiver and spectrum analyzer.

![Diagram for a spatially aligned multi-axial sensor](image)

**Figure 9.1: Diagram for a spatially aligned multi-axial sensor.** Each SCOS sensor on the probe measures an independent axial direction.

### 9.2 Compact multi-axial SCOS sensor

Figure 9.2 illustrates another version of a multi-axial SCOS sensor utilizing three crystals with orthogonal EO axes orientations coupled to the same etched section of D-fiber. When the electro-optic axes \((n_z)\) of the individual crystals are orthogonal to each other, they can be used to monitor electric fields in the three orthogonal directions. With this compact design, multi-axial sensing is accomplished all within a single etched section of D-fiber. The spacing between crystals in this design sets the resolution for 3-D field measurements and is typically better than the resolution of the spatially oriented multi-axial SCOS.
The compact multi-axial sensor uses horizontally polarized light (TE mode), coinciding with the $\phi$-axis of the SCOS global axes reference as shown in Figure 9-3. By using the TE mode, the light launched into the fiber only interacts with a single axis of each of the three crystals. TM mode operation for the multi-axial SCOS is possible but not desirable due to the added complexity of the E-field orientation in the slab as discussed in section 5.4.1.

Table 9-1 identifies, according to Figure 9-3, the crystal that interacts with each field component and includes the related thicknesses, indices and Pockel’s coefficients. With these particulars,
the location of mode resonances can be determined as well as the expected strength of the EO effect.

<table>
<thead>
<tr>
<th>Field Direction</th>
<th>( \vec{x} )</th>
<th>( \vec{y} )</th>
<th>( \vec{z} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal, thickness</td>
<td>( C_2, t_2 )</td>
<td>( C_1, t_1 )</td>
<td>( C_3, t_3 )</td>
</tr>
<tr>
<td>Slab Index</td>
<td>( n_x )</td>
<td>( n_z )</td>
<td>( n_y )</td>
</tr>
<tr>
<td>Pockel’s Coefficient</td>
<td>( r_{13} )</td>
<td>( r_{33} )</td>
<td>( r_{23} )</td>
</tr>
</tbody>
</table>

With the compact multi-axial sensor, only a single fiber is probed to measure the field strength along any of the desired axial directions. The measurement technique for the compact multi-axial sensor requires the same setup as discussed for sensor arrays in section 8.1. In addition to the general principles previously outlined for fabricating SCOS arrays, effective compact SCOS multi-axial sensing requires careful attention to proper crystal alignment with the with sensor axis and some additional considerations in slab material choice to eliminate cross-talk between axes. Proper crystal alignment will depend on the tolerances for cross-talk in a specific application while slab material choice requires that the EO material itself is free from cross-axis sensitivity.
9.3 KTP crystal for compact multi-axial SCOS sensor

Avoiding cross-axis sensitivity between orthogonal fields is a key concern in choosing an appropriate slab material for the compact multi-axial sensor. The existence of both $E_y$ (2nd column) and $E_z$ terms (third column) in the top half of the EO tensor for crystals with trigonal 3m symmetry indicates that the principle axes of the dielectric tensor are sensitive to changes from multiple field directions. This field orientation ambiguity in the EO response precludes the use of LiNbO$_3$ and LiTaO$_3$ crystals from multi-axial sensing applications.

KTP crystals with orthorhombic 2mm symmetry have only $E_z$ terms (third column) in the top half of the EO tensor making it the material of choice for compact multi-axial sensors. In a KTP crystal only a field aligned with the EO axis will produce alterations to its indices. The mixed axis terms, $r_{42}$ and $r_{51}$, in the lower half of the EO tensor relate to the rotation of the dielectric tensor from the presence of $E_x$ and $E_y$ fields [53]. However, due to the relatively large birefringence of KTP crystals, even a large field of 10 MV/m (higher than the dielectric strength of air) in either the $x$ or $y$ direction rotates the dielectric tensor by less than one degree [53].

9.4 Summary

Both versions of the SCOS multi-axial field sensor offer benefits and challenges in their fabrication and use. The spatially-oriented multi-axials SCOS offers the simplicity of making three separate SCOS, but requires precise positioning when placed on the probe and each SCOS must be probed individually potentially requiring extra equipment for a full interrogation system. The compact multi-axial SCOS adds the benefit of a smaller package and the use of a single optical fiber. However, extra care is required in the fabrication process when selecting
appropriate crystal orientations and thicknesses. Added challenges include minimizing overall losses and cross-talk from the resonances of three crystals competing for space in the same transmission spectrum.
10 RECTANGULAR WAVEGUIDE: ELECTRIC FIELD MAPPING

This chapter demonstrates the capabilities of a SCOS for internal cavity sensing. For demonstration, a non-calibrated SCOS is used to map the electric field profile of the TE$_{10}$ mode of an X-Band rectangular waveguide without disrupting the mode.

