Sapphire Fiber in Optical Sensors

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTERS OF SCIENCE
IN
ELECTRICAL ENGINEERING

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March 1995
Blacksburg, Virginia

Key words: Optical Fibers, Optical Sensors, High Temperature Sensors
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(ABSTRACT)

The physical and optical properties of sapphire fiber has been investigated in an effort to create a high temperature optical fiber sensor. Sapphire fiber demonstrates high optical attenuation. This attenuation is very sensitive to injection conditions, and roughly proportional to the cube of the fiber length. The loss was found to be largely due to surface scattering, which causes the fiber to deviate from a perfect cylindrical waveguide. Because of the high optical losses (and high cost) of sapphire fiber, it is desirable to fashion a splice between the sapphire and an inexpensive, low-loss silica fiber so that sapphire is only used in the sensor head. The great physical disparities between sapphire and silica make this a challenging proposition. One solution demonstrated here is the sapphire capillary tube splice, in which the two fibers are aligned in a sapphire capillary tube and bound together with alumino-silicate glass. Sapphire fiber optical sensors cannot use standard interferometric techniques used with silica fibers because sapphire fibers are
not clad, making a strongly guiding, highly multimode waveguide that introduces a great deal of modal distortion to interferometric signals. Consequently a simple intensity-based sensor was developed and tested using sapphire. More exotic intensity-based sensors are explored with their applicability to a sapphire fiber sensor head.
Acknowledgments

I would like to thank Dr. Richard Claus, my committee chair, for his eternal enthusiasm and his skill in subduing bureaucracy. Thanks to Dr. Kent Murphy for his support, both moral and financial. Also, I would like to thank Dr. Anbo Wang for so willingly agreeing to be on my thesis committee.

Special thanks go to the members of FEORC and F&S who have made working in the fiber optics labs so enjoyable, most especially to Russ May who oversaw much of the funded work with the sapphire fibers.

I also want to thank my ever-supportive family for without them none of this would have been possible. This is especially true for my father, Dr. Norman Barnes, who always displayed great interest in my education, and gave me numerous ideas during the pursuit of my thesis. Finally, greatest thanks to my wife, Mandy Wilson, who has been at my side throughout my graduate school career offering her time, love, and support.

This work was supported in part by NASA, the U.S. Air Force, and Fiber & Sensor Technologies.
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1.0 Introduction

Sapphire optical fiber sensors have great potential for high temperature measurement of various parameters, including displacement, strain, and temperature. Such sensors have the advantages of more common silica optical fiber sensors in that they are small, relatively inert chemically, nonconducting, and immune to electromagnetic interference. Silica optical fiber sensors, however, do not function well at temperatures above approximately 800°C. At these temperatures, the dopants that define the waveguide in the fiber begin to diffuse, the devitrification process rapidly occurs which significantly increases scattering losses, and the glass starts to undergo plastic deformation as it nears its softening temperature. Sapphire, conversely, can withstand temperatures up to 2000°C. Additionally, sapphire is extremely hard and completely inert in almost any environment, making sapphire sensors very durable. Unfortunately sapphire optical fibers have a high optical attenuation and cost that prohibits long pieces of sapphire fiber from being used in a sensor system. This gives rise to the study of sapphire fiber in an effort to circumvent the attenuation problem, and produce a viable sapphire optical fiber sensor. Specifically this breaks down into three problems. The first is to investigate the material properties of sapphire, and how it behaves physically, chemically, and optically. Knowledge of this will provide insight into the second problem: a method for splicing sapphire and
silica fibers together. This will allow most of the sensor system to use inexpensive and optically low-loss silica fibers. Sapphire fiber will only be used in the sensor head, which is the only part of the sensor that is expected to undergo harsh conditions. The material properties of sapphire will also influence the solution of the third problem: that is determining the best sensor configuration using sapphire fiber.
2.0 Physical and Optical Properties of Sapphire Fiber

Before constructing a sapphire fiber sensor, it is beneficial to study various properties of the sapphire fiber, so that an understanding of its strengths and limitations can serve as an instructive guide in the sensor development. In the following sections several facets of the material and optical characteristics of sapphire fiber are explored, including physical properties of sapphire, fabrication and preparation techniques for sapphire fiber, general optical properties, and the waveguiding attributes of sapphire fiber.
2.1 Material Characteristics of Sapphire

The sapphire used in optical fibers is a hexagonal crystalline compound of aluminum and oxygen, Al$_2$O$_3$. For purposes of creating a sapphire fiber sensor, the following material properties are of interest, with corresponding values for silica also listed for comparison [6,8]:

<table>
<thead>
<tr>
<th>Property</th>
<th>Sapphire</th>
<th>Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index of Refraction</td>
<td>1.760 a axis; 1.768 c axis</td>
<td>~1.44 to ~1.48</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>2072 C</td>
<td>~1000 C *</td>
</tr>
<tr>
<td>Hardness</td>
<td>9 mohs</td>
<td>7 mohs</td>
</tr>
<tr>
<td>Solability</td>
<td>Fuming HF, molten alkalis</td>
<td>HF, strong alkali solutions</td>
</tr>
<tr>
<td>CTE</td>
<td>8.5x10$^{-6}$ K$^{-1}$</td>
<td>0.53x10$^{-6}$ K$^{-1}$</td>
</tr>
</tbody>
</table>

* Vitreous silica used in optical fibers does not have a melting point per se, but rather a softening point as it is an amorphous solid. Although pure silica does not soften until 1000 C, most optical fibers are doped to create the refractive index changes needed for its waveguiding structure, and these dopants can depress the softening point by as much as 400 C in some cases.
Sapphire’s high melting temperature allows it to be used in environments that would melt silica fibers sensors. The extreme hardness of sapphire indicates that polished surfaces on sapphire (which are necessary in any optical sensor) are unlikely to be scratched by environmental contaminants. Additionally, scratches are likely to cause microcracks in vitreous silica which can make the fiber very brittle, while the crystalline nature of sapphire prevents this effect in sapphire fiber. It should be noted, however, that although it is significantly more robust than silica fiber, even sapphire fiber has to be handled reasonable carefully, since its dimensions of a hundred microns or so simply do not allow for great mechanical strength. Sapphire’s solubility gives a good indication of the chemical inertness of any sapphire sensor. Because of its low reactivity, sapphire sensors should be immune to most caustic environments. Although this would appear generally true for silica fiber as well, in fact silica fibers are quite vulnerable to environmental degradation. This is because OH- ions bonding to the fiber surface create stresses and microcracks that enbrittle the fiber. In all cases, sapphire makes a good durable sensor material. This durability is a potential drawback in another regard, however. Because sapphire is so resistant to almost any environmental condition, it is difficult to alter the waveguiding properties of the fiber to make a sapphire fiber with lower optical attenuation. The coefficient of thermal expansion (CTE) of sapphire
and silica have some impact on splicing techniques and potential sensor configurations, since the respective coefficients of thermal expansion differ by more than an order of magnitude. The index of refraction is of obvious interest for optical applications, as it influences the waveguiding properties of the fiber, as well as the optical compatibility with silica fiber. Sapphire's crystalline structure causes it to be birefringent, although the effects of this are negligible, as discussed in Section 2.4.
2.2 Sapphire Fiber Fabrication

Sapphire fiber available today is grown as a single crystal from an alumina melt. Two methods are typically used, those being Edge Defined Film-fed Growth (EDFG) and Laser-heated Pedestal Growth (LPG). [4] The EDFG method starts with a crucible of molten alumina. A capillary tube, typically made of molybdenum, is dipped into the melt, whereupon capillary action wicks the molten alumina up to the top. The tube is fashioned to a length so that the temperature at the top of the tube is close to the freezing point of alumina. Then a seed crystal of alumina is dipped into the top of the tube and slowly withdrawn, allowing the fiber to crystallize out of the melt.

