Chapter 5. Evaluation of SCIIB Multimode Temperature Sensor System

In this chapter we will make an evaluation on the principle of the SCIIB sensor system and on the performance of SCIIB multimode temperature sensor system. We will introduce the related experiments for the evaluation. First, the experimental evaluation on the principle of SCIIB sensor system will be presented. Then, we will forward an outlook on the performance of the SCIIB temperature sensor system.

5.1 SCIIB Temperature Sensor System Principle Evaluation

In this section, we will concentrate on the evaluation of the principle of the SCIIB temperature sensor system including evaluations on the Self-Calibration principle, the Splitting-Spectrum technique and the EFPI temperature sensor principle.

5.1.1 Self-Calibration Principle Evaluation

The major feature of the SCIIB sensor system is that it has the ability of self-compensating the optical power fluctuations in the system caused by the optical source power fluctuations and optical fiber loss variations by the Split-Spectrum technique. With this feature the SCIIB sensor system is expected to offer higher accuracy compared with traditional fiber optic sensor systems. In order to evaluate the self-calibration capability of the SCIIB sensor system, we conduct an experiment using the developed SCIIB sensor system. Since the Self-Calibration capability of the SCIIB sensor system is to compensate the optical power fluctuations in the sensor system, thus we need to bring about the optical power fluctuations in the sensor system by some means. Here both adjusting the output power of the optical source and bending the transmitting optical fiber in the system are viable. Considering the limited adjustable linear range of the optical source — LED which insures stable output spectrum of LED and the outcome effects of the optical source power fluctuations and optical fiber loss variations are same that cause optical power fluctuations, so we conduct the experiment for evaluating the Self-Calibration capability via bending transmitting optical fiber by which we can obtain larger optical power changes than by adjusting optical power of LED without significant changes to the optical spectrum.

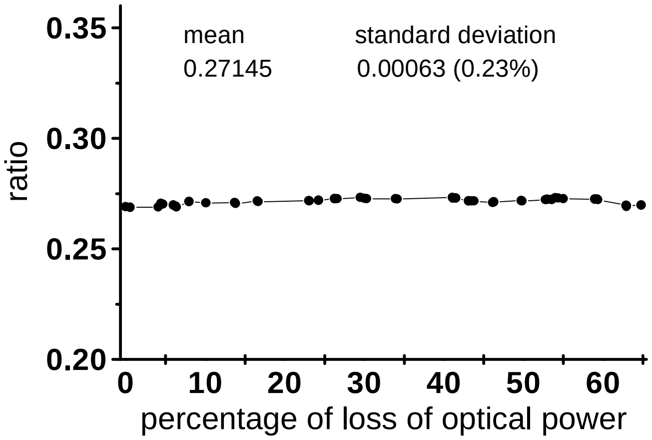


Figure 5-1. Ratio as a function of loss of optical power

As shown in Figure 5-1, we evaluate the Self-Calibrated capacity for compensating optical power fluctuations in the sensor system due to bending-induced fiber loss changes. Here we just connect a piece of optical fiber with well cleaved fiber end to the SCIIB temperature sensor system. From Figure 5-1 we can see the maximal fluctuation of the ratio is just 0.23% caused by up to 70% optical loss induced by fiber bending. Thus it well illustrates that by taking advantage of the Split-Spectrum technique we can obtain good Self-Calibrated capacity with our SCIIB temperature sensor system.

5.1.2 EFPI Temperature Sensor Principle Evaluation

To test the principle of the EFPI temperature sensor, we take advantage of the Whitelight interferometric system to monitor the F-P cavity length change with the change of environmental temperature [27]. First we fabricate a multimode fiber optic sensor head with an initial cavity length of 9.591 μm and gauge length of 1.0 mm by using the tube with OD/ID of 363/132μm. Then we place this sensor head with into an oven and increase the temperature from room temperature to 1400 °F with 50 °F each step. From Figure 5-2 we can see the linear relationship between the F-P cavity length changes and the temperature variations, which proves the validity of the Equation (2-17).