10.1 Device under test: X-Band waveguide

For the experiment, a short section of X-Band waveguide (0.9 inches x 0.4 inches, $f_c = 6.56$ GHz) was filled with paraffin ($n_p=1.45$) to lower its cutoff frequency ($f_{c,p}=4.52$ GHz) and a short was placed at the end to create a standing wave in the waveguide cavity. A 1 mm diameter hole was drilled through the waveguide for SCOS insertion 10 cm from the transducer, placing it at a peak in the standing wave pattern for a driving frequency of 6.16 GHz ($\lambda_{wg}=5$cm).

Figure 10-1 shows the SCOS ready to probe the electric-field distribution of the TE$_{10}$ mode. The picture on the left shows the D-fiber extending outside of the waveguide to where it is held in position with proper orientation by rotating/sliding fiber clamps on each end. The picture on the right shows the crystal sensing element on the D-fiber just outside of the waveguide hole. With this setup the SCOS can be slid in incremental measurements through the waveguide through the probing hole.
With a waveguide operating frequency of 6.16 GHz and a driving power of 100 mW, field measurements were taken at millimeter increments along the cross section of the waveguide using the SCOS with transmission spectrum shown in Figure 10-2 from a 100 μm thick KTP slab. For 100 mW of excitation power into the rectangular waveguide, the maximum field is 540V/m based on [70],

\[ |E| = \sqrt{\frac{4Z_{TE}P}{ab}}, \]

(10-1)

where \( P \) is the power in the waveguide, \( a \) and \( b \) are the dimensions of the waveguide and \( Z_{TE} \) is the characteristic impedance of the waveguide at the operating frequency, \( f \), and is given by,
where $\eta_p$ is the modified intrinsic impedance of free space taking into account the index of the paraffin.

![Graph showing KTP SCOS transmission and operating point used for waveguide field mapping.](image)

Figure 10-2: KTP SCOS transmission and operating point used for waveguide field mapping.

With an output power of 141 $\mu$W at 1552.3 nm, the SCOS output was picked up by a lightwave receiver with variable gain control (Agilent 83434A) and the electric signal processed by a spectrum analyzer (HP 8592L) having a system noise floor at $\sim$18 $\mu$V. The SCOS field measurements showed a maximum signal of 135 $\mu$V in the center of the waveguide corresponding to field strength of 540 V/m. The minimum signal at the edge of the waveguide was limited at 18 $\mu$V by the noise floor of the system.
In order to make a direct comparison, Figure 10-3 shows normalized SCOS E-field measurements for the cross-section of the X-Band waveguide plotted against the known E-field distribution of the TE$_{10}$ mode. The measured E-field data accurately depicts the known field profile everywhere except at the waveguide boundaries where the noise floor of the SCOS interrogation system exceeds the expected signal. These measurements indicate minimal field perturbation from the SCOS sensor for this frequency. Minimal field perturbation is expected for field measurements at frequencies within the Rayleigh regime where the size of the scattering object is assumed to be much smaller than the wavelength of the scattered field. For a SCOS with an average radius of 100 µm at the sensing element, a field with a wavelength of 1mm corresponds to a frequency of 300 GHz.

![Figure 10-3: Actual and measured electric field for an X-Band waveguide cross section.](image_url)
10.3 Cavity resonance analysis

In order to ascertain the reliability of the SCOS sensor for mapping the field strength of resonances within a cavity, it is desirable to know to what extent it disrupts the fields being tested. Too much field disruption from a sensor reduces its efficacy for field sensing. Operating within the Rayleigh regime, Table 10-1 shows a quantitative analysis for the disruption of a cavity resonance for various materials introduced inside the resonant cavity structure of the X-Band waveguide. Each material was threaded through the 1 mm hole in the side of the waveguide in the same manner the SCOS was placed for field measurements. For each material introduced, the $Q$ of its resonance was measured to determine the loss introduced by each material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (μm)</th>
<th>$Q$</th>
<th>Loss/pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>1696</td>
<td>~1%</td>
</tr>
<tr>
<td>Fiber</td>
<td>125</td>
<td>1651</td>
<td>~1%</td>
</tr>
<tr>
<td>Wire</td>
<td>10</td>
<td>297</td>
<td>7%</td>
</tr>
<tr>
<td>Wire</td>
<td>50</td>
<td>131</td>
<td>15%</td>
</tr>
<tr>
<td>Wire</td>
<td>70</td>
<td>75</td>
<td>27%</td>
</tr>
</tbody>
</table>

The results of the resonance test show negligible losses to the resonant structure from the fiber with 125 μm diameter. However, even the thinnest sample of metallic wire (10 μm) introduced within the waveguide cavity added considerable loss to its fields and reduced the
strength of its resonance. For a large range of frequencies, the SCOS is a suitable measurement tool for both forward propagating fields and those in resonance.

