4.2.1 Limitation of the Number of Excited Modes in the Sapphire Fiber

The preliminary experiment employing a sapphire fiber sensing head in the White Light Sensing Fiber Michelson Interferometer (WSFMI) generates data that is not useful. It is not possible to associate any one fringe group with the mode to which it corresponds, or to track any fringe group; minor environmental changes affecting the fiber result in a complete change in the interferogram produced by the interferometer. Although two explanations for this behavior are considered, it is judged to be most likely that the highly multimoded nature of the sapphire fiber is the cause.

For this work, it is desirable to isolate one of the many generated fringe groups from the others. If this is not done, it is nearly impossible to isolate one fringe group from another, determine the zero-order fringe in that group, or be certain that the fringe group selected to represent the reference and sensing fiber endfaces are identical from one scan to another. Because ambiguity in the process of determining zero-order fringes compromises the usefulness of the collected data, it is desirable to cause one fringe group to be of substantially greater amplitude than the others. The corresponding group of fringes as seen at the detector must be easily excited, easily distinguished from the fringes generated by other modes so that proper excitation of the desired mode can be confirmed, strongly coupled, and stable once excited. Both filtering and selective excitation methods are explored in an attempt to remove the extra fringes from the detected signal. Step index multimode silica fiber is used during this survey; silica fiber is easier to handle and manipulate than sapphire fiber.

The first attempt to limit the number of modes propagating in the multimode fiber utilizes the principle of bend loss. The introduction of bends into the physical geometry of an optical fiber is known to induce radiation loss, which primarily affects the higher order modes. When a waveguide is held straight, all points in the modal field j propagate parallel to the fiber axis and possess the same phase velocity,

$$v_{pj} = \frac{\omega}{\beta_j} = \frac{c}{\bar{n}_j} \qquad (4.2.1)$$

in which v_p is the phase velocity, ω is the angular frequency, β is the constant of propagation of the mode j, c is the speed of light in vacuum, and $\bar{n}$ is the effective refractive index of the waveguide. When the waveguide is bent in a curve of radius R, the surface of constant phase remains normal to the axis of the waveguide. This is shown in Figure 4.2.3. Under these conditions, the phase velocities parallel to the fiber axis increase linearly with distance from the center of the spool. When the phase velocity at point A is equal the phase velocity of a plane wave in the medium surrounding the waveguide,

$$v_p = \frac{c}{n_o} \qquad (4.2.2)$$

where n_o is the refective index of the surrounding medium, the energy contained in the mode from point A outward is lost to radiation. Lower order modes are better confined to the core region while higher order modes are more loosely confined and extend farther

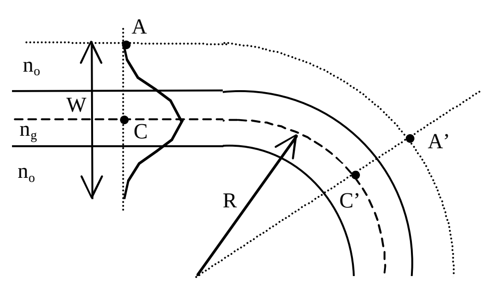

Figure 4.2.3: Propagation of a Mode of Width W Around a Bend of Radius R [4.3]

out into the surrounding medium. Because of this, winding optical fiber around a spool having a specific diameter spool will cause the higher order modes to radiate to a larger degree than the lower order modes.[72, 73]

The principle of selective bending loss is explored qualitatively by winding the step index silica multimode fiber five times around a spool, approximately 5.08 centimeters in diameter, in one experiment, and then winding it nine times around another spool, approximately 2.54 centimeter in diameter, in another experiment. It should be noted that moving the multimode fiber in any way caused, in a seemingly random fashion, dominant groups of fringes to decrease in amplitude while previously suppressed groups of fringes assumed dominance. No evidence of a decrease in the number of generated fringe groups was observed. This is likely due to mode-mixing occurring at perturbations existing in

