

Chapter 4. SCIIB Sensor Fabrication

Up to now, the method used in fabricating EFPI sensors has been limited to using epoxy to bond two fibers with their endfaces cleaved inserted into a capillary tube with a proper inner diameter. Although extensive research has been conducted to find high performance epoxies to fabricate EFPI sensor probes, the fabricated sensors generally failed to provide satisfactory performance in terms of mechanical strength and thermal stability. Another constraint of the epoxy-based sensors is that the maximum operating temperature is limited by the epoxy which is relatively low. Because epoxies have a coefficient of thermal expansion (CTE) different from that of the fibers and the tube, epoxy bonded sensors are usually very sensitive to temperature changes, which makes it difficult to use those sensors to measure parameters other than temperature. It is also found difficult to control the sensor initial cavity length and the bonding size because the relatively long curing time of the epoxy. Furthermore, the viscosity of the epoxy bonding will also degrade the frequency response of the EFPI sensor in case of high frequency signals need to be measured.

In order to reach the performance potentials of SCIIB sensors, innovative methods must be developed to allow fiber sensor probes to be fabricated in a controlled fashion so that good mechanical strength and a high thermal stability can be achieved. This chapter will discuss the research work on the fabrication of high performance SCIIB sensor probes.

4.1 Special Requirements of SCIIB Sensor Probes

The full realization of the advantages of the SCIIB sensor technology requires that the SCIIB sensor probe must possess some unique features. These features include:

- 1) The initial cavity length of the SCIIB sensor needs to be accurately adjusted to a certain optimal value so that the signal channel can output interference fringes with good fringe visibility while the reference channel output excludes any interference effects.
- 2) The initial sensor operating point needs to be precisely adjusted to the starting point of the linear portion of the interference fringe. This allows the operating range of the sensor to cover the full linear portion of the interference fringe.
- 3) To achieve the best thermal stability, the capillary tube and the fibers must be permanently bonded together with a high mechanical strength. Also the bonding should not have adverse effects on the optical properties of the fiber waveguide.
- 4) The sensor effective gauge length (the distance between the two bonding points) needs to be controlled within a tight tolerance so that the fabricated sensors have predictable and repeatable performances.
- 5) The fabrication of the sensor should be automatic or semiautomatic so that the sensor can be made in a large quantity with good repeatability and at a low cost.

Telecommunication optical fibers are usually made by doping very small amount of germania and other materials into pure silica glass. Fused silica capillary tubes of various sizes are also commercially available. Silica glass is an amorphous material. When heated to a certain temperature (about 1500°C), it becomes soft [88]. This indicates that we can use thermal fusion techniques to bond the fiber and the capillary tube together. By locally heating the fiber and tube assembly to a temperature above which the glass is softened, the tube and the fiber can flow into each other and locally join to form a solid bond.

A major research task of the proposed research is to develop an automated SCIIB sensor fabrication system. The sensor fabrication system uses a high-energy carbon dioxide (CO₂) laser to provide the heating power and a whitelight spectrum interferometry mechanism to monitor the cavity length of the sensor in real-time during fabrication. This

system, as described in detail in the following section, allows the automatic fabrication of a large quantity of high performance SCIIB sensors at a low cost.

5.2 Sensor Fabrication System Configuration

As shown in Figure 4-1, the automated SCIIB sensor fabrication system includes three sub-systems. They are the carbon dioxide (CO₂) laser heating sub-system, the white light fiber optic interferometric sensor cavity length monitoring sub-system, and the micro-motion fiber positioning sub-system.