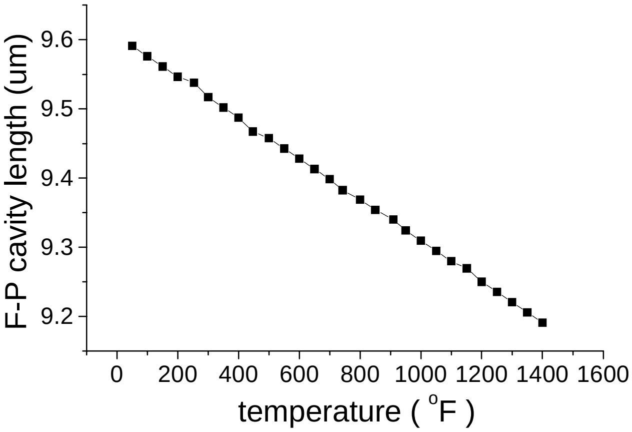


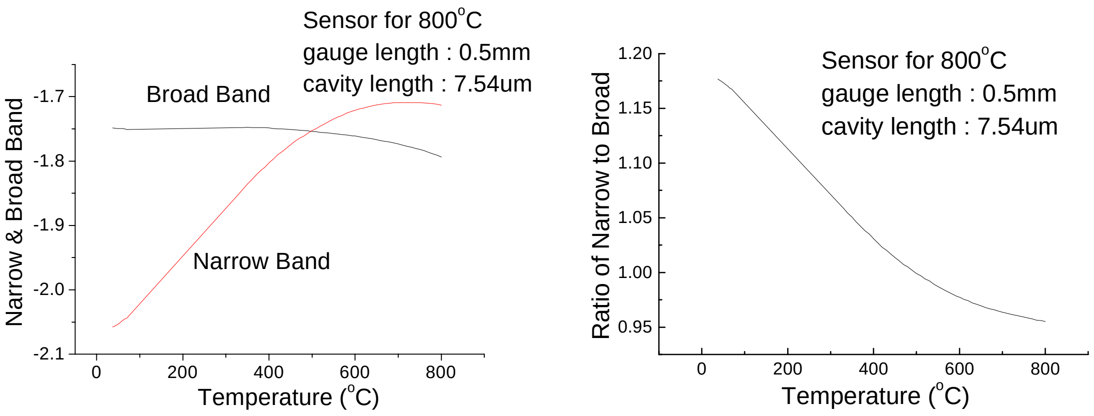
Figure 5-2. F-P cavity length change as a function of temperature change

5.2 Multimode Fiber-Based SCIIB Temperature Sensor System Performance Evaluation

In this section we make a comprehensive evaluation on our multimode SCIIB temperature sensor system overall performance. First a sensor with a large temperature operating range — 800 °C is demonstrated. Then we will introduce the system's stability, resolution, repeatability, etc.

5.2.1 Demonstration of 800 °C Multimode Fiber-Based SCIIB Temperature Sensor

Based on the principle of the SCIIB temperature sensor, we know that a small gauge length leads to a large operating range. According to the theoretical calculation and experimental data, by using the sensor head fabrication system we fabricate a temperature sensor head with a 0.5 mm gauge length which corresponds to a operating range of up to 800 °C from room temperature. Figure 5-3 illustrates the experimental data of this 800 °C temperature sensor head.



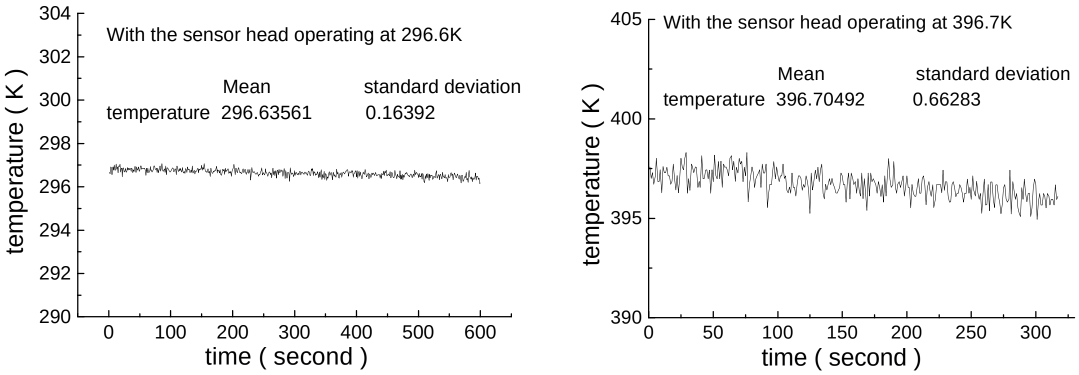
(a) (b)