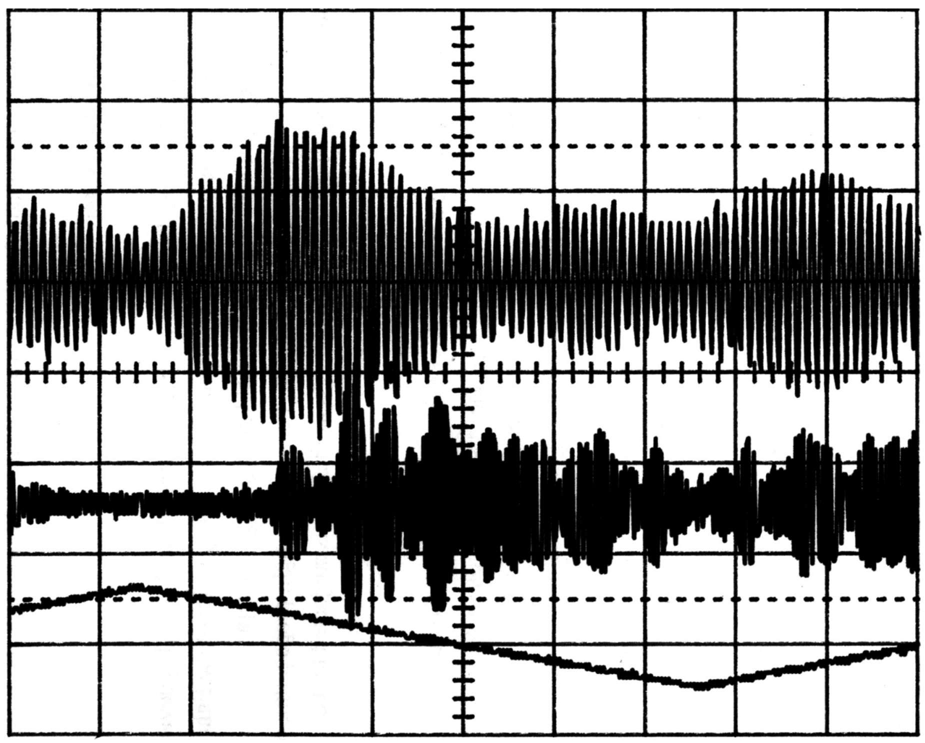

Figure 4.2.4: Interferogram Generated After Bend Loss is Used to Strip Higher Order Modes

the fiber, aggravated by winding the fiber around the spools, which repopulate the higher order modes attenuated by bend-induced loss. A representative oscilloscope trace is shown in Figure 4.2.4. The bottom trace is the voltage input to the actuator, the middle trace shows the interference fringes seen by the detector, and the top trace is a detail of the fringe groups that occur a half a major division on either side of the center of the oscilloscope screen.

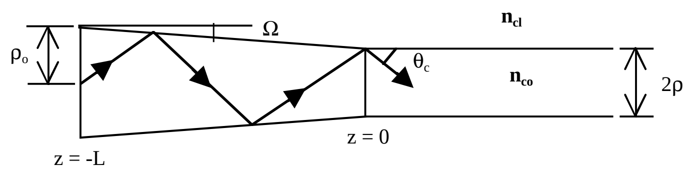

Figure 4.2.5: Geometry of a Linear Taper [72]

The use of a fiber taper to strip some of the higher order modes from the step-index multimode fiber is also explored. The technique of physically tapering a fiber, to a larger or smaller diameter, has been developed as a means to achieve more optimal coupling between fibers of dissimilar core sizes. A successful fiber taper, performed for this reason, allows all of the light contained in the fundamental mode of one fiber to be channeled into the core of another fiber of dissimilar core diameter. This is diagrammed in Figure 4.2.5. In the interest of ease of fabrication, linear tapers are explored for this application. There is a minimum taper length that is required to ensure that none of the power contained in the fundamental mode is radiated from the fiber. Assuming the meridional ray is launched into the taper at an angle θ_o, the minimum taper length can be found from,

$$L_{\min} = \frac{\rho_o - \rho}{\tan\Omega} \cong \frac{(\rho_o - \rho)^2}{\theta_c\rho - \theta_o\rho} \quad \text{for linear tapers} \tag{4.2.2}$$

with

$$\theta_c = \cos^{-1}\left(\frac{n_{cl}}{n_{co}}\right) \tag{4.2.3}$$

where ρ_o is the radius of the fiber prior to tapering, ρ is the radius of the fiber after tapering, θ_c is the complement of the critical angle of the fiber, Ω is the taper angle, n_{co} is the index of refraction of the core, and n_{cl} is the index of refraction of the cladding. By fabricating a taper with length L_{min}, all modes other than the fundamental mode of the tapered fiber will cease to be guided; they will become radiation modes.

