Chapter 4: The WSFMI with a Sapphire Fiber Sensing Head

The description of the White-Light Sensing Fiber Michelson Interferometer (WSFMI) by Li *et al.*[71], indicates that the basic WSFMI system may be successfully used with a sapphire fiber sensing head. The length of the sapphire fiber sensing head need only be long enough to protect the silica fiber, which is used throughout the rest of the WSFMI system, from the hot measurement zone. Limiting the length of the sapphire fiber is expected to limit signal losses and mode mixing, both of which are expected to be significant in the sapphire fiber, that occur in the interferometer.

Section 4.1 discusses the use of a silica graded-index multimode fiber sensing head in the WSFMI as an precursor to the use of a sapphire fiber sensing head. Silica graded-index multimode fibers are well understood and of predictably good quality, unlike sapphire fibers, and will thus serve well for an exploratory experiment. The graded index multimode fiber is designed so that all of the guided modes possess nearly the same optical path length. Because of this, the white light interferogram generated by the interferometer in the multimode sensing head case should closely resemble that of the singlemode fiber sensing head case. However, in the multimode sensing head case, it is expected that the modes can mix at perturbations in the fiber and adversely affect performance through reduced fringe visibility. This experiment is also conducted to identify any other multimode effects that should be recognized before the incorporation of a sapphire fiber sensing head into the system.

After the successful implementation of a silica graded-index multimode fiber sensing-head into the WSFMI, a sapphire fiber sensing head is attached. The results and subsequent improvements to the WSFMI system are described in Section 4.2 . Unlike the described cases of silica fiber sensing heads, the data obtained with the sapphire fiber sensing head is not useful; the interferogram resembles a confused jumble of fringe packets which change in a random fashion with perturbations to the environment of the sapphire fiber. The presence of a large number of guided modes in the sapphire fiber, whose propagation constants have not been equalized, is the most likely cause. Efforts are taken to reduce the number of guided sapphire fiber modes and to boost detected signal power.

With the WSFMI system better optimized to function with a sapphire fiber sensing head, data is taken and presented in Section 4.3. This section presents some details about the components that are used and the alignment technique employed to excite the fundamental mode of the sapphire fiber. Three high temperature tests were performed. Each test reveals improvements that can be made to the system. Subsequent tests incorporate improvements suggested by earlier tests. This section also includes a discussion of our efforts to use the WSFMI system to produce a useful extrisic Fabry-Perot interferometric (EFPI) sensor. In this work the WSFMI acts as an alignment tool for the EFPI sensor.

Section 4.4 discusses the implications of the data obtained by using a sapphire fiber in the modified WSFMI sensor system. A summary of the data obtained in Section 4.3 is combined with an interpretation of the data. Likely sources of error are identified. The performance of the system is related to the limitations of the present system design and components, and the efficacy of the system is considered.

4.1 Use of a Silica Graded-Index Multimode Sensing Head in the WSFMI System

The use of a graded index multimode fiber sensing head is intended to introduce the complications associated with mode-mixing, while excluding those resulting from each of the multiple modes possessing a different velocity of propagation. It is not expected that there should be a large decrease in performance between the silica singlemode and graded index multimode sensing heads. It is, however, advantageous to explore the effects of using a multimode sensing head in the WSFMI systems; what is observed under these controlled conditions may be useful in explaining phenomena observed while employing a sapphire fiber sensing head.