Figure 5-3. Demonstration of 800 °C Multimode Fiber-Based SCIIB Temperature Sensor

Figure 5-3 above illustrates the performance of the sensor that can be used for the operating range from the room temperature up to 800 °C. After reversing the cause-and-outcome relationship between the ratio and the temperature in Figure 5-3(b), we can obtain the temperature as a function of the output ratio in one-to-one quantitative relationship, which is used in the last data processing stage in the computer for specifying the measurand's result temperature. From Figure 5-3(a) we can see the Broad Band is still within the range of its coherence length which should be around 9.03125 um according to the calculation in Chapter 2 while the Narrow Band gets a much better interference fringe than the Broad Band.

5.2.2 Resolution of the Multimode Fiber-Based SCIIB Temperature Sensor System

Resolution of the system is defined as the minimum resolvable value of the measurand. We evaluate the resolution of the multimode fiber-based SCIIB temperature sensor system by testing the standard deviation of measured temperature under two different temperature conditions — 296.6K(≈33.6°C) and 396.7K(≈133.7°C). Here we also use the sensor head with the operating range of 800°C we used before. We define the standard deviation of measured temperature as the resolution of the temperature sensor system. The experimental results are shown in Figure 5-5.



(a) 296.6K(33.6°C)

(b) 396.7K(133.7°C)

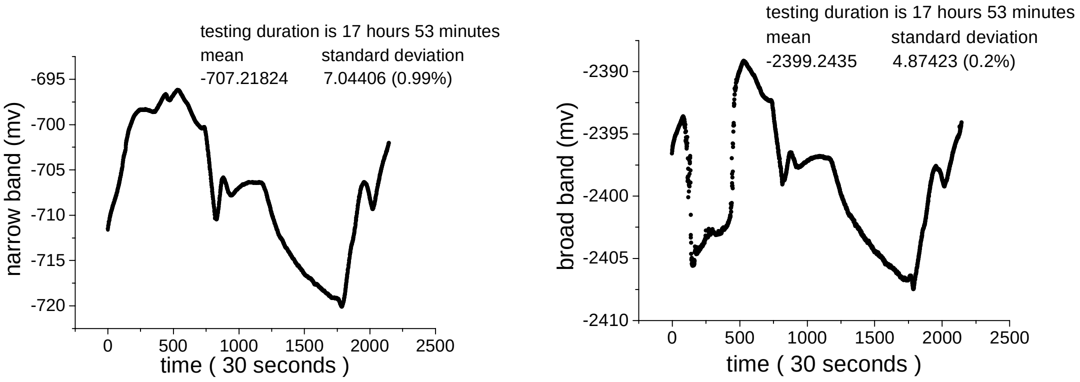
Figure 5-5. Standard deviation of measured temperature using multimode fiber-based SCIIB temperature sensor system

Figure 5-5 above illustrates the performance of the multimode fiber-based SCIIB temperature sensor system with the sensor head operating at 296.6K(≈33.6°C) with the resolution of 0.163°C and at 396.7K(≈133.7°C) with the resolution of 0.662 °C, respectively. Here there are two points needed to be paid attention to 1) There exists a temperature drift when measuring the output result temperature using the SCIIB temperature sensor system due to the temperature-unstable oven containing the sensor head. 2) When the sensor head operating at 133.7 °C the measured temperature drift is much bigger than that when the sensor head operating at 33.6 °C, which causes poorer performance of the standard deviation at 133.7 °C than that at 33.6 °C to some extent. Another reason for better performance of the standard deviation at 33.6 °C is because closer to 800 °C poorer resolution while closer to room temperature better resolution determined by the operating point of the sensor head. Certainly this latter cause just brings about a little poorer effect at the sensor head working at 133.6 °C which is far away from 800 °C.

