Sapphire Fiber Based High Temperature Extensometer

by

Xiaojun Fang

Research Report submitted to the Faculty of the
Virginia Polytechnique Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Electrical Engineering

Approved by:

Dr. Richard O. Claus

Dr. Kent Murphy

Dr. Anbo Wang

May 1994
Blacksburg, Virginia

Acknowledgements

I would like to express my gratitude to Dr. R. O. Claus for his kind and invaluable guidance and for serving as my adviser during this research work. My sincere thanks are also due to Dr. K. A. Murphy and Dr. A. Wang for their understanding and invaluable advice.

I would like to express my sincere appreciation to Russell May, Angie Plante and George Wang for their enthusiastic assistance, cooperation and support during the research, and extremely valuable suggestions in the writing of this report. My thanks are also due to all members and students in FEORC for their kind cooperation and help during my research in the lab.

This research project is partially supported by Fiber & Sensor Technologies Inc., and many researchers in Fiber & Electro-Optics Research Center have made contributions to its development. I would like to express my gratitude to them. Without the efforts they made, it would have been impossible for me to achieve any progress in this work.

I would also to express my thanks to my wife, and my parents for their support, encouragement and understanding that has enabled me to be where I am today.

I. Introduction

High temperature strain sensing is a powerful tool for high temperature material analysis and failure prediction. The standard method today for this purpose is to measure the crack opening caused by cyclic fatigue, which is a function of the strain suffered. Since the temperature in the sensing zone is so high (above 1500°C), no electrical transducer can function well for information gathering. At present, the typical sensing tool is the extensometer, which is a high temperature metal cross with one end attached to the material near the crack in the high temperature zone. The displacement of the crack opening can be read out by a caliper connected to the other end of the cross, where the temperature is much lower than the temperature in the sensing zone.

For real time strain monitoring, a high temperature strain sensor with high accuracy and response time is expected. The approach by using a fiber optic sensing method is very promising. A special single crystal sapphire fiber can withstand temperatures as high as 2000°C, so sensors built with sapphire fiber are good candidates for high temperature measurements. Sapphire fiber-based sensors have been studied extensively at FEORC since 1991, and many sensor structures have been proposed. For high temperature strain measurement, the sensor structures must be compact, flexible and tolerant to the hostile environment. This is not an easy task due to the limited availability of components. Several prototypes of a fiber optic high temperature extensometer have been designed and tested for this purpose, each has its advantages and disadvantages. The key point for evaluation is its performance and cost. The difficulty in sapphire fiber based sensor design using the interferometric method is that the fiber is a multimode fiber with a very large numerical aperture. This means the output light from the sapphire fiber has both low spatial coherence and high modal noise. Also, the sapphire fiber has no cladding at the present time; the transmission property of the fiber will be unstable and sensitive to external disturbances on the fiber, so an intensity based sensor is also too vulnerable to be practical. The question remaining is how to design a proper sensor structure that can guarantee the accuracy and reliability of the measurement with sapphire fiber.

The sapphire fiber based extensometer design should have the following specifications: 0.2% FS accuracy, 1/4 inch dynamic range, 1500°C and above operating temperature. Before designing the sensor, it is helpful to review the sensor structures previously proposed. Many sensor configurations have been proposed and tested. All of the approaches can be classified into two catagories: interferometric methods and non-interferometric methods. The main restriction in the design is the limit of suitable optical components, and the only fiber for this very high temperature (VHT) applications is the single crystal sapphire fiber. The aim of this research is to design a reliable high temperature fiber optic extensometer with the sensor specifications.

II. Designs Review

2.1. Interferometric Method

The general problems for multimode fiber interferometers are the small dynamic range, complex transceiver structure, and relative nature of measurement. In order to lower the noise background and get absolute measurement, white light interferometer methods are commonly used. The disadvantages of common white light interferometry are small dynamic range, strict alignment requirement, and an expensive signal processing unit. Using a laser as the light source can increase the dynamic range a little, but also increases the modal noise and instability. In the sapphire fiber case, the big numerical aperture of fiber makes this problem even worse. It is very difficult to observe interference fringes with sapphire fiber. In order to increase the spatial coherence of the light at the sapphire fiber output, two methods have been tried. One is by replacing the sapphire fiber by a sapphire rod as the light transmission medium to maintain the coherence of light, and the other is by a spatial filtering technique to increase the spatial coherence. The problem of the first method is that the sensor becomes inflexible, and the problems of the second method are the same as those of general multimode fiber interferometers.