Figure 2.2-1 Sapphire Fiber Growth via (a) EDFG, and (b) LPG
The capillary tube controls the geometry of the fiber being grown. Figure 2.2-1(a) illustrates the process. The LPG method begins with a bulk crystal of alumina. A set of two to four CO₂ lasers melts a spot at the top of the crystal. A seed crystal is dipped into the melted alumina and slowly withdrawn. No capillary tube is needed, because the lasers only heat at one point, so that once the fiber is clear of the focus of the lasers it cools readily. The fiber geometry is determined by surface tension. The LPG method has the advantage that it avoids the potential contamination that EDFG method suffers because of the latter's use of a capillary tube. Figure 2.1-1(b) illustrates the LPG method.
2.3 Preparation of Sapphire fiber

Silica fiber is typically prepared for use by cleaving the fiber with a diamond scribe. Once a scratch is initiated, the fiber will break cleanly under tension, creating an optically smooth endface. Sapphire cannot be cleaved in this fashion, because despite its extreme hardness, the crystalline structure of the fiber does not facilitate clean breaks. This necessitates the use of alternative methods for preparing sapphire fibers. Sapphire fiber must be ground and polished to achieve the optically flat endfaces perpendicular to the fiber axis that are needed to allow it to efficiently couple light in and out of the fiber. The perpendicularity of such a polish is of great interest because any deviation will, in effect, create an angular misalignment, which can significantly increase the optical attenuation, as discussed in Section 2.6.4.

For the experiments detailed here, polishing was done with a V-groove block fitted with a bubble level to insure perpendicularity. The sapphire fiber was fixed in the V-groove with phenyl salicilate. The phenyl salicilate melts at a low temperature (under the heat of a heat gun). This allows it to be applied as a liquid to the fiber in the V-groove, where it refreezes, holding the fiber securely to the block. A millimeter or two of fiber extends past the bottom edge of the V-groove block, surrounded by solidified phenyl salicilate. The V-
groove block is then manually held so that the tip of the fiber and surrounding phenyl salicylate touch the polishing wheel, with successively finer grits being used until a smoothness of 0.3 \( \mu \text{m} \) is attained. The V-groove block itself does not come in contact the polishing wheel. During the polishing procedure, the bubble level allows the V-groove block to be held very nearly perpendicular to the polishing wheel. After polishing, the phenyl salicylate can be melted off or dissolved with acetone, freeing the fiber. Figure 2.3-1 shows a diagram of the polishing setup.

![Diagram of polishing setup](image)

**Figure 2.3-1 Sapphire Fiber on a V-Groove Block for Polishing**

The endfaces polished in this fashion typically had an angular deviation of \( 1^\circ \pm 0.75^\circ \) from the perpendicular. Although more sophisticated methods for polishing exist, such as polishing jigs and motor-driven mechanical polishing mounts, that could achieve even greater perpendicularity, these were
unavailable at the time of these experiments. Future work using such equipment could only improve the performance of sapphire fiber sensors.
2.4 Waveguiding Properties of Sapphire Fiber

Sapphire fiber is currently only available as an unclad single crystal. This structure gives rise to a birefringent, strongly guiding waveguide, unlike weakly guiding silica fibers. silica fibers tend to be birefringent due to imperfectly circular core regions. This causes decoupling of degenerate modes in the weakly guiding structure [1]. Sapphire fibers also display birefringence due to imperfect waveguide structure. Unlike silica however, sapphire is inherently birefringent due to the orientation of the crystal lattice that creates ordinary and extraordinary rays propagating through the fiber, as shown below in Figure 2.4-1 [14].

Figure 2.4-1 Incident, Ordinary, and Extraordinary Rays in Sapphire
This birefringence in sapphire effectively leads to two different numerical apertures for the fiber — one for the ordinary ray and one for the extraordinary ray. The ordinary ray numerical aperture can easily be computed through application of Snell's law. To find the numerical aperture of the extraordinary ray requires greater analysis. The effective refractive index, \( n(\theta) \), seen by the extraordinary ray depends on the incident angle \( \theta \), and is given by the equation:

\[
\frac{1}{n^2(\theta)} = \frac{\cos^2(\theta)}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2}
\]  

(2.4-1)

where \( n_o \) is the refractive index for a ray parallel with the ordinary axes of the crystal and \( n_e \) is the refractive index for rays parallel to the extraordinary axis of the crystal.[14] A simple iterative program can be written to solve for the refractive index of the highest angle ray that the sapphire will admit. For an ordinary ray, the admittance angle is 55.4°, while that for the extraordinary ray is 55.5°, which occurs at an effective refractive index of 1.765. Obviously the birefringence of the sapphire is not strong enough to significantly affect the injection of light into the fiber. It does, however, double the number of modes propagating in the fiber. The doubling of the modes does not likely have much effect on the optical propagation in practical terms, since sapphire fiber has such a large
admittance angle that it will support tens of thousands of modes, as computed below [14]:

\[ M \approx \left(4 \frac{a}{\lambda} \sin(\theta)\right)^2 \approx 50,000 \]  

(2.4-2)

where \( a \) is the fiber radius (here taken to be 125 \( \mu \)m) and \( \lambda \) is the wavelength of operation (here taken to be 1.3 \( \mu \)m). For all intents and purposes the difference between 50,000 and 100,000 modes is insignificant for almost any fiber application. The refractive index between the ordinary and extraordinary ray is only 0.005 (only about half of the refractive index between core and cladding in silica fiber) indicating that other possible effects of the sapphire fiber's inherent crystal-induced birefringence are minimal compared to the strongly guiding refractive index differential of 0.76 between the fiber and its air "cladding". As discussed in Section 4.0, the large numerical aperture of sapphire and the huge number of modes it supports renders it unsuitable for most applications in which birefringence would be a concern -- most notably interferometry. For this reason there has been no effort to discover the relative strength of crystal birefringence in sapphire as compared to birefringence caused imperfect waveguiding structure, as birefringence can be disregarded for most sapphire applications.
2.5 Circular Waveguide Structures

An analysis of circular waveguides is instructive in understanding optical transmission through sapphire fiber. The solution to the field equations in a dielectric waveguide have been well studied, and only an outline of them is included below [2, 9, 10, 11].

A cylindrical coordinate system is chosen \((r, \phi, z)\) and it is assumed that there is no radial variation in the fiber so that

\[
\frac{\partial}{\partial \phi} = 0
\]  \hspace{1cm} (2.5-1)

If we look at just the transverse electric modes of the waveguide, we have only \(E_\phi, H_r, \) and \(H_z\) field components. Denoting normal modes of a perfectly circular waveguide with italicized letters, the guided modes are of the form

\[
E_\phi = A_n J_1(\kappa_n r) \exp(i(\omega t - \beta_n z)) \quad \text{for} \quad r < a \quad (2.5-2)
\]

\[
E_\phi = A_n \frac{J_1(\kappa_n a)}{H_1^{(1)}(i\gamma_n a)} H_1^{(1)}(i\gamma_n r) \exp(i(\omega t - \beta_n z)) \quad \text{for} \quad r > a \quad (2.5-3)
\]

\[
H_r = -\frac{i}{\omega \mu} \frac{\partial E_\phi}{\partial z} \quad (2.5-4)
\]

\[
H_z = \frac{i}{\omega \mu} \frac{1}{r} \frac{\partial}{\partial r} (r E_\phi) \quad (2.5-5)
\]
where \( \alpha = \) radius of the circular waveguide

\( \beta_n = \) propagation constant of the \( n \)th mode

\( \kappa_n = (n_s^2 k^2 - \beta_n^2)^{1/2} \)