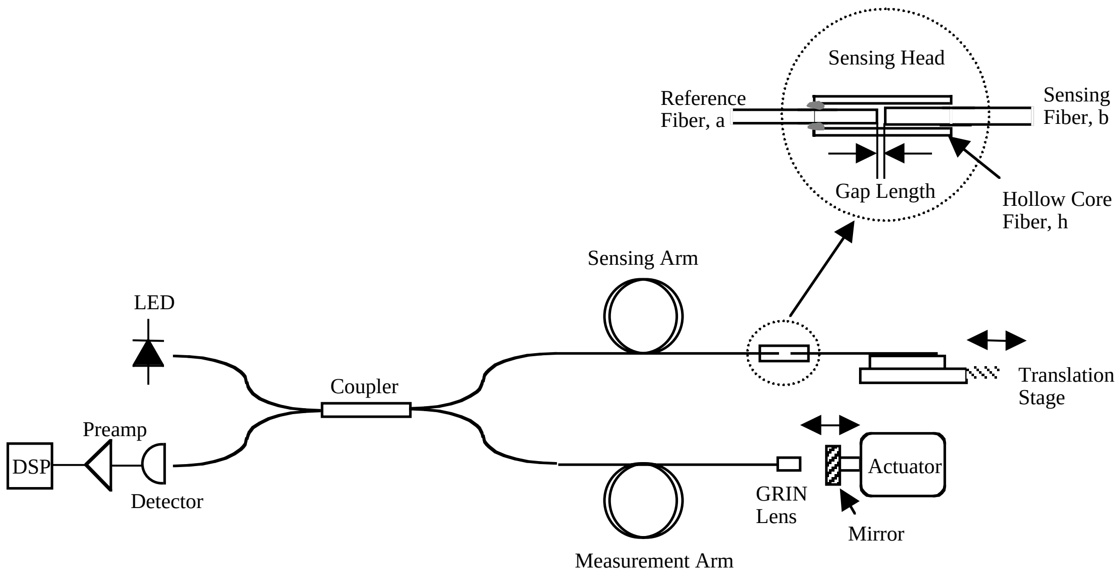

Figure 4.1.1 Basic Configuration of the WSFMI System

The setup used for this experiment, shown in Figure 4.1.1, is identical to that used in the singlemode case, with the exceptions of the light source and the type of reference fiber used in the sensing head. In this instance, the light source, a 1300 nanometer surface emitting LED with an output power of approximately 180 microwatts and a spectral width of between 20 and 30 nanometers, is input to the 3 decibels singlemode coupler. One of outputs of the coupler is spliced to a singlemode, 9/125 micrometer optical fiber terminated in a quarter-pitch graded index (GRIN) lens, and the other output is spliced to a 50/125 micrometer graded index multimode fiber that terminates in the sensing head. In the measurement arm, the coupled beam from the source is collimated by the GRIN lens, directed normally towards a mirror mounted on an actuator, reflected from the mirror, and input back into the GRIN lens. In the sensing head, 4 percent of the coupled beam from the source reflects from the 50/125 micrometer multimode reference fiber endface, and 4 percent of the transmitted light reflects from the 100/140 micrometer multimode sensing fiber endface. The apparatus is configured so that the optical path lengths followed by the coupled beams traveling in the compensation-measurement and sensing arms differ by no more than a few millimeters, as described by Li *et al*. An indium gallium arsenide (InGaAs) detector detects the signal, which is amplified before being displayed on an oscilloscope.

The traces in Figure 4.1.2 were recorded while the endfaces of the reference and sensing fibers were separated by 350 micrometers. An entire cycle of the movement of the mirror is represented. Two pair of desired dominant fringe groups and several others of much lesser amplitude are visible in the middle trace. The fringe groups of much lesser amplitude are a result either stray reflections or imperfectly equalized mode propagation constants in the fiber. Although the graded index of this optical fiber is intended to equalize the optical path lengths of all of the modes traveling in the fiber, this may not be done precisely. If this is the case, different modes possess different optical path lengths, and this results in the non-fundamental modes being detected at positions removed from that of the fundamental mode.

The first pair of fringe groups is generated as the actuator-mounted mirror moves and creates an optical path length that is first greater than the optical path length defined by the sensing fiber endface, then equal to that path length, and next several tens of microns shorter than that path length. The movement of the mirror continues moving in this direction until it repeats this procedure with the reference fiber endface. This movement of the mirror from the farthest to the closest point relative to the GRIN lens represents one half of the cycle. During the second half of the cycle, the mirror reverses its motion and the second pair of fringe groups is generated. Because the light output from the reference fiber is divergent, the amount of light the sensing fiber is able to reflect back to the reference fiber decreases as the size of the gap between the two endfaces increases.