There is also an indirect measurement method that may be implemented by imitating the traditional technique. This technique uses a high temperature metal cross to convert the crack displacement in the high temperature zone to a scaled displacement in the low temperature zone by a metal cross as shown in Figure 1. A single-mode fiber Extrinsic Fabry Perot Interferometer (EFPI) is attached to the low temperature end of the metal cross. It is obvious that the accuracy of this method is determined by the accuracy of the cross. This method in nature is a relative method and as inflexible as the sapphire rod method.

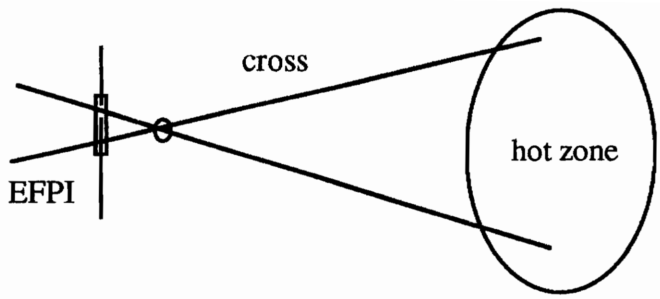
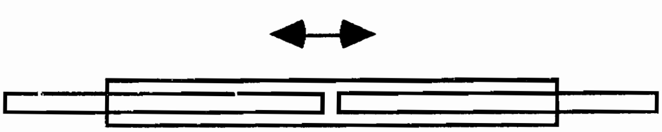


Figure 1. Indirect approach by EFPI sensor

Using an absolute interferometer is another promising method. In order the reduce the complexity of the receiver, two methods have been proposed. One is by using a Fizeau interferometer to demodulate the output of the white light EFPI and the other is by an equal length reference fiber to match the coherence. These two methods can work well under the multimode fiber condition theoretically, but since sapphire fiber has a big numerical aperture and birefringence, modifications to these structures are needed to make them more practical in real field applications.

2.2. Non-interferometric Method

Several non-interferometric sensors have also been proposed. The simplest form is the intensity based sensors. The problem is how to implement a compensation structure to compensate the loss factors associate with instabilities. The simplest sensor example is shown in Figure 2. The air gap between the two fibers will influence transmission loss, so the sensor is intensity modulated by the fiber displacement. The common compensation method is the dual-wavelength method which needs a dispersive component inside the sensor.



Sapphire fiber and tube

Figure 2. Intensity based sensor.

In order to introduce a dispersion component into the sensor, several methods have been tried. One approach is by forming a reflection grating on the endfaces of the sapphire fiber. The purpose of the grating is to make the sensor wavelength dependent or dispersive so that the wavelength referenced compensation method can be used. The drawbacks include the difficulty of cutting fine groves on sapphire fiber end faces, and that a high temperature reflection grating is not available. The mode distribution will also influence the results. The difficulty in grating making can be solved if the sapphire fiber grating is replaced by a relatively soft high temperature optical material rod to rule the grating on.

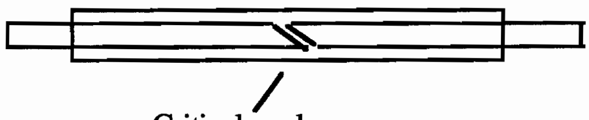


Figure 3. Critical angle sensor by total reflection

A second approach utilizes the total reflection method first proposed by Spillman for multimode fiber. The structure is shown in the Figure 3. Here the sapphire fiber is polished at its critical angle. The evanescent field extending to the other fiber will then depend on the gap distance exponentially. Dual-wavelength compensation is applicable with this method. The disadvantage is that the signal depends on the mode distribution of the fiber; the total reflection for different modes will have a different condition. It would be difficult to develop this sensor into a commercial product because of its small dynamic range.