\( \gamma_n = (\beta_n^2 - k^2)^{1/2} \)

\( k = 2\pi/\lambda_0 \) (propagation constant for free space)

\( n_s = \) refractive index of the waveguide

\( \omega = \) radian frequency

\( J_1 = \) Bessel function of order 1

\( H_1^{(1)} = \) Hankel function of first kind and order 1

Because the boundary conditions require the field components to be continuous at \( r = \alpha \), the eigenvalue equation for \( \beta \)

\[
\frac{\gamma_n}{\kappa_n} \frac{J_1(\kappa_n a)}{J_0(\kappa_n a)} = -\frac{H_1^{(1)}(i\gamma_n a)}{H_0^{(1)}(i\gamma_n a)}
\]  

(2.5-6)

The subscript 0 denotes the Bessel and Hankel functions of zero order. It is now useful to express \( A_n \) in terms of the power carried by each mode.

\[
P_n = -\frac{1}{2} \int_0^\infty \int_0^{2\pi} d\phi E_\phi H_\phi^* \quad \text{with} \quad \frac{\beta_n}{\omega \mu_0} \int_0^\infty r |E_\phi|^2 \quad \text{dr}
\]

(2.5-7)

Now the modes will be normalized to the same amount of power, so that

\( P_n = P \). Then \( A_n \) can be expressed as
\[ A_n^2 = \frac{2\omega\mu}{\pi a^2 \beta_n} P \left( 1 + \frac{k_n^2}{\gamma_n^2} \right) J_0(\kappa_n a) J_2(\kappa_n a) \] (2.5-8)

The modes of the continuous spectrum are given by

\[ E_\phi = BJ_1(\sigma r) \exp(i(\omega t - \beta z)) \quad \text{for } r < a \] (2.5-9)

\[ E_\phi = \left[ CJ_1(\rho r) + DN_1(\rho r) \right] \exp(i(\omega t - \beta z)) \quad \text{for } r > a \] (2.5-10)

\[ H_r = -\frac{i}{\omega \mu} \frac{\partial E_\phi}{\partial r} \] (2.5-11)

\[ H_z = \frac{i}{\omega \mu} \frac{1}{r} \frac{\partial}{\partial r} (rE_\phi) \] (2.5-12)

where \( \sigma = (n^2 k^2 - \beta^2)^{1/2} \)

\( \rho = (\beta^2 - k^2)^{1/2} \)

\( N_1 = \text{Neumann function of order 1} \)

The normalization of the continuous modes involves the Dirac delta function

\[ \rho \delta(\rho - \rho') = \pi \frac{\beta}{\omega \mu} \int_0^\infty r E_\phi(\rho) E_\phi^*(\rho') d\rho \] (2.5-13)

The boundary conditions at \( r=a \) determine the relations between the constants \( C, D, \) and \( B \)

\[ \frac{C}{B} = \frac{\pi}{2} \rho a \left( J_1(\alpha a) N_0(\rho a) - \frac{\sigma}{\rho} J_0(\alpha a) N_1(\rho a) \right) \] (2.5-14)

\[ \frac{D}{B} = -\frac{\pi}{2} \rho a \left( J_1(\alpha a) J_0(\rho a) - \frac{\sigma}{\rho} J_0(\alpha a) J_1(\rho a) \right) \] (2.5-15)
The coefficients can be expressed in terms of the power carried by the mode

\[ P = \pi \frac{\beta}{\rho \omega \mu} (C^2 + D^2) \]  

(2.5-16)

Now with the fields known for the perfect circular waveguide, the fields for an imperfect circular waveguide can be expanded from the normal modes of the perfect waveguide as

\[ E_\phi = \sum_{n=0}^{\infty} C_n E_n + \int_0^{\infty} g(\rho) E(\rho) d\rho \]  

(2.5-17)

The coefficients \( C_n \) and \( g(\rho) \) can be solved for, although this involves considerable mathematical manipulation. The interested reader is referred to references [9, 10, 11]. Only the results will be cited here as they pertain to the discussion of sapphire fiber. It happens that sinusoidal wall perturbations of the strongly-guiding waveguide will couple modes whose beat length,

\[ \Lambda_n = \frac{2\pi}{\beta_0 - \beta_n} \]  

(2.5-18)

coincides with the mechanical period of the wall perturbation. Since any arbitrary wall perturbation can be expanded as a series of sinusoidal functions, this gives a concept of the coupling process due to nonuniformities in the waveguide. As a loss mechanism, the wall perturbations couple guided modes into radiation modes. Due to the visible annular variations visually observed in sapphire fiber, scattering of this nature is inevitably causing
attenuation in the fiber. Not all of the coupling will necessarily be to radiation modes; certainly sapphire fiber supports so many guided modes that there will be significant coupling between guided modes. However, since there are only a finite number of guided modes and a continuous spectrum of radiation modes, one may infer that the loss will be substantial, especially given the magnitude of the annular variations in sapphire fiber. The relative significance of this scattering is explored experimentally in Section 2.6.
2.6 Attenuation in Sapphire Fiber

Experimentally, sapphire fiber has demonstrated a high optical attenuation. This attenuation is extremely sensitive to injection conditions. Understanding the dominant source of the attenuation is necessary if it is to be circumvented or at least taken into account for potential sensor design. The likely causes are either bulk scattering, surface scattering, or absorption. Intuitively, absorption would not be the dominant loss mechanism because it does not explain the extreme sensitivity of sapphire to injection conditions. Further tests are needed, however, to verify this hypothesis. Experiments detailed below used fiber grown by the EDFG method, since EDFG fibers are more available than LPG fibers.
2.6.1 Absorption in Sapphire Fiber

If absorption due to impurities in the fiber were the primary source of loss in sapphire fiber, one would expect light injected into the fiber to essentially disappear. As a first order experiment, a length of sapphire fiber was injected with a HeNe laser. The light appeared to scatter out along the length of the fiber very strongly, suggesting that absorption was not the primary source of attenuation. A more rigorous experiment would be to inject white light into the fiber and monitor the output power over a range of wavelengths. One would expect that there would be absorption peaks at different wavelengths in such an experiment. This was done using an optical spectrum analyzer, as shown in Figure 2.6.1-1.

![Diagram: Spectral Analysis of Sapphire Optical Transmission]

Figure 2.6.1-1 Spectral Analysis of Sapphire Optical Transmission

The results were that the sapphire has a uniform power transmission from 800 nm to 1300 nm. Because they are standard for silica fiber systems, these are the wavelengths most likely to be used in a sapphire sensor system.
Although these experiments support the idea that absorption is not the dominant loss mechanism in sapphire fiber, they are not conclusive. The most likely contaminant in sapphire fiber would be molybdenum, arising from the capillary tube used when drawing the fiber, as discussed in Section 2.2. Molybdenum has a broad absorption range, that would not show up strongly in a spectrum scan, and while the scattering of the HeNe laser light, while suggestive, is not conclusive. Consequently it is necessary to examine the losses from the scattering end of the problem.
2.6.2 Scattering in Sapphire Fiber, Numerical Model

A visual inspection of a sapphire fiber under a microscope will show the fiber to be non-uniform along its axis, having an annular fluctuation along its length. Such deviations will give rise to scattering, as indicated above in Section 2.5. Although a rigorously mathematical theory can model this loss, it is very complex. Consequently, a simpler algorithm to give an indication of the losses in a fiber has been developed (See Appendix for FORTRAN code). The algorithm actually consists of two programs that differ only in that one computes the power throughput for a given fiber length, and the other for a given acceptance angle. The algorithm uses a ray-trace approximation (valid considering sapphire fiber has an effective core size of 125 μm and the wavelength of light used is only one percent of that), as shown below in Figure 2.6.2-1.