A linear taper is made in a length of step index multimode silica fiber, using the technique of simultaneously applying heat and strain along the axis of the fiber. Effort is made to achieve a short taper region, but the fiber is not analyzed to determine the exact taper length nor the resulting diameter of the core. After the fiber is tapered, it is submerged in 1.45 index matching oil. The oil aids in the attenuation of the higher order modes, whose evanescent fields extend beyond the cladding, by reducing the difference in the index of refraction between the cladding and the surroundings of the fiber. This method is more effective for attenuating loosely bound higher order modes than it is for attenuating the tightly bound lower order modes.

We find that the taper results in a slight reduction of the number of generated fringe groups. The decrease does not allow for the identification of the fringe group associated with the fundamental mode, which is the most strongly bound mode, but it indicates that this method could be used to isolate the fundamental mode in silica step index fiber. Figure 4.2.6 is representative of typical results. The bottom trace is the voltage input to the actuator, the middle trace shows the interference fringes seen by the detector, and the top trace is a detail of the fringe groups that occur between one and a half and two and a half major divisions to the right of the center of the oscilloscope screen.

Tapering is an informative technique; it demonstrates and verifies that the multitude of fringe groups that the WSFMI generates when a step index sensing head is employed is directly related to the number of modes propagating in the fiber. However, it can not be used with sapphire fiber, because the fabrication of a sapphire fiber taper is not practical. Because of this, improvements to the tapering process, which could allow for the fabrication of tapers possessing much more precisely known dimensions and improved performance, are not explored.

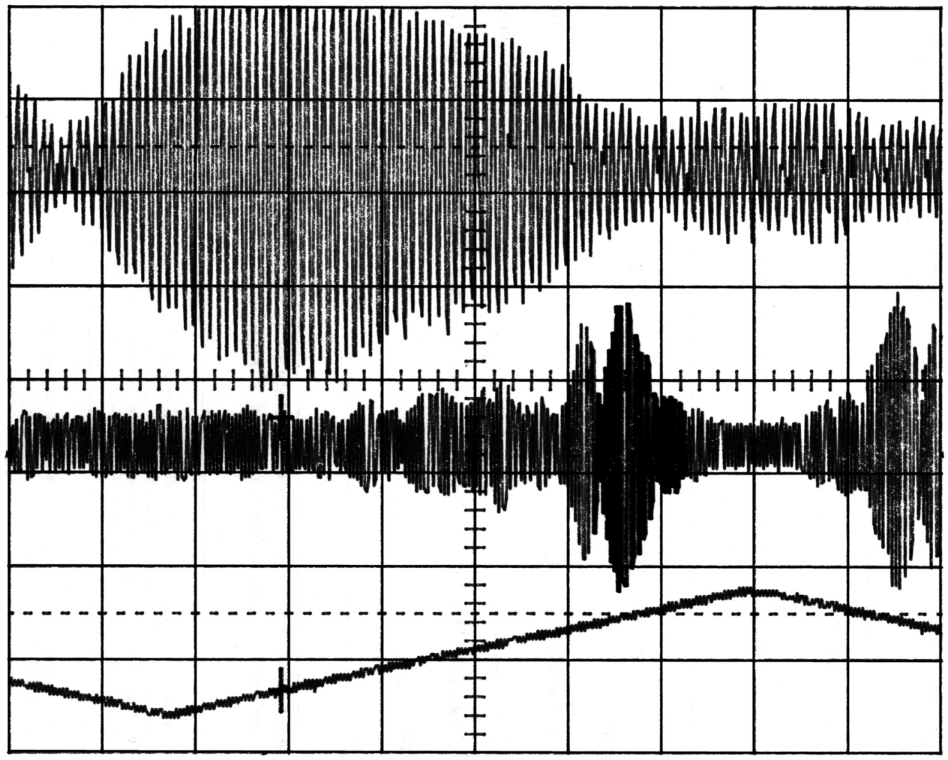

Figure 4.2.6: Interferogram Generated After a Fiber Taper is Used to Strip Higher Order Modes

Selective excitation of the fundamental waveguide mode is an attractive alternative to stripping the higher order waveguide modes, because of power considerations. Injecting all available power into the mode of interest will provide a better signal to noise ratio at the output than distributing the available power among many guided modes and then stripping the unwanted modes. In the former case, more power is contained in the mode of interest at every point in the system than in the latter case. As a consequence of being better confined, it is expected that the fundamental mode interacts less with the surface of the sapphire fiber than higher order modes. As described in Chapters 2 and 3, the nonuniform surface of the sapphire fiber scatters propagating light that encounters it, causing loss and mode mixing.