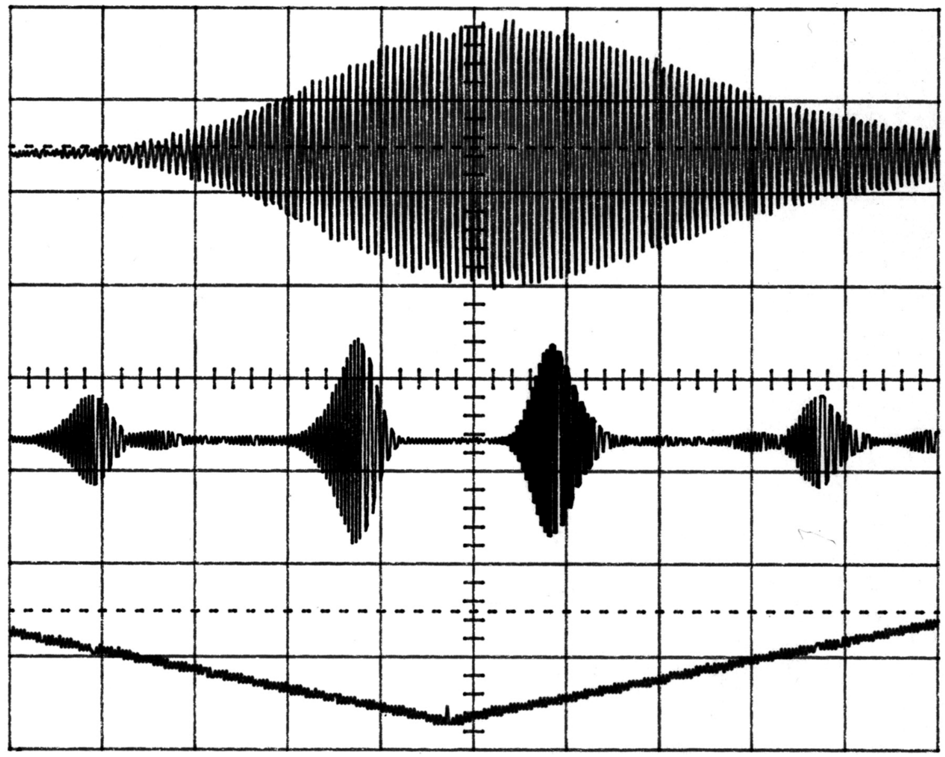

Figure 4.1.2: WSFMI Interferogram Generated Using a Sensing Head Composed of Silica Graded Index Multimode Fiber. Highlight of the Reference Fiber Fringe Group

The divergent light output from the reference fiber results in the fringes corresponding to the sensing fiber endface being lesser in amplitude than those associated with the reference fiber endface. The top trace is a detail of the middle trace, which features the fringe group just to the right of the center line on the oscilloscope plot, and corresponds to the reference fiber endface, are examined. The bottom trace shows the voltage driving the actuator. Figure 4.1.3 repeats most of the information in Figure 4.1.2, except that the top trace detail displays the rightmost interference fringes associated with the sensing endface. The fringe group corresponding to the sensing endface is the worst case of the two, but despite this the zero order fringe possesses a signal to noise ratio of approximately 20 decibels.

The results of this experiment demonstrate that, despite a loss in fringe visibility due to mode-mixing, a sensing head constructed from graded-index silica multimode fiber works well in the WSFMI system. The fringe groups corresponding to the reference and sensing fiber endfaces in the sensing head both contain over one hundred fringes and are