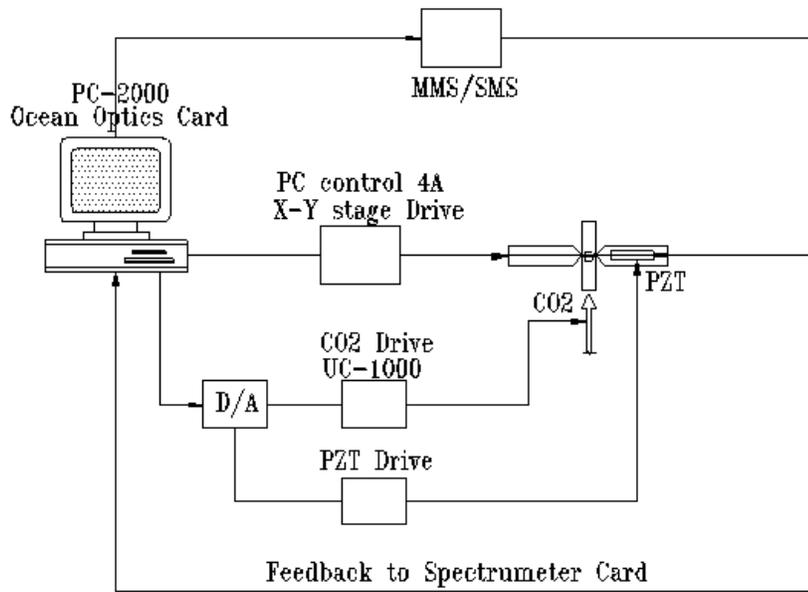


Figure 4-1. Schematic of the automated SCIIB sensor fabrication system

A high-energy CO₂ laser is used as the heating source. It generates high-energy optical pulses at the wavelength of 10.6 μm . When the silica glass material is exposed to the CO₂ laser beam, it absorbs the optical energy and converts it to thermal energy, which allows the silica glass materials to be heated locally up to very high temperatures. The whitelight

fiber optic interferometric system is used for accurate on-line monitoring of the initial cavity length of the fabricated SCIIB sensor. Several ultra-precise micro-positioning stages are also used in the system to allow precisely moving the two fibers in three dimensions. A computer is used to control and coordinate these three sub-systems so that the CO₂ laser output power, the motion of the stages and the sensor cavity lengths can be automatically and precisely controlled during the sensor fabrication process. The functions and principles of these three sub-systems will be discussed in detail in the following sections.

4.3 CO₂ Laser Sub-system

4.3.1 Configuration

The CO₂ laser used in the system is a *SYNRAD, Inc* Model 48-2. The wavelength emitted by the laser is 10.6 μm, and the maximum output optical power under continuous mode operation is 25 W. The original beam diameter of the laser output is 3.5 mm. After using a cylindrical ZnSe lens with a focal length of 5 inches, a laser line with the width of 100 μm and the length of 3.5 mm is obtained at the focal point where the fiber and tube assembly is positioned. The laser can also be used to generate short optical pulses, which are externally modulated through a controller, with a minimum pulse duration of about 200 μs.

The control of the CO₂ laser output involves two parts: the power level control and the lasing duration control. The power level control can be accessed by externally applying a 0-10 V voltage signal (corresponding to 0-25 W output power) and the pulse duration can be controlled by inputting a standard TTL gating signal to enable or disable the laser output. Because it is necessary to precisely control both the heating duration and the temperature during the sensor fabrication, we designed and implemented a special circuit

to allow computer programmable control of the CO₂ laser. The block diagram of the system is shown in Figure 4-2. By properly programming the DIO-24 interface card (National Instruments), the power control signal is sent out to the D/A circuit, which converts the digital signal to an analog output from 0 to 10 volts at a resolution of 16 bits. The laser enabling or disabling signal is also converted to a TTL gating signal through the same circuit.

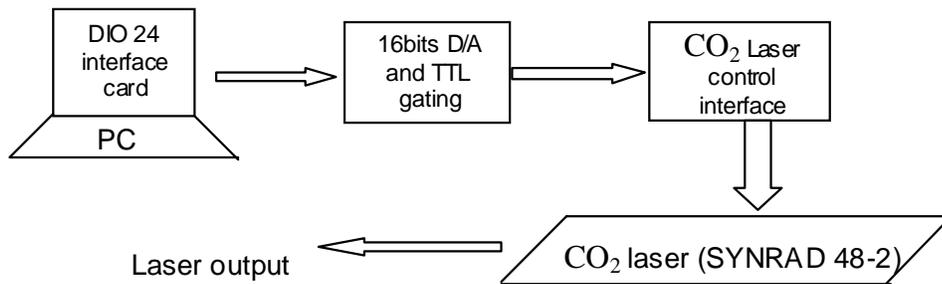


Figure 4-2. Block diagram of the CO₂ laser control subsystem

4.3.2 CO₂ laser power and exposure time optimization

Thermal bonding is the most important step in the SCIIB sensor fabrication. When the tube and fiber assembly is exposed to the CO₂ laser beam, the optical energy is converted to the thermal energy which results in the increase of the temperature at the exposure area. It is important to control the laser output power and exposure duration to ensure solid bonding between the fibers and the tube. Too large laser power can result in degradation of the optical properties of the optical fiber and too much built-in stress at the bonding region. On the other hand, too low laser power can result in incomplete bonding. In order to achieve the best optical and mechanical performance of the fabricated sensor, the CO₂ laser exposure time and the power level need to be set to their optimal values.