10.4 Summary

Mapping the field distribution of a rectangular waveguide with a SCOS device highlights the novelty of SCOS sensors. Not only is the SCOS capable of accurate field measurements, but it is small enough to be inserted inside a device without perturbing its fields. Even though the fields inside a rectangular waveguide have analytical solutions and are well understood, a calibrated SCOS can be used to map unknown fields in more complicated structures.
11 CONCLUSION

Optical sensing provides an attractive alternative to traditional electric field sensor solutions and the availability of fiber optics technologies allows the fabrication of small, non-perturbing electric-field sensors capable of high bandwidth. The SCOS technology developed in this work utilizes D-fibers to create electric-field sensors that are virtually as small as the fiber itself. The novel size and performance of SCOS sensors open its use to applications previously unrealizable with existing technologies.

11.1 Contributions

As mentioned in the introduction, the main contributions in this work are outlined as follows:

- I have developed a new sensing platform based on coupling between a D-fiber and a slab waveguide called slab coupled optical fiber sensing (SCOS).
- I have developed a high-yield fabrication process for SCOS sensors
- I have demonstrated temperature sensing using the SCOS technology.
- I have pioneered the application of SCOS to electric field detection.
- I have developed a detailed theoretical model of the SCOS.
- I have used the theoretical model to optimize the various SCOS design parameters.
I have developed a highly linear SCOS electric field sensor capable of measuring fields as low as 15.8 V/m with 1 kHz resolution bandwidth.

I have developed, fabricated, and tested an array of SCOS electric field sensors on a single optical fiber.

I have designed a multi-axial electric field sensor for monitoring 3-D fields.

I have demonstrated the potential for internal cavity sensing by mapping the electric field of the TE$_{10}$ mode in an x-band waveguide.

### 11.1.1 SCOS sensing platform

SCOS sensors were developed as an alternative to the side-polished fiber (SPF) technique for evanescent field based sensing applications. SPF sensors utilize standard circular core fiber which has been mounted in a polishing block for cladding removal and subsequent slab placement. The SCOS sensing platform utilizes D-fibers where the cladding removal is accomplished via wet-etching and the flat surface of the D-fiber serves as the reference for slab placement. The geometry of the D-fiber and the wet-etch cladding removal process provides unique benefits in terms of design control for these types of sensors. Several challenges were overcome in order to develop SCOS technology as a virtually fiber sized sensor.

### 11.1.2 High-yield fabrication process

Developing a suitable fabrication process required characterizing the appropriate amount of fiber cladding to remove via hydrofluoric (HF) acid etching in order to expose enough of the evanescent field for coupling with a slab waveguide. The fabrication process further required the
proper technique for placing the slab waveguide onto the etched section of D-fiber such that modes would efficiently couple from the fiber into the slab. This step was enhanced by in-situ monitoring so that the SCOS transmission could be monitored as the slab was positioned on the fiber and later attached with a hard-setting index matching adhesive.

The highlights of the fabrication process for the D-fiber SCOS are the in-situ monitoring techniques for both fiber etching and slab attachment and the potential for a virtually fiber-sized final product. In-situ monitored etching yields a highly predictable and repeatable process for exposing the desired amount of evanescent field for coupling the fiber with an external waveguide. In addition the in-situ monitored slab application and adhesion process with a UV curable adhesive ensures the desired performance of the final product. Whereas SPF devices require mounting the fiber into a curved groove in a polishing block, the SCOS fabrication steps are all accomplished with bare fiber, requiring no more than a fiber holder to maintain correct fiber orientation.

11.1.3 Temperature sensing with SCOS

The general SCOS sensor creates periodic dips in the transmission of the D-fiber corresponding to resonant modes with an external slab waveguide. The SCOS sensor can be used to detect or monitor any phenomena correlated with index changes in the slab waveguide by monitoring spectral shifts associated with variation in the slab index. The SCOS was characterized as a temperature sensor by measuring peak shifting while placed in a temperature controlled environment. Materials with different thermo-optic responses exhibited different sensitivities to temperature change.
11.1.4 SCOS sensors for electric field detection

Electric field detection with the SCOS required finding an appropriate material with an electric-field sensitive optical index for the slab waveguide. It was additionally required that the slab could be readily obtained in the suitable dimensions and polish quality required for coupling with the core of the D-fiber. The materials used for the electro-optic slabs include both crystals and polymers that are manufactured with the proper thickness, excellent parallelism and surface quality.