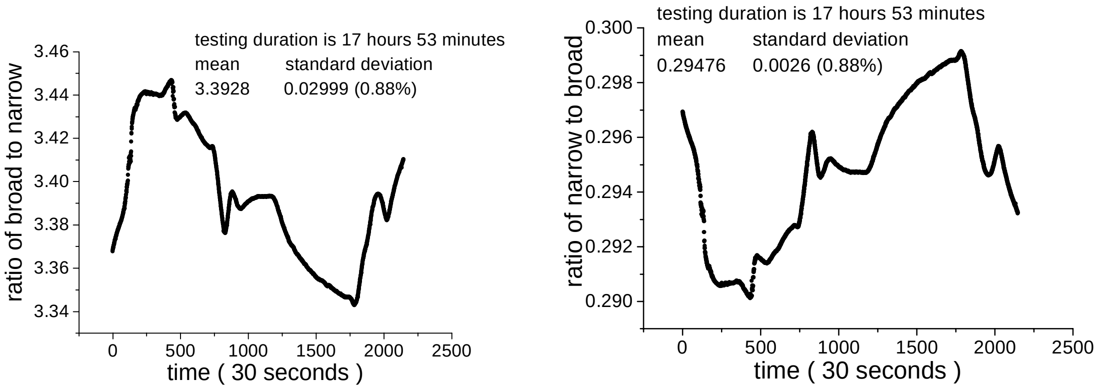
In addition, Figure 5-5 shows that the resolutions at different temperatures are changing linearly which is dependent on the operating point of the used sensor head. In this 800 °C temperature sensor system case, the resolution tends to be decreased with increase of the temperature.

5.2.3 Stability of the Multimode Fiber-Based SCIIB Temperature Sensor System

Another important criterion is the stability of the multimode fiber-based SCIIB temperature sensor system, which means the long-term performance of the system. It is defined as the ability of the system to maintain the same specification within a specific length of time period. The stability of the system is usually measured by the quantity of drift, which is defined as the time dependent change in the characteristics of the system. This criterion also puts big influence on the accuracy and the reliability of the system. Here we evaluate the stability of the system via testing the long-term drift of the output ratio, the Narrow Band and the Broad Band as shown in Figure 5-6. In our experiment we record the outputs from the multimode fiber-based SCIIB temperature sensor system during about 18 hours. Here we also evaluate the stability by analyzing the standard deviation of the ratio.



(a) Narrow Band (b) Broad Band



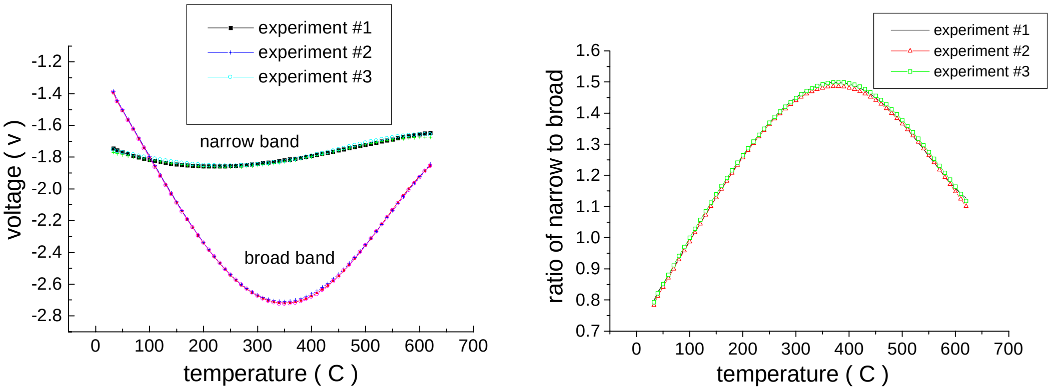
(c) ratio of Broad to Narrow (d) ratio of Narrow to Broad