There is an optimal time duration in which the glass materials are softened. A review of fiber optic fusion splicer designs reported in the technical literature suggests that the duration at which the glass is softened should be limited to a few seconds [89].

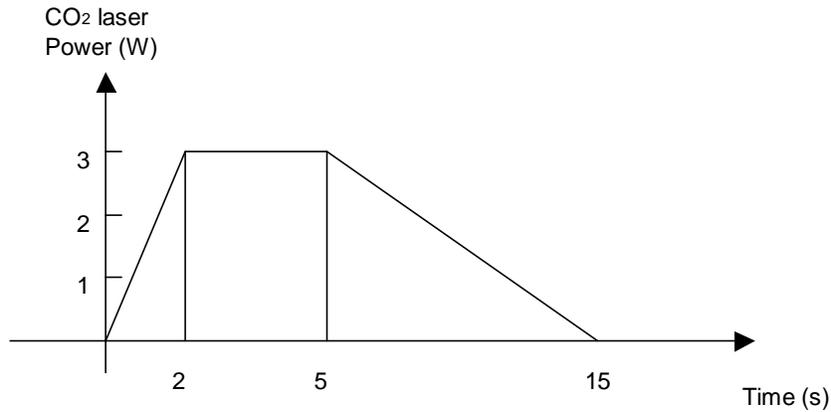


Figure 4-3. Optimized CO₂ laser power level and exposure time

A large number of experiments have been conducted to reach an optimal CO₂ laser power and exposure time curve as shown in Figure 4-3. This design allows 2 seconds of preheating time, 3 seconds of heating time and 10 seconds of annealing time. The total fabrication time is about 15 seconds.

4.3.3 CO₂ laser power calibration

The CO₂ laser output is quite non-linear when it is controlled through the external analog port. To achieve precise control of the output power, we conducted a calibration experiment for the CO₂ laser. The laser output power was measured using a power meter. The results are plotted as shown in Figure 4-4. Based on the calibration data, the CO₂ laser power can be accurately mapped to the external control voltages. Thereafter, precise control of the laser output power can be realized.

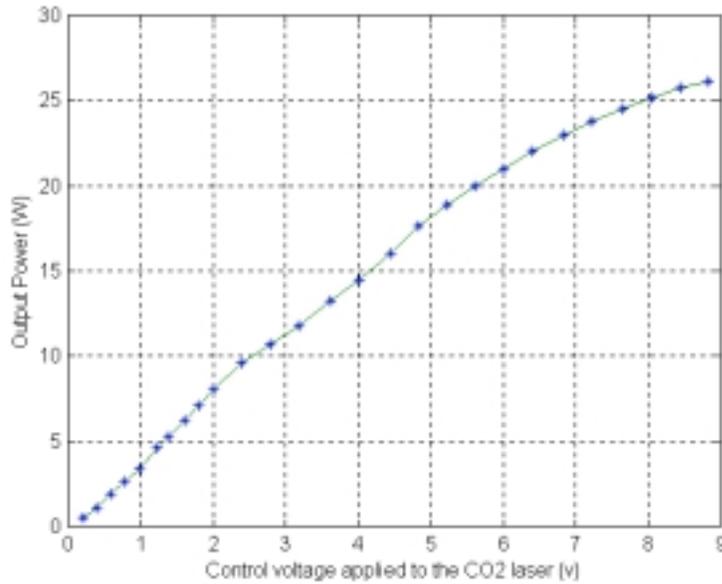


Figure 4-4. CO₂ laser output power calibration results

4.4 Whitelight Interferometric Sensor Cavity Length Monitoring Sub-system

The whitelight fiber interferometric sub system for sensor cavity length on-line monitoring is the main part of the automated sensor fabrication system. The measurement of the sensor cavity length is achieved by demodulating the interference spectrum of the SCIIB sensor.

4.4.1. Principle of the Whitelight Interferometric Cavity Length Monitoring

The basic principle of the white light interferometric sensor cavity length monitoring can be illustrated using Figure 4-5. When the sensor is fabricated, two fibers with cleaved endfaces are inserted into a capillary tube. The partially reflected optical waves at these two endfaces will generate an interference signal which is transmitted back to the spectrometer through a 2x2 fiber coupler.