In addition to creating a portable and functional SCOS sensor with an EO slab material, its use as a viable electric-field sensor also required an appropriate technique for measuring the EO signal from its transmission spectrum at the frequencies associated with electric fields of interest. While many optical sensors having resonant or grating-like transmission features utilize peak tracking to monitor environmental variables, electric-field detection requires speeds much higher than possible with current interrogation equipment. The selected measurement technique involves monitoring the output power of the SCOS at a bias point along a mode resonance. The result is an optical signal that is linearly proportional to electric field strength on top of a dc bias. Spectrum analysis of the final signal shows the frequency and relative strength of the electric field which can be calibrated with a known field.

11.1.5 Theoretical model of the SCOS

The theoretical model for the SCOS was developed in order to understand the nature and behavior of its performance as an electric field sensor. This model incorporates the concept of mode coupling between D-fiber and slab waveguide with the consequences of the electro-optic
effect on the slab modes. The result is a detailed understanding of how an incident electric field imposes changes in the output power of a SCOS sensor. This analysis also shows the interdependencies of design factors on SCOS sensitivity.

11.1.6 Optimizing SCOS performance and minimizing losses

Optimizing SCOS performance for improving sensitivity to small electric fields required developing an understanding of each of the aspects of the fabrication process that affect SCOS performance. The main topics explored in this analysis include the effects of coupling strength, slab index and slab thickness on the two mechanisms that determine the strength of the SCOS EO signal: (1) the lineshape or slope of mode resonances and (2) the degree of resonant shifting due to an electric field.

This analysis shows that the slope of the mode resonances is strongly affected by the coupling strength between waveguides as well as the difference in dispersion between the slab and fiber modes. In general, weaker coupling and a higher dispersion contrast between waveguides both increase the selectivity and slope of resonant modes. Weaker coupling is accomplished by increasing the separation distance between waveguides by reducing the amount of cladding removed during fiber etching. High dispersion contrast as achieved with thicker, higher index slab waveguides.

The degree of resonant shift from an electric field was mostly determined by the index of the slab material, its EO coefficient and RF permittivity. In the analysis, materials with higher indices caused a greater spectral shift on the mode resonances. However, high index materials typically have higher permittivity which reduces the field inside the EO material. In addition,
the EO coefficients are largely material dependent. Due to the number of factors that affect resonant shift with field, a table with several EO materials was developed to identify the overall strength of a material for electric-field sensing.

Optical losses in SCOS devices were strongly tied to slab waveguide parameters. In general, high surface quality is necessary for efficient coupling and slab thickness is strongly correlated with unnecessary optical loss. These unnecessary losses are avoided by restricting the thickness of the slab material to promote mode continuity. However, minimum thicknesses are adhered to in order maintain sufficient free spectral range. General guidelines are constructed for selecting waveguide thicknesses that are economical and help optimize sensitivity and avoid excessive optical losses.

The design guidelines generated by this analysis have helped improve the fabrication of high quality SCOS sensors that are economical to produce in terms of fabrication time and material cost. Furthermore, this analysis has also helped identify application specific guidelines for slab waveguide selection in SCOS fabrication.

11.1.7 Sensitivity of SCOS electric field sensor

Using guidelines obtained from the analysis on SCOS optimization, an electric field sensor was developed that is capable of measuring a field strength as low as 30 V/m utilizing a spectrum analyzer with a resolution bandwidth of 1 kHz. This SCOS was fabricated using a 50 \( \mu \)m thick polymer slab featuring an optical index of \( n=1.75 \), a high EO coefficient of 70 V/m and a relatively low permittivity of \( \varepsilon_r=4.0 \). The polymer slab was fabricated according to optimal design parameters by JingDong Luo at the University of Washington who specializes in
developing EO polymers. Better sensitivity can be expected with this SCOS using higher optical power levels and a suitable optical receiver.

11.1.8 Fabrication and testing of a SCOS array

One of the benefits of using SCOS for electric field sensing is the potential for sensor multiplexing. This work outlines guidelines for correctly multiplexing SCOS devices on a single fiber. The main considerations involved in building and using an array of SCOS electric field sensors are selecting proper waveguide thicknesses and appropriate bias points for operating each sensor. The resonances of each SCOS in an array are identifiable by their unique mode shape and free spectral range. In order to ensure an appreciable difference in the free spectral range of SCOS devices, slab waveguides must be chosen with either appreciable differences in their indices, thicknesses or both. In the case that the same material is used for each SCOS in an array, appropriate thicknesses can be determined by first calculating the expected FSR.