![Figure 2.6.2-1 Ray Tracing Through Sapphire Fiber](image-url)

Figure 2.6.2-1 Ray Tracing Through Sapphire Fiber
Although this only takes into account meridional rays, for the purposes of the algorithm it is only necessary to analyze a few rays in the fiber and assume that other rays will have a proportionately similar loss. The number of reflections for a given fiber length is given by:

\[
N = \frac{L_f}{L_b} = \frac{L_f \tan(\theta)}{2a}
\]  

(2.6.2-1)

Assuming the input to the fiber has a gaussian profile, then the power throughput can be computed from:

\[
P \approx \frac{2}{\pi \theta_o^2} \int_0^{\pi/2} R^\theta \exp\left( -\frac{2\theta^2}{\theta_o^2} \right) \sin(\theta) d\theta
\]  

(2.6.2-2)

where \( R \) is the reflection coefficient at the sapphire-air interface. For the algorithm, \( R \) was based on the reflection coefficient for a perpendicularly polarized wave, modified with a scattering loss factor. For purposes of numerical analysis, it is convenient to write equation (2.6.2-2) as:

\[
P \approx \frac{2}{\pi \theta_o^2} \int_0^{\pi/2} \exp\left[ -\frac{2\theta^2}{\theta_o^2} + \frac{\tan(\theta)L_f}{2a} \ln(R) \right] \ln(R) \sin(\theta) d\theta
\]  

(2.6.2-3)

For a set of values the power throughput is normalized with respect to the greatest value. It is also weighted according to scattering length or for light volume for a given acceptance angle, depending on whether attenuation is being computed for fiber length or acceptance angle respectively. This
algorithm was compared with experimentally measured values for both the
case of attenuation versus fiber length and the case of attenuation versus
acceptance angle. Both experiments are described below and compared to
the theoretical values derived from the algorithm.
2.6.3 Attenuation versus Fiber Length

To test the attenuation versus length in sapphire fiber, a length of fiber was spliced onto a silica fiber (see Section 3.0 for splicing techniques), to insure that the injection conditions into the sapphire would remain as constant as possible. The spliced silica fiber was injected with laser light and a photodetector measured the light emerging from the sapphire fiber. The laser light passed through a mode mixer to insure a uniform distribution of modes to lessen the possibility of preferentially exciting modes in the sapphire fiber. Figure 2.6.3-1 shows the experimental setup.

![Figure 2.6.3-1 Setup for Attenuation Measurements of Sapphire Fiber](image)

The spliced fibers were removed, a small section of the sapphire fiber was broken off, and the spliced fiber was repolished. Then the amount of light getting through the fiber was again measured. This was repeated several times to generate a set of data points showing attenuation versus sapphire fiber length. It should be noted that even with the spliced fiber some variation in the injection conditions still occurred. This is probably due to
inconsistent modal excitation experienced by the spliced silica fiber, despite
the use of the mode mixer to make the injection distribution more nearly
uniform. However, the variation was not as severe as has been seen for
unspliced sapphire. However, due to this potential source of error, several
measurements were taken at each length of the sapphire fiber and averaged.
Figure 2.6.3-2 shows a plot of the attenuation computed by the algorithm
versus the experimental values. Given potential experimental error in
measuring sapphire fiber, the theoretical and experimental curves match
relatively well. This justifies the use of the algorithm to analyze some of the
attenuation properties, at least to a first-order approximation.

![Graph showing optical attenuation vs. sapphire fiber length]

Figure 2.6.3-2 Optical Attenuation vs. Sapphire Fiber Length
The computer algorithm points out two interesting facts about optical attenuation in sapphire. First, from Figure 2.6.3-2 one notes that the loss goes to zero not when the fiber length goes to zero, but when it goes to 5 cm. This would suggest that the scattering loss does not establish itself until the light propagates some distance into the fiber. Such behavior can be explained as the beat length of the sapphire fiber’s annular variations with the injected light, as described in Section 2.5. It would appear then that surface scattering in the fiber dominates over bulk scattering. Additionally, this lends greater weight to the idea that absorption is not a significant loss factor, for if it were the loss would not approach zero for a non-zero length of fiber. The beat length is not likely to be the same for any two fibers, however, since the annular variations that are the likely cause of the surface scattering are dependent on individual fiber growth. This could potentially differ from fiber to fiber, especially between fibers grown by different methods. The second point that the algorithm exposes is that the slope of the curve indicates that the attenuation is approximately proportional to the cube of the fiber length. Consequently, the loss in the fiber increases very rapidly as the length of the fiber increases. In light of this, any sensor system using sapphire fiber should keep the sensor head length as short as possible.
2.6.4 Attenuation versus Acceptance Angle

The attenuation of sapphire fiber as a function of acceptance angle can be inferred from the optical profile of the sapphire fiber. The profile was measured by injecting an expanded HeNe laser beam into the fiber and monitoring the optical power throughput while rotating the fiber on a stage to change the injection angle, as shown in Figure 2.6.4-1.

![Diagram of optical profile measurement setup]

Figure 2.6.4-1 Measurement of Optical Profile of Sapphire Fiber

The resulting optical profile is plotted with the theoretically determined profile below in Figure 2.6.4-2.
Figure 2.6.4-2 Optical Profile of Sapphire Fiber

The theory and experimental data agree reasonably well up to an angle of 35°, although the theoretical curve is slightly low. This may be attributed to the fact that the theory assumes scattered light is lost, while in actuality it may be coupled from one guided mode to another. Beyond 35°, another loss mechanism seems to take precedence over the scattering. Most likely, reflection off the endface of the sapphire becomes significant enough that not as much light is coupled into the fiber in the first place. If one looks at a plot of transmission versus incidence angle, as shown in Figure 2.6.4-3, it can be seen that the transmission is relatively constant up to about 30°, after which point it starts to decrease rapidly.
Figure 2.6.4-3 Transmission vs. Incidence Angle at Air/Sapphire Interface

In any event, the most likely candidate for coupling light into the sapphire fiber is silica fiber, which has a transmittance angle of only around 10 degrees; well within the range at which the theoretical and experimental curves agree. Also note in Figure 2.6.4-2 that, even though sapphire has an acceptance angle of 55 degrees, some light is still present out at 60 degrees. This is likely due to either noise or light being scattered off the circumference of the fiber into internally guided modes. The most significant point to be noticed from the optical profile is that the power entering the fiber drops off sharply with any deviation from normal incidence, unlike silica fiber, which has a gaussian-shaped profile, as shown in Figure 2.6.4-4.
Figure 2.6.4-4 Optical Profiles of Sapphire and Silica Fiber

Whereas silica fiber has a rounded optical profile, sapphire has a peak in the center of its profile. This would explain the extreme sensitivity of sapphire fiber to injection conditions; even a small misalignment will significantly impact the power throughput of the fiber. Hence, for splicing and sensor applications, it is necessary to take extreme care with aligning the sapphire fiber. Additionally, the more nearly perpendicular the polished endface on the sapphire the better, as any deviations will effectively introduce angular misalignment.
3.0 Sapphire-Silica Splices

Because of the high optical attenuation and cost associated with sapphire fiber, it is desirable to use as little sapphire as possible in the sensor system. The other fiber leads can be made of inexpensive, low-loss silica fiber. This scheme requires the development of a reliable, rugged, low-loss sapphire-silica splice. Because sapphire melts at a much higher temperature than silica, the standard silica fiber splicing technique of fusion splicing is not an option. Investigations into several splicing techniques have been made, including diffusion splicing, splicing with coated fibers, splicing with intermediate fiber binders, splicing with ceramic, and splicing inside capillary tubes [4]. Most of the splicing techniques run into one of two problems. First, because sapphire and silica have largely differing coefficients of thermal expansion, techniques that involved heating the splice tended to be very weak mechanically, with the silica fiber breaking in many cases. Second, due to the sensitivity of sapphire fiber to the injection conditions, most techniques could not provide adequate alignment for an optically low-loss splice. Table 3.0-1 shows a summary of the relative strengths of these methods.
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Table 3.0-1 Sapphire-Silica Splices