Ideally for this application, only the fundamental mode would be excited. Injecting collimated light parallel to the axis of the multimode fiber excites only the fundamental mode; it is therfore easy to excite. It is the most strongly bound mode, and hence the least lossy and most stable mode. If other lower order modes are also excited, the fringe group associated with the fundamental mode is readily identifiable. The fundamental mode possesses the shortest path length of all of the excited modes, and therefore will correspond to the first fringe group detected as the mirror in the measurement arm moves away from the graded index (GRIN) lens assembly. Because of this, the technique of selectively exciting lower order modes is incorporated into the WSFMI system.

4.2.2 The Impact of Polarization Mode Fading

Polarization mode fading is widely recognized as having the potential to cause a marked decrease in fringe contrast in fiber Michelson interferometers. As discussed in Section 3.4, the fundamental LP01 fiber mode consists of two orthogonal polarizations, which can couple at perturbations in the optical fiber. Because of imperfections and environmental factors, such as bends, optical fiber is not perfectly cylindrical. This asymmetry results in the fiber being weakly birefringent. Each birefringent axis, $\hat{x}$ and $\hat{y}$, possesses a different propagation constant. In weakly birefringent fiber, unlike in highly birefringent fiber, the two polarizations can be easily coupled at bends and other discontinuities, whose number and nature cannot be predicted, in the fiber. This coupling changes the characteristics of the propagating light, and for reasons discussed in Section 3.4, leads to a reduction of fringe visibility at the output of Michelson interferometers. This loss of fringe visibility is referred to as polarization mode fading.

Polarization mode fading is observed in the WSFMI system. When the length of singlemode fiber in either the sensing or measurement arm approaches several meters and a singlemode sensing head in place, the signal at the output of the interferometer is barely distinguishable above the noise. The use of polarization mode controllers increases the signal to noise ratio, but the controllers must be positioned differently depending on the environment of the fiber. The reduction in fiber length also lessens the effect of polarization mode fading. Because the light propagates a shorter distance, the two LP01 modes are presented with fewer opportunities for inter-coupling.

Methods to combat polarization mode fading in Michelson interferometers are presented in the literature. One involves placing 45 degree Faraday rotating elements just before the last reflecting element in both the sensing and measurement arms.[74, 75] This is illustrated in Figure 4.2.7. When this is done, the state of polarization of the light exiting the fiber in each arm is rotated a total of 90 degrees before it reenters the fiber. Because the light has been rotated, as the light propagates back through the fiber the polarization effects of each arm are unwound and a stable state of polarization results at the detector. Other techniques developed to combat this problem include active polarization controllers,[76] the use of polarization preserving fiber and components,[77, 78, 79] and polarization diversity detection schemes.[68, 80]

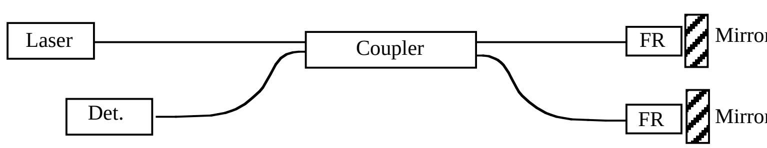

Figure 4.2.7: Faraday Rotators Used in a Michelson Interferometer Configuration [74]

The methods, discussed in the literature, used to combat polarization mode fading are not practical for use in the WSFMI system. Faraday rotators are expensive and can not be used in the high temperature test environment. Polarization preserving fiber (PPF) and couplers are expensive and difficult to use. There is also some doubt that they will be effective in this application, because the light would be required to propagate from the PPF through the sapphire fiber and then back into the PPF. Sapphire fiber is inherently birefringent, but the launch conditions would be very difficult to control, and the fiber possesses microvoids and dislocations that cause coupling between different modes and polarizations in the manner discussed in Section 3.4. The other methods are impractical because of the complexity, requirement of bulky equipment, and/or requirement that the fibers remain stationary. Because the technique of reducing the length of the singlemode fiber has been shown to be satisfactory, it seems a preferable solution to the problem of polarization mode fading. It is decided to use a meter of fiber in each arm of the WSFMI to combat polarization mode fading. This length of fiber gives the system some flexibility with respect to how it may be physically configured, and it also results in acceptable fringe contrast.