Once the proper slab parameters are chosen, the SCOS array follows the same general fabrication process as a single SCOS. The electric field at each element in the SCOS array can be monitored by tuning a laser source to one of its resonances. Cross talk is avoided by choosing bias points where resonances do not overlap. The SCOS array developed and tested in this work showed a sensitivity as low as 100 V/m and no cross-talk.

11.1.9 Multi-axial electric field sensor

This work outlines two possible configurations for multi-axial sensing with SCOS technology. In one configuration, three SCOS sensors are oriented orthogonally on a single
probe with close proximity to each other. The second configuration is for a compact multi-axial sensor and is an extension to SCOS arrays, using three crystals with orthogonal EO axis orientations on the same etched section of D-fiber. The feasibility of this compact multi-axial sensor is addressed including the suggestion for use of KTP crystals in order to minimize cross-axis measurements.

11.1.10 Internal cavity sensing of X-Band waveguide

This work showcases the mapping of the TE$_{10}^0$ field in an X-Band waveguide with millimeter resolution in order to demonstrate the novelty of SCOS electric field sensors for measuring fields inside an enclosed cavity. The virtually fiber-sized SCOS sensor fits readily inside enclosed spaces for measuring fields with minimal perturbation. The field mapped by the SCOS in this test accurately depicts the known fields for a rectangular waveguide. Furthermore, the results from this test assert the feasibility of using SCOS based E-field sensors to map unknown fields in cavities with unknown and more complicated field patterns without concerns of disturbing the field.

11.2 Future work

This dissertation explores the current and intended uses of SCOS technology for electric-field sensing. However SCOS technology opens the door for additional sensing applications. In addition to the straightforward electric-field measurements in earlier chapters, Chapter 10 shows field measurements within an X-Band waveguide, demonstrating the potential for non-intrusive field monitoring in more complicated structures with unknown fields. So long as the optical
fiber can be threaded into an internal cavity, SCOS devices can be used to monitor internal fields. Future intentions and applications for SCOS sensors include measuring electric fields in devices such as rail guns or near-field patterns around antennas.

Chapter 9 furthers the idea of E-field sensing to accommodate multiple dimensions. It contains the design and considerations necessary to develop a multi-axial sensor capable of mapping 3D field profiles. The development of multi-axial E-field sensors will further the ability to map unknown fields.

### 11.2.1 Dual variable sensing

Dual variable sensing is also possible with SCOS technology following the development of a suitable detection scheme. While electric field measurements with SCOS technology involves monitoring power changes along mid-resonant wavelengths, the resonant modes also shift with temperature and other environmental variables as mentioned in Section 2.4. Because temperature varies at relatively low frequencies, interrogation techniques involving peak tracking are capable of monitoring its effects. In environments with expected temperature changes, the SCOS can be configured to monitor temperature variation by tracking the migration of the resonant mode center wavelength while electric fields are monitored at the appropriate mid-resonant wavelength. Such a system requires active monitoring because as the resonant mode center wavelength migrates with temperature, the appropriate mid-resonant wavelength for electric-field sensing must adjust accordingly.
11.2.2 Magnetic field SCOS sensors

Magnetic field sensing is another potential application of the SCOS technology. Monitoring magnetic fields requires the use of magneto-optic materials for the slab waveguide. With an appropriate magneto-optic slab, the SCOS can measure magnetic fields such as those existent surrounding a current bearing wire. In such an application, the SCOS can measure the presence and strength of transient currents.
APPENDIX A. DETAILED FABRICATION PROCESS

Fiber Preparation

1. Obtain a 1 meter length of Optical D-fiber (KVH Industries, Inc).
2. Strip a ~2 cm section of jacket from the middle of the 1 meter fiber using a hot stripper.
3. Strip ~1 cm of jacket from both ends of the 1 meter length of D-fiber.
4. Cleave the fiber ends using a precision fiber cleaver.
5. Place the fiber in an etch holder so that the 2 cm stripped section is in centered and the flat face of the fiber is facing up and secure the fiber at the ends of the holder with the rubberized magnetic fasteners.
6. Holding the etch holder by the ends, slide the fiber fasteners at the ends of the etch holder toward the center to observe how the D-fiber forms a loop.
7. Ensure that the center of the section with the jacket removed is at the bottom of the loop.
8. Ensure that the D-fiber forms a uniform loop beneath the etch holder without any twisting.
9. Slide the fiber fasteners back to the ends of the etch holder and readjust the position/orientation of the D-fiber within the fasteners until it forms a centered, untwisted loop.
Fiber Cleaning

1. After the fiber has been prepared and properly placed in the etch holder, clean it in an ultrasonic cleaner filled with isopropyl alcohol by resting the etch holder on the top of the ultrasonic cleaner and sliding the fiber holders toward the center of the etch holder until the D-fiber forms a loop and lowers into the alcohol such that the stripped section is fully submerged in the alcohol. Clean the fiber for 5 minutes in the ultrasonic bath.