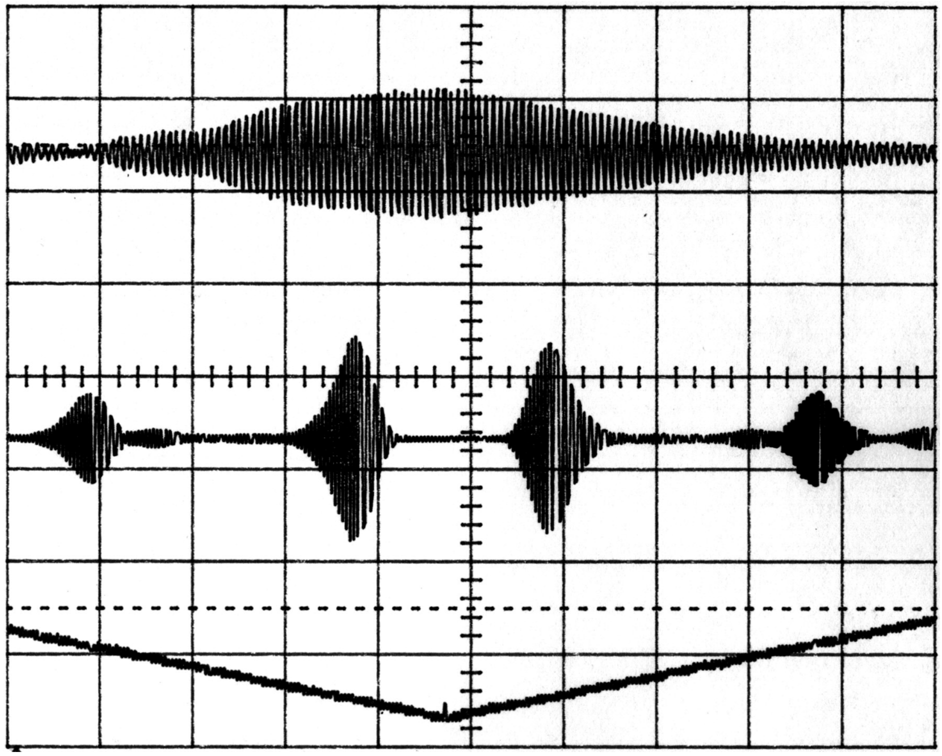

Figure 4.1.3: WSFMI Interferogram Generated Using a Sensing Head Composed of Silica Graded Index Multimode Fiber. Highlight of the Sensing Fiber Fringe Group

well differentiated from each other and the noise. The distance separating the two fiber endfaces can be determined through the relation between the position of the corresponding zero order fringes of the fringe packets corresponding to the sensing and reference fiber endfaces and the voltage driving the actuator.

Figure 4.1.4 is obtained by holding the mirror in a stationary position, and plotting a trace while the sensing and reference fiber endfaces are moved from a touching position to one in which they are separated by a few tens of microns. This mimics the operation of an Extrinsic Fabry-Perot Interferometric (EFPI) fiber optic sensor. In this type of sensor, the light reflecting from the reference and sensing endfaces interfere at the detector. Fringes result when the gap separating the two endfaces changes. The top trace, a detail of the bottom trace, illustrates the limitations of multimode EFPI sensors: because of degradation of the effective coherence length due to mode fading in multimode fibers, no usable fringes are generated after the fiber endfaces are separated by more than a few tens of micrometers.