Figure 5-6. Long-term drift of ratio, Narrow Band and Broad Band

Figure 5-6 illustrates the long-term testing results for evaluating the stability of the multimode SCIIB temperature sensor system. Because the 800 °C temperature sensor head is broken when we do experiments, we connect another sensor head with the sensor system under almost constant temperature environmental condition. The testing duration is 17 hours and 53 minutes. The fluctuation of the ratio is about 0.88%. From these figures we can see the long-term drifts of the Narrow Band and the Broad Band are pretty random which brings about the corresponding random drift of the ratio of them. Although the Broad Band also causes certain fluctuation of the ratio, the major drift of the ratio results from the fluctuation of the Narrow Band, which can be seen from the Figure 5-6(c) (ratio of the Broad Band to the Narrow Band). In Figure 5-6(c) the fluctuation of ratio looks much like the fluctuation of the Narrow Band in Figure 5-6(a). The reason for this random drift is still under investigation. It may be caused by the spectral fluctuation of the optical source — LED, or the fluctuation of the output from the amplifiers in the Narrow Band's and the Broad Band's transimpedance front-ends. Thus we still need to improve the performance of the long-term drift to insure good stability and reliability of the sensor system.

5.2.4 Repeatability of the Multimode Fiber-Based SCIIB Temperature Sensor System

The repeatability of the sensor system is an indication of its ability to give the same results when it is used to measure the same quantity several times in succession under the same condition. Here we evaluate the repeatability of the system by testing the same sensor head's outputs three times under the same environmental condition. Figure 5-7 shows the experiment results.



(a) (b)

Figure 5-7. Repeatability of multimode fiber-based SCIIB temperature sensor system

Because the 800 °C temperature sensor head is broken when we do experiments, so we use another sensor head with the cavity length of 6.92 μm and the gauge length of 1.5 mm to test the repeatability of the system. Figure 5-7 above illustrates the good performance of the repeatability of the multimode SCIIB temperature sensor system. We test the same sensor head three times under the same experimental setup condition. Each time we record measured temperature values from the sensor system in both temperature-increasing condition and temperature-decreasing condition.

5.2.5 Accuracy of Multimode Fiber-Based SCIIB Temperature Sensor System

The accuracy is defined as the closeness of the agreement between the result of a measurement and the true value of the measurand. We use a commercial thermal couple Omega CN76000 as the evaluation standard for the true value of the temperature. The accuracy of Omega CN76000 is 0.1°C. First we bind the sensor head and the thermal couple together, then we insert them into an almost hermetic small ceramic cabinet which is put inside the oven. Under this setup the temperature inside the ceramic cabinet is more stable than that just inside oven since there exists air streams floating inside the oven. Figure 5-8 illustrates the evaluation results with this experiment. The average deviation of measured temperature $\Delta T_{average}$ is 0.5°C.