<table>
<thead>
<tr>
<th>Splice Type</th>
<th>Optical Loss</th>
<th>Mechanical Strength</th>
<th>Ease of Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion Enhanced</td>
<td>?</td>
<td>Very Fragile</td>
<td>Simple</td>
</tr>
<tr>
<td>Fusion</td>
<td>~6.5 dB</td>
<td>Fragile</td>
<td>Simple</td>
</tr>
<tr>
<td>Silica Coated Sapphire</td>
<td>~7 dB</td>
<td>Fragile</td>
<td>Difficult</td>
</tr>
<tr>
<td>ALG Coated Sapphire</td>
<td>~3.5 dB</td>
<td>Moderate</td>
<td>Very Difficult</td>
</tr>
<tr>
<td>ALG Intermediate Fiber</td>
<td>~5.5 dB</td>
<td>Fragile</td>
<td>Moderate</td>
</tr>
<tr>
<td>Silicone Adhesive</td>
<td>?</td>
<td>Very Fragile</td>
<td>Simple</td>
</tr>
<tr>
<td>Silica Capillary Tube</td>
<td>~3 dB</td>
<td>Fragile</td>
<td>Moderate</td>
</tr>
<tr>
<td>Steel Capillary Tube</td>
<td>~25 dB</td>
<td>Strong</td>
<td>Difficult</td>
</tr>
<tr>
<td>Sapphire Capillary Tube</td>
<td>&lt;1 dB</td>
<td>Very Strong</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

This is because sapphire fiber is so sensitive to injection conditions that some splices, while potentially low loss, aggravate the loss in the sapphire fiber, and so the overall loss in the system is great. The splice loss above was determined by measuring the optical power through the splice, and then the power through the silica fiber alone. The splice loss, \( L_{\text{splice}} \), is then computed as:

\[
L_{\text{splice}} = 10 \log \left( \frac{M_{\text{splice}}}{M_{\text{silica}}} \right) - FL_{\text{sapphire}} \quad (3.0-1)
\]
where $M_{splice}$ and $M_{silica}$ are the optical power measurements through the splice and silica fiber alone respectively, $F$ is the fiber length, and $L_{sapphire}$ is the loss per unit length in the sapphire fiber itself. This is computed by taking a sample piece of fiber, and measuring the optical power through it. Then it is cut back, repolished, and a second power measurement is taken. Then it can be computed as:

$$L_{sapphire} = 10 \log \left( \frac{M_{short}}{M_{long}} \right) \frac{1}{F}$$

(3.0-2)

where $M_{long}$ and $M_{short}$ are the optical power measurements of the long and short pieces of fiber respectively.

As can be seen from Table 3.0-1, the most reliable splice is the sapphire capillary tube splice. This splice is made by sandwiching a small piece of alumino-silicate glass (ALG) between the sapphire and silica fibers to be spliced together inside of a close-fitting sapphire capillary tube. The ALG, which softens at a temperature lower than silica, is then melted on an arc-fusion splicer, and the sapphire and silica fibers are then pushed into the molten ALG. Upon cooling, the ALG hardens, holding the fibers in place. The set-up for this splice is shown below in Figure 3.0-1. Because a small section of bare silica fiber, which is very prone to break, protrudes from the
sapphire tube, it is necessary to put a silica tube over the whole assembly and fix it in place with ceramic adhesive for protection.

![Diagram of sapphire capillary tube splice setup]

Figure 3.0-1 Sapphire Capillary Tube Splice Setup

This splice holds the fibers in good alignment because of the tight fit between the capillary tube and the fibers, which will not allow axial or angular misalignment. The sapphire capillary tube has the advantage that it does not fracture due to thermal stress upon cooling after the splice has been made, as the silica tube is prone to do. The sapphire tube is superior to the steel tube in that the sapphire is also transparent, so the splice can be monitored as it is made, allowing for better splices. Finally, the ALG acts as a binder and prevents the formation of mullite at the splice interface, while
providing an intermediate refractive index between the two fibers that reduces Fresnel reflections at the splice interface.

Although the sapphire capillary tube splice has proven effective, there are two potential problems with this method. The first is the use of ALG. Although the ALG melts at a lower temperature than the silica fiber, it is not typically the limiting factor on the temperature resistance of the splice. This is because the silica fiber is likely to be clad in acrylate or polyimide, which burn at much lower temperatures than at which ALG begins to significantly soften. However, if gold-coated silica fiber is used, then the ALG does become the limiting temperature factor, only allowing the splice to reach temperatures of 600 C or so before the fibers could potentially slip. These factors should be taken into account when designing a sapphire sensor head; the sapphire fiber should be kept as short as possible for attenuation reasons discussed in Section 2.6.3, but should be long enough to keep the splice away from excessive temperatures. Overall, the ALG does not pose a serious limitation. A more troublesome aspect of this method is that sapphire capillary tubes of the necessary dimensions are not readily available. The process for making the tubes is not yet perfected, so that there is no reliable way to obtain them at the present time, although work continues on their development.
4.0 Sapphire Optical Fiber Sensors

Sapphire fiber, unlike silica fiber, is a strongly guiding structure. It has no cladding per se, except its surrounding environment. Because of this, sapphire fiber is a highly multimode waveguide, supporting tens of thousands of modes, as computed in Section 2.4, and has a high numerical aperture. This poses a difficulty with interferometric sensing techniques that are used in many silica-fiber sensors. The large number of modes and high numerical aperture give rise to high modal noise and low spatial coherence, which make interferometry impractical. A sapphire fiber with a small enough diameter to be single mode would be on the order of half a micron in diameter, making nearly impossible to handle without breaking and making injection of light into the fiber extremely difficult. And to date, no sapphire fibers have been suitably clad to reduce the numerical aperture.

Consequently, it is desirable to develop an intensity-based sensor that is immune to the modal problems faced by interferometric sensors. Some possible sensors are described below.
4.1 Basic Sapphire Intensity Sensor

Figure 4.1-1 shows one simple intensity-based sensor, with a detail of the sensor head shown in Figure 4.1-2. In this sensor configuration, the sapphire fiber and reflector that comprise the sensor head are located in the test region, ostensibly at high temperature or in a hostile environment that the sapphire can withstand. The injected light goes through the sapphire fiber, across the gap between the sapphire fiber and reflector, whereupon it is reflected back into the sapphire fiber and goes to the photodetector.

![Diagram of the sapphire sensor system]

Figure 4.1-1 Intensity-Based Sapphire Sensor System
As the gap size changes, the intensity of the reflected light will change correspondingly, growing dimmer with increasing longitudinal separation between the fiber and reflector. The intensity measured from the sensor head is then divided by the intensity measured for the reference arm of the sensor, which is unaffected by the environmental parameter being measured, to compensate for possible source fluctuations. Mathematically, this is expressed as:

\[ G \propto \log\left(\frac{P_s}{P_R}\right) \]  

(4.1-1)

where \( G \) is the gap size between the fiber and reflector, \( P_s \) is the power from the sensor arm, and \( P_R \) is the power from the reference arm.
The sensor can be configured so that the gap between the sapphire fiber and reflector is dependent on the parameter to be tested; generally this is accomplished by choosing the substrate upon which the sensor head is mounted to be one that expands or contracts in the presence of the test parameter. The most obvious application is measuring temperature. The substrate is chosen with a known coefficient of thermal expansion. As the temperature increases, the substrate will expand, thereby increasing the gap size in the sensor head.