Prepare Fiber for Etching

1. After the stripped section of fiber has been fully cleaned, set the fiber holder into the position where it will be etched.

2. Place the input end of the fiber flat-side facing up into the fiber clamp of the 3 axis stage where 1550 nm light is to be launched.

3. Ensure that a polarizer is set between the 1550 nm source and D-fiber rotated to 45 degrees in reference to the flat face of the D-fiber.

4. Secure the output end of the D-fiber into the cylindrical fiber clamp and insert the clamp into the fiber positioner with collimating lens output.

5. Ensure that a polarizer is placed between the fiber and collimating lens rotated at 45 degrees in reference to the flat face of the fiber.

6. Ensure the IR power detector is placed to receive the light output from the fiber.

7. Dress in the necessary personal protective equipment according to MSDS guidelines for use of Hydrofluoric acid.
8. Set the etch holder holding the fiber onto an open container of water for quenching the HF after the etch is to be terminated.

9. Remove the lid from the plastic container holding the 25% hydrofluoric acid and set it in front of the water container with the etch holder on top.

10. Place the etch holder atop of the acid container and slide the fiber fasteners toward the center of the etch holder until ~1.5 cm of the stripped section of fiber is submerged in the hydrofluoric acid.

11. Using Labview to monitor the output power of the D-fiber during the time of etching, remove the D-fiber from the hydrofluoric acid after 3 oscillations of power and place it in the water container to quench the etch.

12. After 3 oscillations the fiber will have been etched enough such that almost all of the cladding above the core has been removed. Adjust the length of stripped fiber that is placed in the acid or the number of oscillations if too much or not enough cladding is removed.

**Etch Trouble Shooting**

1. If the polarizers and fiber orientation are not properly aligned, only partial power oscillations may be visible. This does not affect the etching process at all, however if alignment is too poor, power oscillations might be too small to observe properly. This can be prevented by adjusting the wavelength of the source which should cause a significant change in output power if the fiber and polarizers are aligned properly. If little power change is observed, the fiber should be rotated and tested again.
2. Polarimetric etching involves additional variables that may affect the number of oscillations necessary for enough cladding removal. Factors include HF concentration (dilutes over time with evaporation) temperature, and the bend radius of the D-fiber loop (stress changes the effective index in the fiber). Due to these factors it may be necessary to adjust the number of oscillations in a new lab setting.

**Fiber Cleaning**

1. After etching, clean the D-fiber in the ultrasonic alcohol bath as done previous to the etch. The fiber is now ready for mating with the slab waveguide.

**Slab Preparation**

1. Crystal slab waveguides can be purchased already cut and polished to the necessary size.

2. Larger crystals may be cleaved into smaller pieces by placing onto an adhesive film and scoring into smaller pieces. The desired piece is removed by folding and creasing the adhesive so that the main body of the crystal piece peels off except at the edge of the crease. The crystal slab can then be grabbed and removed with a set of tweezers.

3. Polymer slabs must be cut to the desired size by placing a razor blade along the lines that are to be cut and then applying sufficient force to pierce through the polymer slab. After cutting the edges to the desired size, the corner of the razor blade is used to scrape the polymer slab off of its substrate. Polymer slabs can be cleaned with a
cloth moistened by alcohol but care should be taken to make sure that it is not dissolved in any degree by the solvent.

**Slab Placement**

1. Prepare the fiber for slab placement by launching an IR Amplified Stimulated Emission (ASE) source into the input and coupling the output into an Optical Spectrum Analyzer (OSA).

2. Polarize the input light either vertically or horizontally depending on which polarization the SCOS is intended to operate in (Usually chosen parallel to the EO axis of slab waveguide)

3. While holding the slab waveguide with forceps, dab a small drop of index-matching UV-cure adhesive onto the face of the slab waveguide (obtained from MY Polymers) by placing the tip of a clean disposable rod into the adhesive bottle (make sure UV adhesive is not exposed to any UV light or its shelf life can be dramatically decreased) and then contact the rod with the slab waveguide.

4. Carefully place the slab waveguide on the etched flat section of D-fiber. Keep the fiber in the etch holder to ensure the flat face of the D-fiber is still oriented upwards.