If we assume that the broadband light source (LED or SLED) has a Gaussian spectral power distribution given by

$$I_s(\lambda) = I_0 \exp\left[-\frac{(\lambda - \lambda_0)^2}{(\Delta\lambda)^2}\right], \quad (4-1)$$

where λ_0 is the central wavelength, I_0 is the peak value, and $\Delta\lambda$ is the source spectral width. The output interference signal is then given by:

$$I = 2I_s(\lambda) \left[1 + \gamma(L) \cos\left(\frac{4\pi L}{\lambda} + \varphi_0\right) \right], \quad (4-2)$$

where the factor γ takes into account the decreased visibility due to the numerical aperture of the fiber as well as other attenuating effects, and φ_0 is the initial phase difference between the two interference signals.

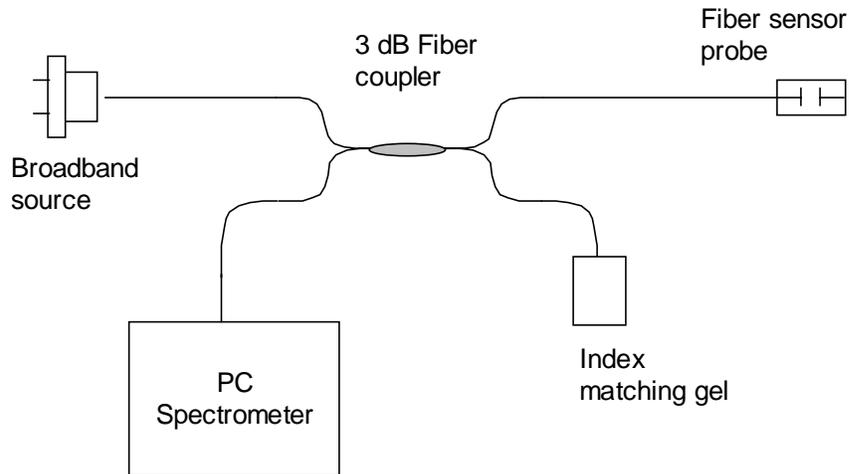


Figure 4-5. Basic principle of the whitelight interferometric sensor cavity length monitoring

If we normalize the interference spectrum given by Equation (4-2) with respect to the source spectrum, we have the normalized interference output expressed as

$$I_n = 2 \left[1 + \gamma(L) \cos \left(\frac{4\pi L}{\lambda} + \varphi_0 \right) \right] . \quad (4-3)$$

It is shown in Equation (4-3) that the output spectrum of the sensor is modulated by a sinusoidal function due to the interference. Because the interference spectrum is a function of the sensor cavity length L , the successful demodulation of this spectral signal can render an accurate and absolute measurement of the sensor cavity length.

A simple case can be considered in which two different spectral components of the source (λ_1 and λ_2) are utilized. These two wavelength components arrive at the spectrometer with different phases, which can be expressed as

$$\varphi_{1,2} = \frac{4\pi L}{\lambda_{1,2}} + \varphi_0 . \quad (4-4)$$

Thus the phase difference between these two spectral components is given by

$$\Delta\varphi = \varphi_1 - \varphi_2 = \frac{4\pi L(\lambda_2 - \lambda_1)}{\lambda_1 \cdot \lambda_2} . \quad (4-5)$$

Rewriting Equation (4-5), we have

$$L = \frac{\Delta\varphi \cdot \lambda_1 \cdot \lambda_2}{4\pi(\lambda_2 - \lambda_1)} . \quad (4-6)$$

If the phase difference of these two spectral components are known, the absolute value of the sensor cavity length L can be calculated by Equation (4-6).

Although it is not easy to measure the phase difference of two arbitrary spectral components, there exist a few special points with fixed phase relation. For example, the phase difference between two adjacent peaks (or valleys) is 2π . Therefore, by detecting the spectral locations of the peaks or valleys in the interference spectrum, we can obtain the cavity length L by applying Equation (4-6).