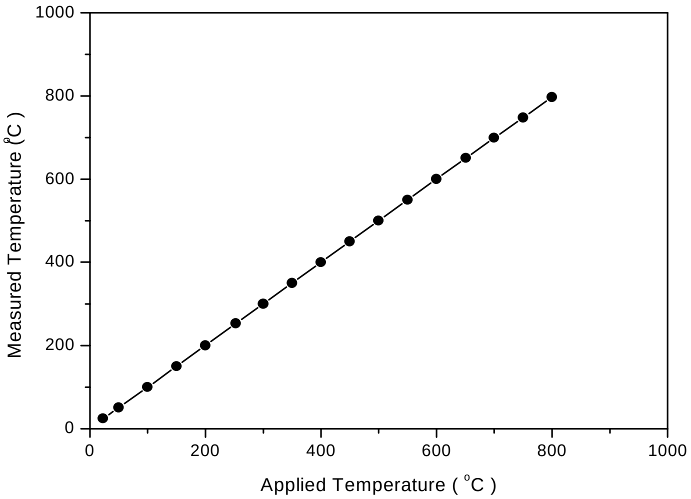


Figure 5-8. Accuracy evaluation of multimode SCIIB temperature sensor system

5.2.6 Warm-up Duration of Multimode Fiber-Based SCIIB Temperature Sensor System

Since there is no built-in Thermoelectric Cooler (TEC) inside the optical source — LED of the multimode SCIIB temperature sensor system, the output optical power and spectrum of the LED will be drifting within certain time after the LED startup. Hence, in order to ensure we can obtain correct measured temperature values from the SCIIB temperature sensor system, a warm-up duration for the LED's stability exists. Figure 5-9 illustrates the stabilization process of the LED. The warm-up duration for our SCIIB temperature sensor system is at least half an hour, an hour warm-up duration will be better.

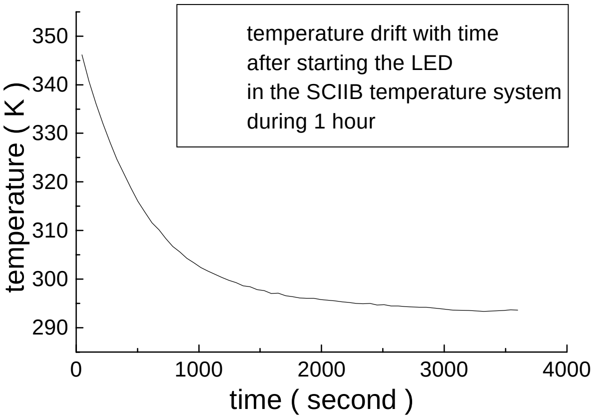


Figure 5-9. Warm-up duration of multimode SCIIB temperature sensor system

5.3 Multimode Sensor Head Evaluation

Our multimode SCIIB sensor head is fabricated by using the standard 62.5/125μm multimode optical fiber and tube with OD/ID of 363/132μm provided by SpecTran Inc. and Polymicro Technologies Inc., respectively.

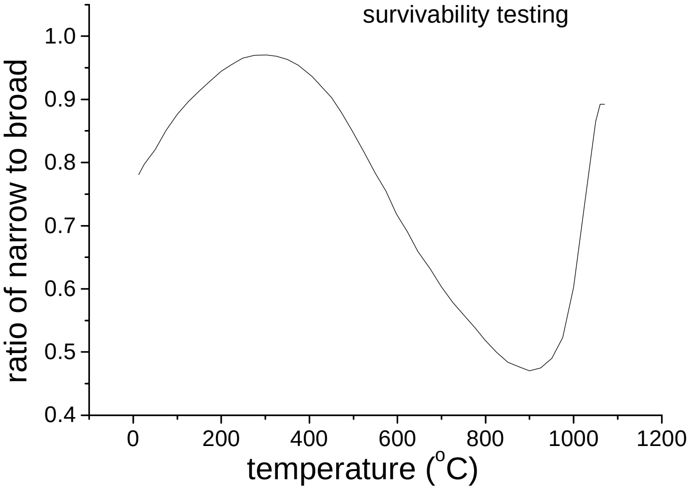
5.3.1 Survivability of the Multimode SCIIB Sensor Head

Survivability of the sensor head can be divided into two sub-standards. The first sub-standard means that the sensor head is seriously physically damaged by the harsh environment (e.g. high temperature or high pressure) so hard that it can not be used for measurement applications at all. The second sub-standard means that although the sensor head is without the physical damage, it can not work correctly due to the impact of the harsh environment.