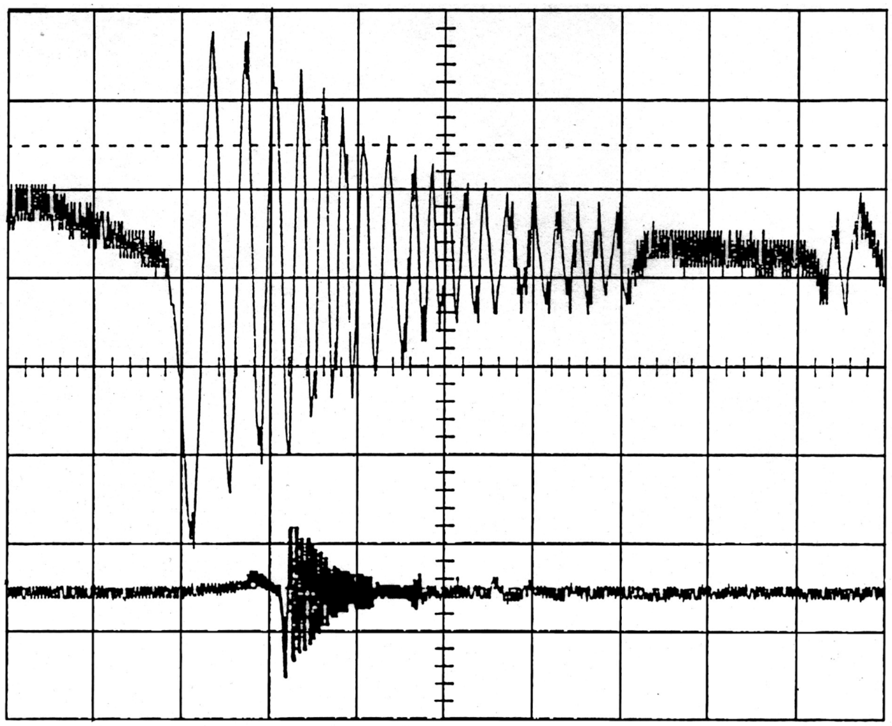

Figure 4.1.4: Generation of EFPI Fringes Using the Isolated WSFMI Sensing Head

The difference between the maximum displacements that can be measured using the WSFMI and EFPI techniques derives from the method in which the distance separating the fiber endfaces in the sensing head are measured. The EFPI technique requires that both of the interfering beams be composed of light having substantial coherent length. If the light is semi-coherent, as in this experiment, a separation of a couple tens of microns, where the exact value depends on the coherence length of the source, between the reference and sensing fiber endfaces exceeds the coherence length of the light. This subsequently prohibits the production of detectable fringes. In the case of the WSFMI technique, the fewer fringes generated, the easier the data is to interpret. The only fringe of interest in the fringe group generated for each endface in the sensing head is the one that corresponds to a perfectly matched path length, the zero order fringe. Although this fringe should theoretically be the largest in amplitude, the more fringes are generated, the harder it is to pinpoint the zero-order fringe. The WSFMI technique benefits from the use of sources having short coherence lengths.

The short coherence length inherent to this experiment is partly a result of the LED source and partly due to the effect of mode fading in the multimode fiber. This is seen by comparing Figures 4.1.2 and 4.1.4. In Figure 4.1.2, one beam from the singlemode fiber and one from the multimode fiber interfere. Over 100 fringes are produced for each fiber endface in the sensing head. Half of these fringes are generated as the optical path length (OPL) of the measurement arm progresses from being shorter than to being matched with the OPL defined by the endface of the reference fiber. The second 50 are produced as the mirror moves from this matched OPL to one which is slightly greater than that defined by the endface of the sensing fiber. In Figure 4.1.4, instead of 50 fringes being generated when the sensing head is moved in the EFPI technique, only 19 are produced. In the WSFMI case, the mode-faded beam from the multimode fiber interferes with the preserved beam from the singlemode fiber. In the EFPI case, two mode-faded beams from the multimode fiber interfere. The later case experiences more severe mode fading, and an effective shortening of the coherence length, as a result of both interfering beams coming from the multimode fiber, and therefore produces only 19 fringes. Although the composition of the sensing head is the same for both the WSFMI and multimode EFPI techniques, the WSFMI method possesses a larger measurement range.

4.2 Initial Experiment with a Multimode Sapphire Fiber Sensing Head in the WSFMI System and Subsequent Improvements to the WSFMI System

The success of the experiments conducted with the graded index multimode fiber encourages the replacement of the standard silica graded index multimode fiber sensing head with a single 100 micrometer diameter sapphire fiber. The sapphire fiber was manufactured by laser pedestal growth at the University of Southern Florida. Both endfaces of the sapphire fiber are polished normal to the longitudinal axis of the fiber. As depicted in Figure 4.2.1, the sensing head consists of only the reference fiber and should not be mistaken for a sapphire fiber version of the sensing head described in the preceding sections. When the path length defined by the polished end face, *H*, of the sapphire fiber is matched by the mirror in the GRIN lens arm, instead of one group of fringes being generated as expected, a series of seemingly random fringe groups were