4.4.2 Whitelight system implementation

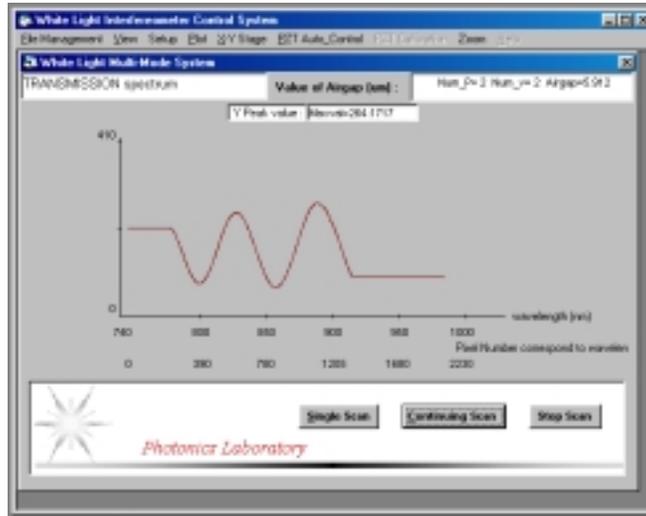
Because we need to fabricate multi-mode and single-mode fiber SCIIB sensors, two white light interferometric sensor cavity length monitoring systems were constructed, one for single-mode fiber-based sensor fabrication, and the other for multimode fiber sensor fabrication. The two systems share the same spectrometer but use different sources and fibers.

The spectrometer used is a fiber optic PC plug-in spectrometer (PC2000 manufactured by Ocean Optics, Inc.). The PC-2000 spectrometer card uses a 600-line holographic grating to diffract the input light to a CCD array, and interfaces with the computer using a 12-bit A/D converter through the ISA bus. The blaze wavelength is 850 nm, and the best efficiency is from 750 nm to 950 nm, which covers the whole light source spectrum of interest. The resolution of this spectrometer is approximately 0.3 nm.

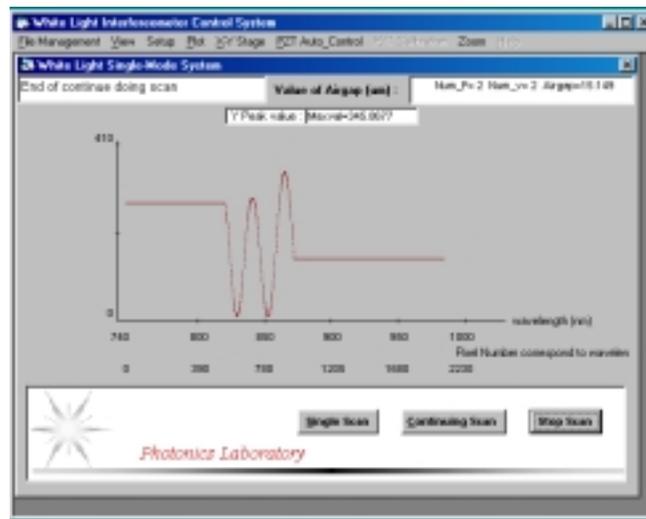
The whitelight source used in the multimode fiber system is a Honeywell high power LED pigtailed with a 62.5/125 μm multimode fiber. The central wavelength is 850 nm. The source used in the single-mode fiber system is an SLED (EG&G Canada) pigtailed with 9/125 μm single-mode fiber with the central wavelength of 850 nm and the spectral width of 20 nm.

A computer program was developed to demodulate the interference spectral signals output from the white light subsystem so that the cavity length of the sensor can be monitored accurately while the sensor is fabricated. The computer program is based on the previously discussed phase detection method in which peaks and valleys in the interference spectrum are detected. The software is implemented in a combination of Visual Basic and C languages so that both graphic interfaces and high computational speed are achieved and optimized. The interfaces of the designed software is shown in

Figure 5-6, where (a) is the multimode fiber sensor case, and (b) is the single-mode fiber case.



(a) Multimode



(b) Single-mode

Figure 4-6. Whitelight interferometric cavity length monitoring software

4.4.3 Whitelight system performance evaluation

1. Standard deviation test

The standard deviation of the white light subsystem was measured using SCIIB sensors with their cavity lengths fixed. The standard deviation of the multi-mode fiber system was calculated to be $\sigma = 0.001\mu m$. The standard deviation for single-mode fiber system was found to be $\sigma = 0.002\mu m$.

2. Frequency response test

Using the software, the sensor cavity length can be calculated in less than 0.1 second. The corresponding frequency response of the system is higher than 10 Hz. The average fabrication time of the SCIIB sensor is about 15 seconds; therefore the frequency response of the white light system is high enough for our applications.