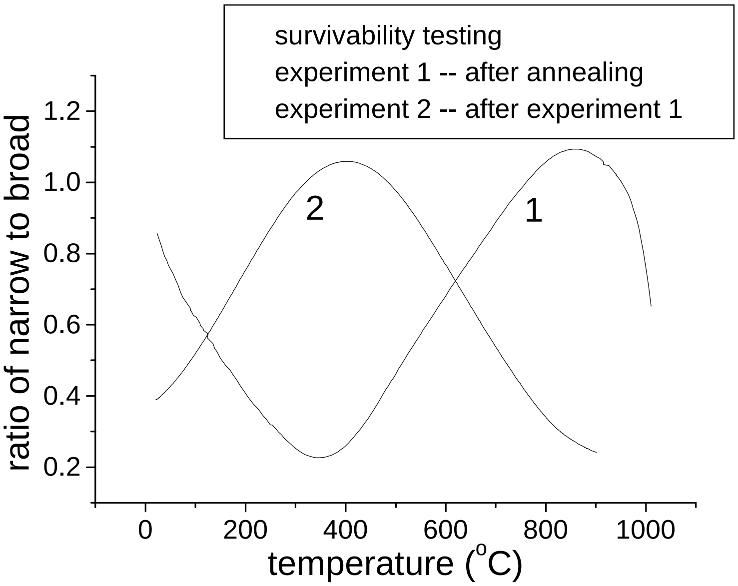
We did many experiments to test the survivability of the SCIIB sensor head under these two sub-standards. Figure 5-10 illustrates the typical temperature characteristic response curve of the sensor head. Due to the limitation of the oven we used in the experiments, here the highest temperature reached is 1075 °C. Based on the experiments, we got the highest temperature for our SCIIB sensor head is around 950 °C which satisfies the second sub-standard of the survivability. From Figure 5-10 we can see before around 950 °C the temperature characteristic curve is an approximately standard sinusoidal curve, after around 950 °C the cycle of the sinusoidal curve varies obviously. However, in our experiments after the sensor is cooled back to the room temperature we test it again. We find that the cycle of the sinusoidal curve is almost the same as that before heating up to 1075 °C but with apparent shift of operating point (see Figure 5-10 b). The apparent shift of operating point indicates the sensor head can not work correctly for the continuous measurement application. Therefore the highest temperature for the sensor head is around 950 °C which satisfies the second sub-standard of the survivability.

Meanwhile the highest temperature for the sensor head which satisfies the first sub-standard of the survivability is about between 950 °C and 1000 °C. After we heat the sensor head up to 1000 °C, the sensor head turns to be very brittle and fixed bending. When we touch it gently, it is broken immediately which means that it can not endure tiny stresses, therefore it can not be used at all in practical measurement applications.

When we heat the sensor head just beyond 900 °C and less than 950 °C, it still can be used for continuous measurement applications with acceptable strength property.



(a) Sensor 1



(b) Sensor 2

Figure 5-10. Survivability testing

5.3.2 Relationship between Gauge length and Operating Range of Sensor

We test several multimode sensor heads to evaluate the relationship between the gauge length and the operating range of the sensor head (the definition of the linear operating range is described in Chapter 2). We fabricate several multimode sensor heads with the same gauge length but different F-P cavity lengths. After temperature characteristic testing experiments on each sensor head, we find that the operating ranges of the sensor heads are still different with each other in spite of the same gauge length (see table 5-1).

Sensor Head Number #	Gauge Length (mm)	F-P Cavity Length (μm)	Operating Range (°C) (fringe valley/peak ~ fringe peak/valley)	Linear Operating Range (°C) (starting point ~ ending point)
1	1.5	6.4467	510 (350 ~ 860)	220 (495 ~ 715)
2	1.5	7.5304	446 (467.6 ~ 913.6)	208 (588 ~ 796)
3	1.5	6.5272	483.8 (58.8 ~ 542.6)	239 (181 ~ 420)
4	1.5	6.9037	462.93 (18.24 ~ 481.17)	223 (138 ~ 361)
5	1.5	7.4645	496.25 (28.09 ~ 524.34)	240 (156 ~ 396)
6	1.5	7.5797	435.05 (170 ~ 605.05)	273 (251~ 524)
7	1.5	7.5873	469.2 (299.82 ~ 769.02)	241 (414 ~ 655)
8	1.5	8.118	474.4 (376 ~ 850.4)	262 (482 ~ 744)
Mean of Operating Range (°C)			472.2	238.25
Standard Deviation of Operating Range (°C)			24.8	21.6

Table 5-1. Relation between gauge length and operating range