4.2.3 Modifications Made to the WSFMI System

Due to the lossy nature of sapphire fiber, the fringe groups obtained through the use of a sensing head composed of sapphire fiber are expected to be smaller in amplitude than those obtained with the silica step-index multimode sensing head. Because of this, the signal to noise ratio of the output signal must be optimized. This is addressed by developing a method to preferentially excite the fundamental mode of the sapphire fiber, finding a suitable source, and taking measures to prevent the saturation of the preamplifier.

The WSFMI system is altered to allow more control over how light is launched from the singlemode fiber into the sapphire fiber in the sensing arm. While optimizing this aspect of the WSFMI system, a sensing head constructed with silica step-index multimode optical fiber is used. Both the singlemode and the multimode fibers are secured in ST-type fiber optic connectors, and a 1 millimeter diameter quarter-pitch GRIN lens is placed between them. The GRIN lens is held in place through the use of a ST-type fiber optic connector mating sleeve. Before placing it inside of the mating sleeve, the GRIN lens is inserted into a ring whose inner diameter is fabricated to match the outer diameter of the GRIN lens, and whose outer diameter is fabricated to match the inner diameter of the mating sleeve. This ring holds the GRIN lens immobile inside of the mating sleeve. This is shown in Figure 4.2.8. The motivation behind the use of this technique is the paper by Murphy *et al*.,[7] in which the authors use a GRIN lens to couple light into the sapphire rod sensing head. The reduction in extraneous fiber groups is substantial, although not great enough to allow the isolation of the fringe group

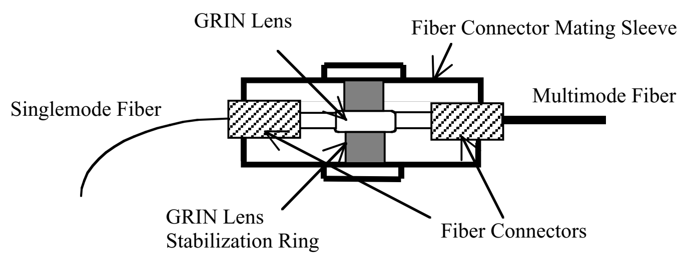

Figure 4.2.8: Inflexible Apparatus Used to Couple Light From a Singlemode Fiber to a Multimode Fiber

corresponding to the fundamental mode. Through adjustment of the positions of the two fiber ends and the GRIN lens, nearly perfect alignment is achieved with difficulty, and is easily lost. The alignment of these three components is highly sensitive to the surrounding environment; normal room vibrations cause misalignment and result in the change of the positions of the fringe groups. Any physical distortion of the multimode fiber causes the configuration of the fringe groups to change. Despite the imperfect results obtained using the GRIN lens, these experiments show that this method holds promise as a means to preferentially excite the fundamental mode.

It is suspected that the mating sleeve does not perfectly align the silica singlemode fiber, the multimode fiber, and the GRIN lens. Manual manipulation of the two connectorized fibers inside of the mating sleeve indicates that the alignment of the singlemode fiber is more critical than the alignment of the multimode fiber. Because of this, the mating sleeve is cut in half, along a plane perpendicular to the longitudinal axis, so that, with the help of a three-axis micropositioner, the singlemode fiber endface can be freely aligned with respect to the lens. This is depicted in Figure 4.2.9. The multimode fiber is held against the lens by mating the sleeve to the connector that secures the sapphire fiber.

Through optimization of the alignment, the fringe group associated with the fundamental mode can be made highly dominant, and the signal to noise ratio approaches that of the case in which a singlemode fiber sensing head is used. Disturbing the multimode fiber degrades the amplitude of the fringes corresponding to the fundamental mode, but it does not result in the scrambling of the dominant and suppressed fringe groups.