3. Dynamic range of the white light system

The multimode fiber system can measure sensor cavity lengths from 4 μm to 20 μm , and the single-mode fiber system can measure from 8 μm to 70 μm . The standard deviation of the sensor cavity length measurement is constant over the whole dynamic range. Typical initial cavity lengths for SCIIB sensors are about 8 μm for multimode fiber-based and 25 μm for single-mode based. Therefore, the dynamic ranges of the whitelight systems are large enough for the purpose of sensor fabrication.

4.5 Micro-Motion Fiber Positioning Sub-system

During the sensor fabrication, the fibers and the capillary tube must be kept precisely aligned. The sensor cavity length needs to be accurately adjusted to the preset value, and the bonding distance, which determines the sensor effective gauge length, also needs to

be precisely controlled. Therefore it is necessary to design a fiber positioning system for the sensor fabrication.

4.5.1 Stage system design and construction

The computer controlled micro-motion fiber and tube positioning sub-system is schematically illustrated in Figure 4-7.

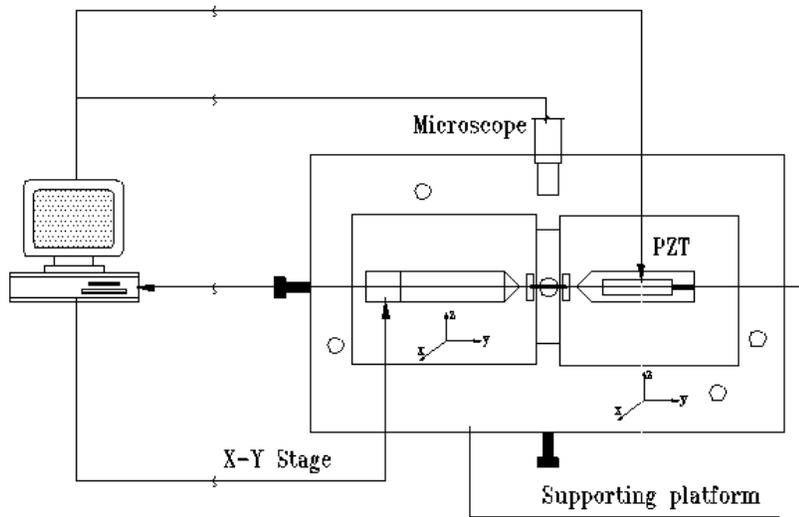


Figure 4-7. Micro-motion fiber positioning subsystem

The two fibers are positioned on two V-grooves using magnets, and the V-grooves are mounted on two 3-dimensional translation stages respectively. Between the two translation stages, a supporting block with another V-groove on top is used to position the capillary tube. All the V-grooves are specially designed and manufactured to hold the fibers or the capillary tube tightly. After installation, the three V-grooves are precisely aligned to fall in a straight line so that there is no angular offset during sensor fabrication. The fibers can be inserted into the central capillary tube by moving the two translation stages in three dimensions. To allow precise adjustment of the sensor cavity length,

another small PZT-actuated stage is used to move the reflector fiber with ultra-high resolution along z-direction. The movement of the stage is controlled by the central computer through a PZT driver and a 16-bit D/A circuit. In order to control the sensor gauge length, a large translation stage is used to move the whole setup in two directions with respect to the CO₂ laser beam. After the tube is bonded to the lead-in fiber, this stage can precisely position the second bonding point with respect to the CO₂ laser beam. A video microscope system is used to help the alignment process and to monitor the whole sensor fabrication. The photograph of the implemented stage system is shown in Figure 4-8.



Figure 4-8. Photograph of the sensor fabrication stage system

4.5.2 PZT stage calibration

The final fine adjustment of the sensor cavity length is achieved by moving the PZT stage. The movement of the PZT stage is controlled by the computer programs through a 16 bit D/A circuit and a PZT driver. However, the relationship between the PZT displacement and the external control voltage is not linear. In order to adjust the cavity

length to a preset value at an ultra-high accuracy, we need to calibrate the PZT stage movement with respect to the input control voltages. The calibration was conducted by using the whitelight interferometer and an extrinsic Fabry-Perot interferometric (EFPI) sensor. First we implemented an EFPI micro-displacement sensor with one fiber sealed to the tube and the other fiber fixed to the PZT stage. When the PZT stage moves, it generates an interferometric displacement signal through the EFPI sensor, which can be measured by the whitelight interferometric cavity length monitoring system. Relating the PZT control voltage to the whitelight interferometer output, the PZT stage can be precisely calibrated. Figure 4-9 shows the PZT calibration results. We can control the PZT stage movement with a very high accuracy by referring to the stored calibration data.