5. Gravity and surface tension will hold the slab waveguide in place, but its position must be manipulated with the tips of the forceps on the etched section of fiber until transmission dips are seen in the fiber output on the OSA. Manipulating the position and orientation of the slab is necessary to ensure good coupling between the slab and fiber before the adhesive is cured. Moving the slab along the fiber helps spread excess adhesive along the length of the fiber to reduce the thickness of the layer of
adhesive between the slab and fiber until coupling is sufficiently strong and resonant dips are seen in the transmission spectrum.

6. Before curing the adhesive, reposition the slab waveguide until the optimal transmission dips are reduced by ~ 7dB and then expose the adhesive with a UV lamp. As the UV adhesive cures, its index increases and a slight amount of shrinkage occurs which will increase the coupling strength so that optimal transmission dips are permanently set.

**Slab Placement Trouble Shooting**

1. A confocal microscope may be used to observe the contact between the D-fiber and slab waveguide to ensure that no contaminants are visible between the fiber and slab.

2. If no transmission dips are observed after manipulating the slab position for some time, the fiber may not have been etched far enough. Clean the fiber again and do a quick timed etch for a few seconds at a time and try placing the slab again.

3. Polymer slabs can develop a slight curl when pealing or releasing from the substrate which can cause only the edges to make good contact with the fiber. Try flipping the polymer slab upside down if curl is suspected or replace with a flatter sample.

4. Upon curing, if the transmission dips become too deep and begin to widen, then coupling is too strong. The slab can be easily removed with solvent before the cure is complete. Clean the fiber and slab and restart the process.

5. Upon curing, if the transmission dips don’t become deep enough, remove the slab with solvent, clean the slab and fiber and begin the slab placement process again.
6. If using the UV cure adhesive is too tedious because it is difficult to obtain a final product with proper coupling strength and optimal transmission dips, a two-part adhesive may be used. The drawbacks to two-part adhesives are the cure time required and the difficulty in finding an adhesive with low enough index and strong enough bonding strength.

Packaging

1. SCOS sensors may be packaged in various ways depending on the intended use. The following guidelines will help ensure successful packaging:

2. The slab waveguide and etched portion of fiber should be protected from potential contaminants.

3. If encased, a low index non-lossy material should be used to surround the SCOS to eliminate optical losses from the exposed core.

4. When dealing with high dynamic temperature ranges, choose packaging that expands at a similar rate as the fiber.

5. Any protective tubing used in packaging should be inserted before fusion splicing.

6. Splicing

7. For proper use, the SCOS D-fiber ends should be spliced to polarization maintaining fiber with connectorized ends. The proper splicing technique has been developed by Kvavle [44]. To ensure proper splicing and accurate PM extinction ratios, in-situ splicing may be used to monitor the transmission spectrum before the final splice is made.
APPENDIX B.  EO MATERIAL DATA

Lithium Niobate: LiNbO$_3$ [53, 71-73]

Crystal Group: Trigonal, 3$m$

Optical Indices: $n_x = n_y = 2.211$, $n_z = 2.138$

EO coefficients: $r_{13} = 8.6$, $r_{22} = 3.4$, $r_{33} = 31$, $r_{51} = 28$

Permittivity: $\varepsilon_r = 30$

Lithium Tantalate: LiTaO$_3$ [53, 72, 74]

Crystal Group: Trigonal, 3$m$

Optical Indices: $n_x = n_y = 2.1208$, $n_z = 2.1253$

EO coefficients: $r_{13} = 7.5$, $r_{22} = 1$, $r_{33} = 33$, $r_{51} = 20$

Permittivity: $\varepsilon_r = 43$

Potassium Titanyl Phosphate: KTP [65, 75, 76]

Crystal Group: Orthorhombic, mm$^2$

Optical Indices: $n_x = 1.7295$, $n_y = 1.7369$, $n_z = 1.8158$

EO coefficients: $r_{13} = 8.8$, $r_{23} = 13.8$, $r_{33} = 35$, $r_{51} = 6.99$, $r_{42} = 8.8$

Permittivity: $\varepsilon_r = 13$
**Strontium Barium Niobate: SBN** [65, 77, 78]

Crystal Group: Tetragonal, 4mm

Optical Indices: $n_x=n_y=2.312$, $n_z=2.273$

EO coefficients: $r_{13}=67$, $r_{33}=1340$

Permittivity: $\varepsilon_r=3400$

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**4-(4-dimethylaminostyryl)-1-methylpyridinium tosylate: DAST** [64, 79]