As a proof-of-concept experiment, the sensor configuration in Figure 4.1-1 was set up to measure displacement. Figure 4.1-3 shows the data obtained

![Figure 4.1-3 Sapphire Intensity-Based Sensor Output](image)
for two test runs. In this instance, the reflector was a mirror mounted on a
translation stage, that allowed measurement of the gap size by means of the
micrometer that was mounted on the translation stage. Although the results
are reasonable, they are not as linear as would be desired. Some of this may
be attributed to the fact that the mirror and the endface of the sapphire fiber
may not have been parallel, as trying to align fibers with bulk optics is a
tricky endeavor. In the case of a fiber reflector held inside a capillary tube,
the degree of parallelism could be controlled with greater precision, allowing
for a more nearly linear plot. A few points should be made about the use of a
capillary tube and reflector fiber in this sensor, and other possible sapphire
sensors using this basic sensor head design. First, the fiber and the reflector
must have very nearly parallel endfaces. If they do not, the attenuation in
the sapphire fiber for the reflected signal will be high due to the angular
misalignment, as described in Section 2.6.4. Hence the polish on both the
fiber and the reflector needs to have a high degree of precision. Second, the
capillary tube must be smooth and straight to maintain endface parallelism.
Unfortunately, sapphire capillary tubes with these specifications and the
necessary dimensions are not readily available, as discussed in Section 3.0.
However, because the sensor head does not necessarily require an optically
transparent capillary tube as does the sapphire-silica splice, other tube
materials might be utilized, such as high-temperature metals or ceramics.
Unfortunately, this will almost invariably mean that the tube will have a different CTE than the sapphire fibers. If the CTE is too high, at high temperatures the tube may expand to the point that it will no longer hold the fibers tightly enough to maintain the necessary degree of endface parallelism. If the CTE is too low, the tube will not expand enough and consequently hold the fibers so tightly that they cannot move. Because the capillary tube must be close-fitting to begin with, in order to achieve the alignment requirements there is not much room for CTE mismatch. Additionally, ceramic capillary tubes are not commercially available, and may not be possible to fabricate with the necessary dimensions and tolerances. Work is continuing in this area, however, so that a reliable source of capillary tubes may be found in the future.

Second, because of the high attenuation of sapphire fiber, a large amount of light needs to be reflected back to allow the sensor operation to remain above the noise floor. Consequently, the reflector fiber needs a coating to increase the reflectivity. The sensor in Figure 4.1-1 was attempted using an uncoated sapphire fiber reflector in a silica tube for a room-temperature demonstration of the sensor. However, the uncoated sapphire failed to reflect a sufficient amount of light to generate a usable signal, confirming the speculation that a reflective coating is required. This poses some difficulty in itself, however, as
All of these metals have sufficiently high melting temperatures that they will not be the limiting factor in a sapphire intensity sensor. The CTEs differ by at most a factor of two from sapphire, so that potential damage to the reflector at high temperatures due to CTE mismatch is minimized. The most promising metal appears to be tantalum, due to its very high reflectivities at 1300 nm, although any of the metals would have a significantly higher reflectivity than uncoated sapphire. Further investigation is needed to determine whether tantalum, or any other metal, will be an adequate reflector, though, due to potential problems with reactivity at high temperatures (most likely oxidation, although possibly diffusion into the sapphire) or with applying the metal to the sapphire endface. It may be possible to apply with a thin layer of aluminum oxide over the reflector metal in order to prevent or reduce oxidation or other chemical attack if that becomes a problem. It would be tempting to just use a thin metal wire as a reflector rather than coating a sapphire fiber for that purpose. Experimentally, however, this approach is not feasible, because metals are too ductile when they have the dimensions of a fiber, so that polishing the end to form a reflector and inserting it into the sapphire tube is difficult. Although this procedure has been accomplished, the metal reflector endface is typically not parallel to the sapphire fiber endface, resulting in poor alignment and consequently high attenuation.
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4.2 Diffraction Grating Intensity Sensor

Another potential intensity-based sensor design would use a dispersive element, such as a diffraction grating between the tip of the sapphire fiber and the reflector. This would cause the monitored intensity to be wavelength-dependent, and so by observing the relative power between two distinct wavelengths, absolute position can be determined. This is given by:

\[ G \propto \log\left(\frac{P_{\lambda_2}}{P_{\lambda_1}}\right) \]  

(4.2-1)

where \( G \) is the gap size between the fiber and the reflector, \( P_{\lambda_1} \) and \( P_{\lambda_2} \) are the powers of the two wavelengths under interrogation. Such a sensor has been demonstrated using all silica fiber [15]. In this configuration, a bulk optic diffraction grating is used on the reflector as the dispersive element,

![Diagram of Intensity-Based Sensor Incorporating a Diffraction Grating](image)

Figure 4.2-1 Intensity-Based Sensor Incorporating a Diffraction Grating
and two wavelengths are monitored at the output of the coupler, as shown in Figure 4.2-1. Although this scheme has been shown to work in concept, there are some difficulties adapting it to a sapphire sensor system. It requires the use of a high-temperature diffraction grating, which, to date, does not exist. Part of the reason for this is the difficulty in finding a reflective material that will withstand high temperatures without degradation, as mentioned earlier. Further, most materials capable of withstanding such temperatures are extremely hard, so that ruling a grating in them is generally impractical if not impossible. Finally, it would be desirable to use a fiber diffraction grating instead of a bulk diffraction grating reflector in order to keep the size of the sensor head to a minimum and to allow the use of a capillary tube to provide good alignment between the sapphire fiber and reflector fiber. But in using a fiber diffraction grating reflector there is the problem of machining a grating into a fiber endface that is only a little over a hundred microns in diameter. Nonetheless, it may be possible to create such a grating on a sapphire fiber endface by exotic methods such as ion milling. Dozens of fiber reflectors could then be made simultaneously, which would bring down the cost of individual grating reflectors. Once made, the gratings could be coated with a metallic thin film to boost reflectivity. Such techniques hold enough promise to warrant further study of a diffraction intensity sensor, although several technical challenges still need to be resolved.
4.3 Other Sapphire Optical Sensors

The previous two sensors utilize modified Fabry-Perot cavities in their design. Although this configuration can allow for a highly versatile sensor (since the displacement can be made to be dependent on a wide variety of test parameters), other configurations are possible. A few are mentioned below.

If the tip of the sapphire fiber is coated with a thin film of a suitable metal (such as iridium), that metal will act as a blackbody radiator at high temperatures. The sapphire fiber will capture some of the radiated light, and carry it out of the hot zone. The blackbody radiation can be analyzed and the temperature determined from this information [3]. Such a sensor has not only been demonstrated, but is commercially available from Accufiber, Inc. The sapphire “fiber” in this sensor is 1.27 mm in diameter -- roughly ten times the diameter of a standard silica optical fiber. However, it is large enough that the fiber can be polished longitudinally so as to remove surface scattering losses. The largest limitation on this sensor is that it can only measure temperature, but it fulfills this function very well.