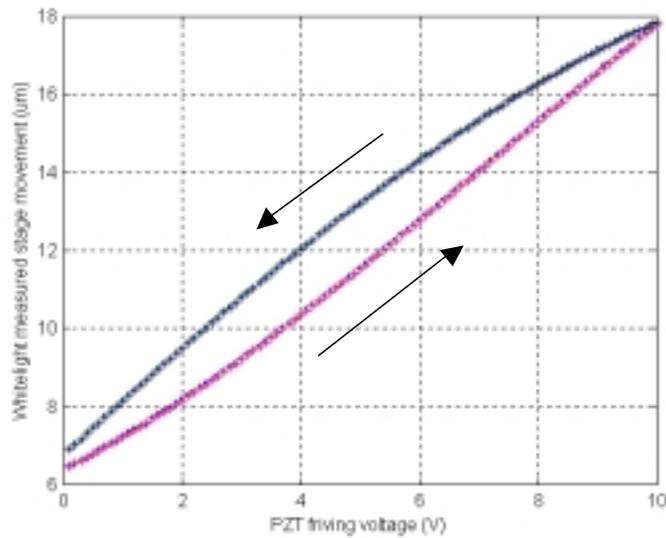


Figure 4-9. PZT stage movement calibration results

4.6 SCIIB Sensor Fabrication

With the completion of the sensor fabrication system, we are now ready to fabricate SCIIB sensor probes. Fibers used to fabricate the sensor probe are carefully cleaned and cleaved using a York fiber cleaver. The capillary tube is also cleaned and cleaved to the desired length. With the help of the microscope, two fiber ends prepared by the cleaver are then inserted into the capillary tube and held on the positioning stages. By adjusting the micromotion stage system, the two fibers are moved to the preset positions where the desired initial sensor cavity length is obtained. By moving the 2-dimensional translation stage underneath the micromotion stage system, the fiber and capillary tube assembly is brought to the center of the laser spot. The CO₂ laser emits light to heat the assembly with its power level and duration controlled by the computer program. After one side of the sensor is fused, the fiber and capillary assembly is then move to the other side to perform the same fusion process.

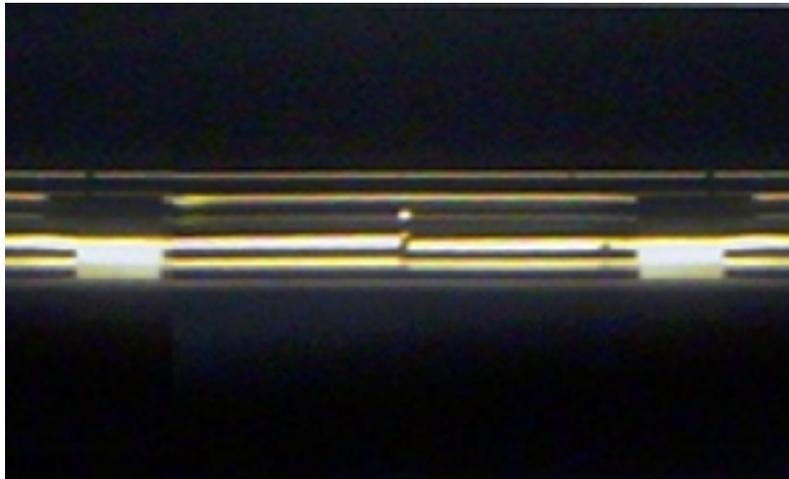


Figure 4-10. Microscopic photograph of the SCIIB sensor probe
(Gauge length: 1.5mm, initial cavity length: 25.74 μ m)

Figure 4-10 shows the photograph of a typical sensor probe imaged by the microscope. In the picture, we can clearly see the sensor cavity formed by the fiber endfaces and the two fusion points. So far, the shortest sensor gauge length that can be fabricated with the system is 0.5mm for the single-mode fiber-based sensor and 0.7mm for the multimode fiber-based sensor, respectively. It is very difficult to further reduce the sensor gauge length because the fiber endfaces can be damaged resulting from the too close fusion point.