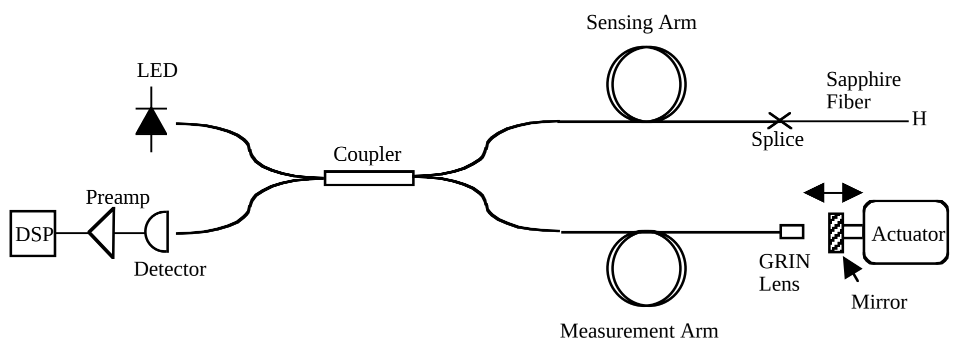

Figure 4.2.1: WSFMI System Without a Sensing Fiber in the Sensing Head

detected as shown in Figure 4.2.2. The bottom trace is the voltage input to the actuator, the middle trace represents the interference fringes seen by the detector, and the top trace is a detail of the middle trace in which the fringe group to the right of center is examined. These fringe groups are detected throughout a 1 to 2 millimeters translation of the mirror in the compensation-measurement arm and together they create a continuous sinusoidal pattern with randomly modulated amplitudes, as seen in the top trace.

Two possible explanations for the multitude of fringe groups are considered. One is the multimode effect. The 100 micrometer diameter step sapphire fiber can support many modes, and different modes propagate along different physical paths. Because of this, each mode travels a different OPL to arrive at the same transverse destination plane.

Mode-mixing that occurs at perturbations in the sapphire fiber will effectively add components of the other modes to the fundamental mode before it is coupled into the singlemode fiber; only the fundamental mode is coupled into the singlemode fiber.

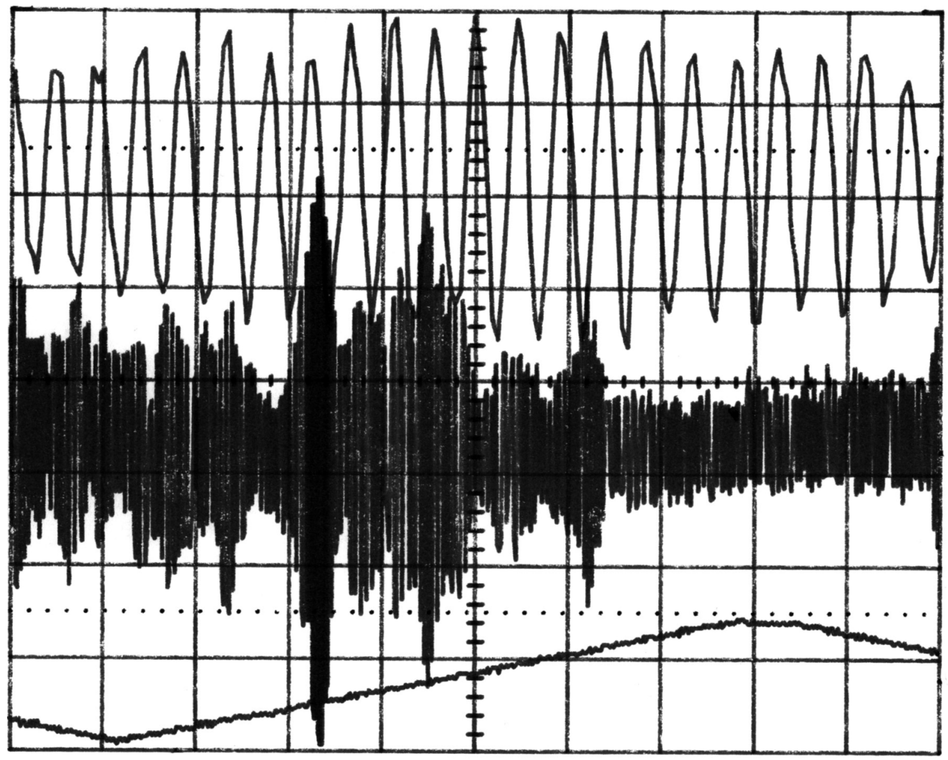

Figure 4.2.2: Interferogram Generated When a Sensing Head Consisting Solely of a Sapphire Reference Fiber is Used in the Basic WSFMI System

During the translation of the mirror, the OPL of the measurement arm may match the OPLs of the different modes guided by the sapphire fiber and produce the corresponding conglomeration of different overlapping fringe groups. The second possible source of the multitude of fringe groups may be the interaction between the sapphire material composing the fiber and the light propagating within it. As described in Chapter 2, a sapphire fiber has many surface defects, and visible light is readily seen to be scattered by internal microvoids which are present in varying densities along the length of the fiber. The nonuniformity of the sapphire fiber may scatter part of the light back to the detector port, which might then interfere with the light from the compenstation-measurement arm.