Aluminum oxide is the basis not only for sapphire fibers, but also for ruby laser crystals. A sapphire fiber doped with a sufficiently high concentration
of chromium ions could potentially be made to lase. If the fiber were then strained, the effective lasing cavity would elongate, which would cause a wavelength shift in the laser output. By monitoring this shift, the strain could be computed. If the fiber laser were attached to a substrate that will expand in the presence of temperature, electromagnetic fields, or some other parameter to be measured, the elongation of the substrate could be measured and correlated to the change in the parameter to be measured. There are several potential advantages to fiber lasers. Because of the small diameter of the fiber, excellent optical confinement would be possible. Additionally, the thermal stresses found in standard ruby-laser rods would be reduced because of the smaller fiber volume. Given a long enough length of fiber, the number of supportable lasing modes would be a near continuum, allowing for fine measurement. Unfortunately, there are many difficulties with fiber ruby-lasers. Most obviously the high scattering losses in sapphire fiber may be so great as to preclude lasing altogether. Potentially one could use a large sapphire "fiber," as is done with the blackbody radiation sensor, so that it could be longitudinally polished to eliminate surface scattering. However, for this sensor configuration that is not wholly desirable as it will make the sensor less sensitive because a greater stress would be necessary to elongate the fiber. The largest failing of this sensor is that it will not lase at elevated temperatures. Typical rod ruby-lasers are almost never operated above 130
C because of spectral broadening and reduced laser efficiency [12]. Further, at temperatures above 500 C the ruby will cease to lase altogether because the thermal energy in the crystal will be too high for the electrons to return to ground state, which is necessary for stimulated emission to take place [7]. Although it may be possible to create a fiber ruby-laser for low temperature applications, there are other fiber sensors that have already been developed and are much less expensive that would suffice. The high temperature tolerance of sapphire, which is its strongest asset for sensor applications, can not be exploited by the fiber ruby-laser, making its development significantly less attractive.

Work has been done with self-mixing laser-diode interference that would be applicable to fiber sensors [5]. When light from the laser diode is reflected back into the lasing cavity from some reflector surface, it can modulate the diode output. If the back-facet photodetector in the laser diode cavity is monitored, the velocity of the reflector surface relative to the laser diode can be determined. Doppler velocimeters have been constructed in this fashion [16]. The advantage to this approach is that the self-mixing is not dependent on either the coherence length of the laser or on whether the fiber used is single or multimode [5]. This opens up the possibility of using a sapphire fiber in conjunction with the laser-diode self-mixing effect for high
temperature sensors. The major drawback of using sapphire fibers in such a sensor configuration is that because the self-mixing phenomenon is power dependent, the high losses in sapphire fiber may lower sensitivity significantly. Because the performance of the sensor is dependent on relative velocity, it could not be used in quasi-static applications; the overall sensitivity of the sensor would determine how low the velocity could be before the sensor failed to detect it. Given the high attenuation in sapphire fiber, this could severely limit the number of potential applications for this sensor configuration.
5.0 Conclusions

Sapphire fiber holds promise for the development of compact optical sensors usable in harsh environments and adverse conditions. Of particular interest are high temperature applications, but sapphire sensors could also see use in applications that would expose the sensor to caustic or oxidizing environments, or to high electromagnetic fields and discharges. Sapphire fiber displays considerable optical attenuation, however, largely due to surface scattering effects. This scattering is caused by coupling between guided and radiation modes whose beat length corresponds to the period of the annular variations in the fibers. This loss is roughly proportional to the cube of the fiber length, and creates an optical profile with a sharp central peak that makes the sapphire fiber very sensitive to injection conditions. Because of the high attenuation, practical sapphire fiber optical sensors will only use sapphire in the sensing region, and use low-loss silica fiber in the rest of the sensor configuration. To this end, the sapphire capillary tube splice has been developed, which provides mechanically strong, optically low loss coupling between sapphire and silica fibers. The strongly guiding, highly multimode nature of sapphire fiber makes standard interferometric sensing techniques used with silica fibers impractical. A simple intensity-based sensor has been demonstrated for sapphire fiber, although further
work is needed in this area to realize a practical sapphire sensor usable in the field.
6.0 Future Research

The major technical challenges that need to be addressed in a sapphire fiber sensor include: 1) the development of a suitable reflector for use at high temperatures or other harsh conditions; 2) finding a reliable source of suitable capillary tubes for splicing and sensor head design to meet the stringent alignment requirements of sapphire fiber; 3) improving sapphire fiber growth techniques to reduce the surface scattering that dominates optical attenuation in sapphire. Additionally, more testing is needed with the basic sapphire intensity-based sensor detailed in Section 4.1, including use of a fiber reflector and high temperature testing of the sensor. Other intensity-based sensors, such as one incorporating a dispersive element in the sensor head, may also be possible with further research. With a greater understanding of the material and optical properties of sapphire fibers, work can be focused on overcoming the present limitations and developing the full potential of sapphire fiber optical sensors.
References


Appendix

Presented below is the FORTRAN code used to compute various parameters in this paper. These include programs SPHIREL (which computes attenuation versus length in sapphire fiber), SHPHIREN (which computes the optical profile of sapphire fiber), OPTPROF (which computes the optical profile of silica fiber as compared to sapphire fiber), and TRANS (which computes the transmission coefficient for parallel and perpendicular polarization at an air/sapphire interface). The first three programs are driver modules that all utilize the same set of subroutines and user defined functions. The driver modules are all presented separately from the set of subroutines and user defined functions, which are only listed once following the modules.
PROGRAM SPHIREL

SAPPHIRE computes the power getting through a step index dielectric waveguide, developed here for sapphire fiber.

A = Lowest ray angle with the axis of the fiber
   (i.e., zero)
B = Highest ray angle with the axis of the fiber
   (limited in the case of sapphire fiber by the numerical aperture of the input beam)
AIRN = Refractive index of air
SAPHN = Refractive index of sapphire
PT = Power throughput
FL = Fiber length

IMPLICIT DOUBLE PRECISION (A-H, I-Z)
EXTERNAL PTHRU
OPEN ( 1, FILE = 'A:SPHIREL.OUT')
AIRN = 1.D+00
SAPHN = 1.76D+00
A = 0.D+00
B = SNELL ( AIRN, SAPHN, DASIN( 0.25D+00))
ISTART = 5
DO 400 I = ISTART, 12
   FL = I*(1.D-02)
   CALL DQSIMP ( PTHRU, A, B, PT, FL)
   FLCM = FL * 100.D+00
   IF ( I .EQ. ISTART) DUM = PT/(I*I*I)
   PTDB = 10.D+00 * DLOG10(PT/(I*I*I*DUM))
   WRITE ( 1,* ) FLCM, PT, PTDB
   WRITE (*,(1X,F3.0,3X,F10.4,3X,F9.4)') FLCM,PT,PTDB
400 CONTINUE
STOP
END
PROGRAM SPHIREN

SAPPHIRE computes the power getting through a step index dielectric waveguide, developed here for sapphire fiber.

A = Lowest ray angle with the axis of the fiber (ie, zero)
B = Highest ray angle with the axis of the fiber (limited in the case of sapphire fiber by the numerical apertature of the input beam)
AA = Incremental angle in radians
AIRN = Refractive index of air
SAPHN = Refractive index of sapphire
PT = Power throughput
FL = Fiber length

IMPLICIT DOUBLE PRECISION (A-H, P-Z)
EXTERNAL PTHRU
OPEN (1, FILE = 'A:SPHIREN.OUT')
AIRN = 1.D+00
SAPHN = 1.76D+00
A = 0.D+00
FL = 10.D-02
ISTART = 1
DO 400 I = ISTART, 75, 5
AA = I*DACS(-1.D+00)/180.D+00
B = SNEIL (AIRN, SAPHN, AA)
CALL DQSIMP (PTHRU, A, B, PT, FL)
FLCM = FL * 100.D+00
IF (I .EQ. ISTART) THEN
  DUM = PT
ELSE
  PT = PT/I
END IF
PTDB = 10.D+00 * DLOG10(PT/DUM)
J = I - 1
WRITE (1,*) J, PTDB
WRITE (*,'(1X,I3,3X,F9.4)') J, PTDB
400 CONTINUE
STOP
END
PROGRAM OPTPROF