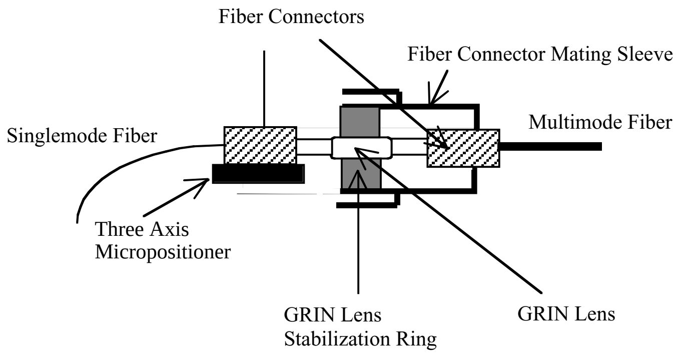

Figure 4.2.9: Flexible Apparatus Used to Couple Light From a Singlemode Fiber to a Multimode Fiber

The light returned from the measurement arm is attenuated to avoid saturating the preamplifier. The preamplifier is placed between the detector and the oscilloscope to boost the power of the signal. The intensity returned by the sensing arm is considerably greater than the intensity returned by the measurement arm. Recalling Equation 3.1.13, in this case the detector receives a useful modulated signal of moderate intensity added to a large DC signal that carries no information. It is anticipated that, when a sapphire fiber sensing head is used, the signal returned from the sapphire fiber will be greatly attenuated and will require the maximum gain available from the preamplifier. Reducing the intensity of the large DC signal permits the preamplifier to amplify the useful information more strongly. Two techniques for reducing the amplitude of the signal returned form the sensing arm were investigated: placing a pinhole diaphragm between the GRIN lens and the actuator to block all but the center portion of the beam, and replacing the pinhole diaphragm with a graded neutral density filter.

It is found that the performance of the pinhole diaphragms are superior to that of the graded neutral density filter. The signal to noise ratio of the fringes increases when the pinhole diaphragm replaces the graded neutral density filter. This observation is explained by considering that the spatial distribution of the light emitted from the GRIN lens is Gaussian, and that the neutral density filter is uniformly attenuating. It is the light occupying the center of the Gaussian distributed intensity that excites the fundamental modes and therefore contributes predominantly to the generation of the interference fringes at the detector. The light outside of that region is carried in weakly guided modes, and introduces intensity to the detector without information. Because the pinhole diaphragm passes the portion of the distribution that carries the information while the neutral density filter attenuates it, the performance of the pinhole diaphragm is superior.

The use of a sensitive detector coupled with a source wavelength that is preferentially passed by sapphire will contribute to stronger detected signal. The 180 microwatt 1300 nanometer light emitting diode (LED) that is used in the preceeding work is believed to emit too little power to be used successfully in a WSFMI system that employs a sensing head composed of sapphire fiber. Superluminescent light emitting diodes (SLED) are readily available at 830, 1300, and 1550 nanometers and emit more power than LEDs. From Figure 2.3 it can be seen that all of these wavelengths fall within the transparency window for sapphire. Because a SLED emitting at 830 nanometer is readily available, it is used in this work. A silicon-based detector is the best choice of a detector for this wavelength. While a InGaAs detector is used in the tests previously described, a silicon-based detector is used in all subsequent work.

A problem with this silicon detector may arise because it detects visible light, and ambient light may add noise to the system. Singlemode fiber for use at the 830 nanometer wavelength has a core (~4.5 micrometers) roughly half of that of the singlemode fiber to be used at the 1300 nanometer wavelength (~9 micrometers). Because of this the splice between the silica and the sapphire fiber will be more lossy in the 830 nanometer, as opposed to the 1300 nanometer, case. The loss occurs when the light travels from the sensor back towards the detector. It must be transferred from the sapphire fiber, possessing a core of roughly 150 micrometers, into the ~4.5 micrometer core of the 830 nanometer fiber. This loss is less severe when a larger core silica singlemode fiber is used.

With the 830 nanometer source connected to the WSFMI system, a reflection that originates in the fiber collimator, at the junction between the silica fiber and the GRIN lens in the measurement arm, is found to saturate the preamplifier. The reflection results because the index of refraction between the silica fiber and the optical adhesive are not perfectly matched. This is not a problem in the 1300 nanometer setup because the LED source is less powerful than the 830 nanometer SLED.