Crystal Group: Monoclinic, m

Optical Indices: $n_x=2.132$, $n_y=1.602$, $n_z=1.575$

EO coefficients: $r_{11}=47$, $r_{22}=21$, $r_{13}=5$

Permittivity: $\varepsilon_r=5.2$

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**AJL8/APC**

Crystal Group: Polymer

Optical Indices: $n_x \sim 1.75$, $n_y \sim 1.75$, $n_z \sim 1.75$

EO coefficients: $r_{13} \sim 23$, $r_{23} \sim 23$, $r_{33} \sim 70$

Permittivity: $\varepsilon_r \sim 4$

*Polymer and data parameters acquired from JingDong Luo at University of Washington*
APPENDIX C. THICK WAVEGUIDE LOSS SIMULATION CODE

The MATLAB code used to demonstrate the effects of waveguide thickness on overall SCOS loss is listed in this appendix. While this code is not intended to give an accurate depiction of the SCOS transmission characteristics, it does show how mode ambiguities, arisen from imperfect slab waveguide specifications in parallelism and polish quality, increase optical losses with thicker waveguides.

%%% This will show several mode numbers and at what wavelength various thicknesses will couple. The superposition of each mode number with the corresponding army of modes will be simulated as well.

close all

clear all

% 1 generates a new slab profile, to keep a profile and observe the effects of different thicknesses, change to 0 and adjust the thickness of the slab

new=1;
%Wavelength Range based on usable EDFA Range
minLam=1530;  %Start Wavelength
maxLam=1560;  %Finish Wavelength
spread=abs(minLam-maxLam);  %Wavelength Range
wl=1.55;  %Center Wavelength in microns

% Slab Waveguide Properties
polish=4;  %Polish Quality in wl/polish
t=200;  %Average Slab Thickness
Nf=1.451;  %Fiber mode index
no=2.12;  %Slab bulk Index
l=2;  %slab length in mm
prll=20;  %slab parallelism in arc seconds

% Set thickness Profile

totVar=l*tan(20/60/60*3.14/180)*1e3;  %Finds thickness variation
thicknesses=linspace(t-totVar/2,t+totVar/2,l*20/polish);
if new
    variation=rand(1,length(thicknesses))*wl/polish;
    variation=variation-max(variation)/2;
    save variation variation
end
load variation
thicknesses=thicknesses+variation;

subplot(2,1,1)
plot(thicknesses)
axis([0 length(thicknesses) t-1 t+1])
subplot(2,1,2)

% Determines mode range of interest
FSR=wl^2/(2*t*sqrt(no^2-Nf^2))*1e3;
centerMode=floor(2*t/wl*sqrt(no^2-Nf^2));
numberModes=ceil(spread/FSR)+2;
modes=(centerMode-numberModes): (centerMode+numberModes);
noise=0.001; % sets noise in spectrum

% Find the wavelengths of resonant modes for each mode of each
% thickness present in the non-uniform slab
for m=1:length(modes)
    for t=1:length(thicknesses)
        Lambda(m,t)=2*thicknesses(t)*sqrt(no^2-Nf^2)/modes(m)*1e3;
    end
end

% Create a generic transmission dip
dk=linspace(-1e3,1e3,spread*1e3);
lambda=linspace(minLam,maxLam,spread*1e3);
c=10; % Coupling strength
ResMode = \( c^2 / (c^2 + dk^2 / 4) \);  % Creates a Lorentzian shaped mode

ResMode = ResMode + noise * rand(1, length(ResMode));

ResMode = circshift(ResMode, [0 (spread * 500)]);

Spectrum = ones(1, spread * 1e3);  % A fully transmitting spectrum

%% This double loop subtracts the transmission dips from the full
%% spectrum at the wavelengths previously calculated according to
%% the device parameters.

[a b] = size(Lambda);

for n = 1:a
  for m = 1:b
    cwl = Lambda(n, m);
    if cwl > minLam && cwl < maxLam
      temp = circshift(ResMode, [0 floor((cwl - minLam) / 1e-3)]);
      Spectrum = Spectrum - temp + .001;
    end
  end
end

if max(Spectrum < .04)
  display('Loss Greater than -14 dB');
else
  display(strcat('Loss:', num2str(real(10*log10(max(Spectrum)))), 'dB'));
end
end

loss = real(-10*log10(max(Spectrum)));

Spectrum = Spectrum - min(Spectrum);

Spectrum = Spectrum / max(Spectrum);

y = Spectrum(1000:end-1000);

x = lambda(1000:end-1000);

y = 10*log10(y+.01) - loss;

plot(x,y)

title('Simulation - Ideal thick slab waveguide')

xlabel('Wavelength (nm)')

ylabel('Transmission (dB)')
BIBLIOGRAPHY