OPTPROF computes the optical profile for silica and sapphire fiber

A = Lowest ray angle with the axis of the fiber
   (i.e., zero)
B = Highest ray angle with the axis of the fiber
   (limited in the case of sapphire fiber by the numerical aperture of the input beam)
AA = Incremental angle in degrees
AIRN = The refractive index of air
SAPHN = The refractive index of sapphire
PT = Power throughput for sapphire fiber
SILICA = Power throughput for silica fiber
FL = Fiber length

IMPLICIT DOUBLE PRECISION (A-H, P-Z)
EXTERNAL PTHRU
OPEN ( 1, FILE = 'A:OPTPROF.OUT')
AIRN = 1.D+00
SAPHN = 1.76D+00
A = 0.D+00
FL = 10.D-02
CNST = 2.D+00/DACOS(-1.D+00)
CNST0 = 0.25D+00
ISTART = 1

DO 400 I = ISTART, 16
   AA = I*DACOS(-1.D+00)/180.D+00
   SILICA =CNST/CNST0*DEXP(-2.D+00*AA*AA/((CNST0*CNST0))
   B = SNELL ( AIRN, SAPHN, AA)
   CALL DQSIMP ( PTHRU, A, B, PT, FL)
   FLCM = FL * 100.D+00
   IF ( I .EQ. ISTART) THEN
      DUM = PT
      DUMSI = SILICA
   ELSE
      PT = PT/I
   END IF
   PTDB = 10.D+00 * DLOG10(PT/DUM)
   PTDBSI = 10.D+00 * DLOG10(SILICA/DUMSI)
   J = I - 1
   WRITE ( 1,*) J, PTDB, PTDBSI
   WRITE (*,'(1X,I3, 2(3X,F9.4))') J, PTDB, PTDBSI
400 CONTINUE
STOP
END
SUBROUTINE DTRAPZD ( FNCTN, A, B, S, N, FL)

This routine computes the Nth stage of refinement of an extended trapezoidal rule. FNCTN is input as the name of the function to be integrated between limits A and B. For N=1, the routine returns the crudest trapezoidal approximation of the integral of interest. Subsequent calls with N=2,3,... improve accuracy. This routine is based on the TRAPZD routine presented in Numerical Recipes by Press, Flannery, Teukolsky, and Vetterling.

IMPLICIT DOUBLE PRECISION (A-H, P-Z)
EXTERNAL FNCTN
IF ( N .EQ. 1) THEN
   S = (0.5D+00)*(B-A)*( FNCTN(A, FL) + FNCTN(B, FL))
   IT = 1
ELSE
   TNM = IT
   DEL = (B-A)/TNM
   X = A + (0.5D+00)*DEL
   SUM = 0.0D+00
   DO 100 J = 1, IT
      SUM = SUM + FNCTN(X, FL)
      X = X + DEL
  100 CONTINUE
   S = (0.5D+00)*( S + (B-A)*SUM/TNM)
   IT = 2*IT
ENDIF
RETURN
END
SUBROUTINE DQSIMP ( FNCTN, A, B, S, FL)

C
C Returns as S the integral of the function from A to B, integration being performed by Simpson's rule, using subroutine DTRAPZD as a base. This routine is based on the QSIMP routine presented in Numerical Recipes by Press, Flannery, Teukolsky, and Vetterling.
C
C IMPLICIT DOUBLE PRECISION ( A-H,P-Z)
EXTERNAL FNCTN
PARAMETER ( BPS = 1.D-06, JMAX = 20)
OST = -1.D30
OS = -1.D30
DO 100 J = 1, JMAX
    CALL DTRAPZD ( FNCTN, A, B, ST, J, FL)
    S = ( (4.D+00)*ST-OST)/(3.D+00)
    IF ( ABS(S-OS) .LT. EPS*ABS(OS)) RETURN
    OS = S
    OST = ST
100 CONTINUE
PRINT*, 'Terminal error. Too many steps in subroutine & QSIMP.'
STOP
END

*****************************************************************************

DOUBLE PRECISION FUNCTION RFLCOEF ( RI1, RI2, THETA1)

C
C Function computes the reflection coefficient for perpendicular polarization given the incident angle and the refractive indices
C
C DOUBLE PRECISION RI1,RI2,THETA1,THETA2,RI1COS,RI2COS
THETA2 = DASIN((RI1/RI2) * DSIN(THETA1))
RI1COS = RI1*DCOS(THETA1)
RI2COS = RI2*DCOS(THETA2)
RFLCOEF = DSIN(THETA1)*
& DABS((RI1COS - RI2COS)/(RI1COS + RI2COS))
RETURN
END

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DOUBLE PRECISION FUNCTION PTHRU ( THETA, FL)

Function evaluates the power throughput integral for a meridional ray in a round dielectric waveguide for input rays at a given incidence angle

RC = Reflection coefficient for oblique incidence at a dielectric interface
THETA02 = Square of the standard deviation of the Gaussian input beam
THETA = Angle between the fiber axis and the ray propagation path
AIRN = The refractive index of air
SAPHN = The refractive index of sapphire
PI5 = The value of pi/2
DIA = Fiber diameter
FL = Fiber length

IMPLICIT DOUBLE PRECISION (A-H, P-Z)
AIRN = 1.D+00
SAPHN = 1.76D+00
DIA = 125.D-06
PI5 = DACOS(0.D+00)
THETACMP = PI5 - THETA
RC = REFLCOEF ( AIRN, SAPHN, THETACMP)
THETA02 = ( PI5 * 0.6D+00)**2
BT = -2.D+00*THETACMP**2/THETA02
XT = FL*DLOG(RC)/DIA
PTHRU = 4.D+00/(PI5*THETA02)*DEXP(-BT & +XT)*DSIN(THETACMP)
RETURN
END

******************************************************************************

DOUBLE PRECISION FUNCTION SNELL ( RI1, RI2, THETA)

SNELL computes the angle of refraction given the input angle (THETA) and the two refractive indices (RI1 and RI2) in question

DOUBLE PRECISION RI1, RI2, THETA
SNELL = DASIN( RI1*DSIN(THETA)/RI2)
RETURN
END
PROGRAM TRANS

TRANS computes the transmission coefficient for both parallel and perpendicular polarization at an air/sapphire interface over a range of angles

TPERP = Transmission coefficient for perpendicular polarization
TPARL = Transmission coefficient for parallel polarization
AIR = Refractive index of air
SAPH = Refractive index of sapphire

OPEN ( 1, FILE = 'A:TRANS.OUT')
AIR = 1.0
SAPH = 1.765
PI = ACOS(-1.0)
DO 100 I = 0, 90, 5
   AI = I*PI/180.0
   AT = ASIN( AIR*SIN(AI)/SAPH)
   CAI = COS(AI)
   CAT = COS(AT)
   TPERP = (2.0*CAI)/(CAI + (SAPH/AIR)*CAT)
   TPARL = (2.0*(AIR/SAPH)*CAI)/(CAI + (AIR/SAPH)*CAT)
   WRITE (1,'(1X, I2, 2( 3X, F4.2))') I, TPERP, TPARL
   WRITE (*,'(1X, I2, 2( 3X, F4.2))') I, TPERP, TPARL
100 CONTINUE
CLOSE (1)
STOP
END
Vita

Long, long ago, in a galaxy far, far away, an evil empire was attempting to crush a valiant group of rebel fighters. Fortunately, these terrible battles had no impact on the life of Adam Edmund Barnes, who was born into a charmed life here on planet Earth. His wonderful parents raised him in a loving, sheltered environment, where he flourished and went on to receive a BS degree in Electrical Engineering from Virginia Tech in 1992. After marrying fellow Tech graduate and most terrific wife Mandy Wilson, he went on to earn a MS degree in Electrical Engineering from Virginia Tech in 1995.