Commercial low backreflection fiber collimators are available, but they are expensive and require several weeks for delivery. A fiber collimator of this type consists of a fiber pigtailed to a GRIN lens, which have their mating ends both polished at 8 degree angles. Connectors in lengths of fiber used for communications purposes are also polished to 8 degree angles in order to minimize back reflections. A Logitech polishing system, owned by Fiber and Electro-Optic Research Center, makes it possible to polish optical fiber, GRIN lenses, and other samples to a specified angle. This system is used to enable the in-house fabrication of a fiber collimator having low back reflections. Care is taken to polish the smallest amount of glass possible from the end of the GRIN lens, so as not to disturb its collimating properties. The final assembly is found to have good collimating properties and negligible back reflections.

4.3 Experimental Results

Successive high temperature tests result in experience and further system modifications that combine to increase the fringe contrast of the output interferograms and that lead to the successful operation of the system at 800 degrees Celsius. Higher temperatures are not attempted because the fused silica hollow core alignment tubing cannot reliably withstand higher temperatures. The object of these tests is to verify that this sapphire fiber is capable of returning a usable signal when subjected to a high temperature environment, and to identify setup modifications to permit the WSFMI system to be used for high temperature applications.

4.3.1 System Alignment and Component Specifications

The basic system configuration is diagramed in Figure 4.1.1. An 830 nanometer SLED is used as a source, both the sensing and measurement arms have a 1 meter length of silica singlemode fiber extending from the coupler, a shielded silicon detector is placed at the output of the interferometer, and the signal from the detector is sent to a preamplifier before being displayed on an oscilloscope. The light is coupled from the singlemode silica fiber into the sapphire fiber head as described in Section 4.2. The fiber collimator, also described in Section 4.2 is used in the measurement arm.

The 40 centimeter long sapphire fiber used in the preliminary experiments is a product of the University of Southern Florida (USF), and it is characterized by remarkably low loss and few microvoids. This fiber is used in the room temperature test described in Section 4.3.2, but then this fiber is accidentally broken. It is discovered that no replacement of similar quality exists. An approximately 30 centimeter length of sapphire fiber grown by Advanced Crystal products (ACP) is used as a replacement. It possesses a multitude of microvoids and is estimated to be 3 to 4 times as lossy as the USF fiber, and it has a core diameter of approximately 150 microns.

Alignment of the 1millimeter quarter pitch GRIN lens in relation to the silica singlemode fiber in the sensing arm has been performed using a micropositioner to adjust its position while observing the detected white-light interference pattern signal on an oscilloscope. Because the process of aligning the GRIN lens using this method can be time consuming and is difficult to automate, it is of interest to investigate another method of alignment.

It is reasoned that when the light from the singlemode fiber is collimated and directed into the sapphire fiber such that the fundamental mode is made dominant, there will be very little energy exciting the non-fundamental modes. Because of this, there should be less attenuation of the signal due to energy directed into the lossy higher order modes than in any other GRIN lens configuration. The power of the light exiting the sapphire reference fiber end is monitored and when the maximum transmitted power is found, the white light interferogram displayed on the oscilloscope is observed. Results show that the position of the peak power transmitted and the optimum position for making the fundamental mode dominant are in the range of approximately +/- 2.5 micrometers apart. This method is concluded to be helpful for coarse adjustment of the GRIN lens position, but the interferogram must be monitored on the oscilloscope in order to optimize the power in the fundamental mode.

It is reasonable to assume that this method would enjoy much greater success if the sapphire fiber were a more perfect crystal. The sapphire fiber used in these experiments contains many microvoids, each of which scatters light, and a rough outer surface. The results are be attributed to mode-mixing caused by the imperfections in the sapphire fiber. The condition of maximum power emitted by the sapphire endface may result from the addition of intensities from many modes, and not just the fundamental mode.

Because there are no suppliers of sapphire fiber hollow core tubing adequate for our purpose, the sapphire fibers that compose the sensing head are placed in a length of fused silica hollow core tubing. This tubing is not perfectly matched to the diameters of the two sapphire fibers composing the sensing head, because the ACP sapphire fiber is of non-standard optical-fiber diameters. In an effort to reduce the slop that exists between the fibers and the tube, a long tube of approximately 6 centimeters is used. The manufacture of an alignment tube composed of sapphire material is planned. It will be fabricated from three sapphire rods of predetermined dimension laid lengthwise in the shape of a pyramid and adhered together. The tunnel created at the junction of the three