III. Proposal for New Sensor Structure

In view of the sensor structures discussed above, several new methods are proposed here and will be tested. One of the methods uses the stress-induced birefringence inside sapphire material. The basic structure of the sensor is shown in Figure 4. The sapphire flat is used as the polarizer and polarization analyzer. The two orthogonal sapphire blocks are balanced to cancel the intrinsic birefringence of the material, thus eliminating the temperature sensitivity. White light is input into the sensor, and modulated by the stress-induced birefringence. The sensor is a wavelength encoded sensor. The problems in this method are the uncertainty of material property at high temperature condition, and its relatively large size.

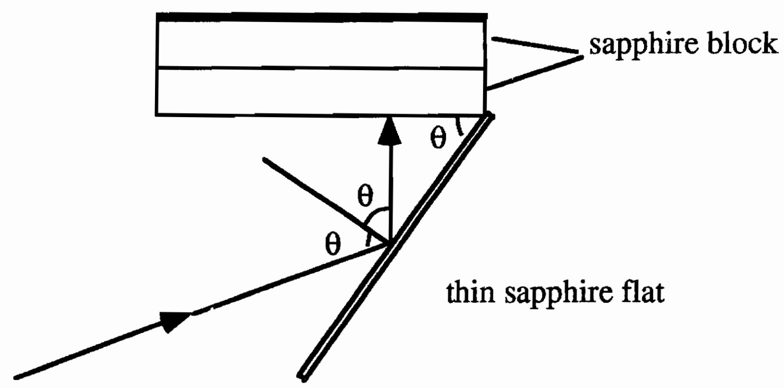


Figure 4. Birefringence based strain sensor. θ is the Brewster angle which is about 60°.

Another method uses a piece of sapphire fiber as a beam resonator. One end of the fiber beam is fixed in a sapphire tube, and the other end is free. There is a small coil attached to the free end of the fiber, and driven by a strong electromagnetic field to make it resonant. The displacement of the sapphire tube will change the length of vibrating fiber, and hence the resonant frequency. Experiments showed that the resonant frequency of a 2 cm long silica fiber beam is about six hundred Hertz. The difficulties of this method include the problems in making a small electrical coil that will provide sufficient electromagnetic force to drive the resonator, and the temperature dependence of Young's modulus.

The third method is a self-mixing interferometer. This method utilizes the positive feedback of laser light into the laser cavity. The intensity of laser output will oscillate according to the position and velocity of the external feedback mirror. The advantage of this method is the ease of obtaining a fringe pattern with multimode fiber. The main problem is that the signal is sensitive to fiber perturbations for which there is no good compensation method. Since this method has many interesting properties, it will be analyzed and tested in detail.

A promising method to build a stable sensor is to use Moiré interferometry. When two gratings are placed to near each other, the output mixing will appear as a wide fringes pattern, which is called Moiré fringes. When the angle between two gratings is small the fringes will be very wide. If one of the gratings moves a distance of the grating constant d relative to the other, the wide Moiré fringe will also move a period. This method is a widely used technique in computer controlled machinery for position indicating. The high temperature grating is a viable possibility to be made, since there are several high temperature optical substrate materials available. It has the potential to be developed into a product.

Another promising method is the equal-length coherence matching absolute interferometer. Modifications are made to improve the performance in sapphire fiber conditions. Using low coherent light source and observing the interference between light signals from two different paths, the interference happens only when the path lengths are equal. By optimizing the interference signal by feedback signal, the absolute value of the displacement can be determined.

All the methods available now are outlined above. Among these new methods proposed here, the self-mixing method will be discussed in detail, and experimental results and suggestions for further investigation are given. Moiré interferometer will be discussed and several alternative structures are outlined. The coherence matching interferometer will also be analyzed theoretically. Since the gratings are presently unavailable, experimental data is not given for the Moiré interferometry.

IV. Self-mixing interferometer method

The self-mixing method is widely used as a velocimeter. The basic idea here is that the threshold of the laser can be modulated by the optical feedback, so the intensity of laser output will be modulated. When the reflector is moving, the laser output intensity will change one fringe when the reflector moves $\lambda/2$ distance. This phenomenon will exist even though the reflector is well beyond the coherence length of the laser. Many papers have been published about this property and its relation to laser noise. Several papers discussed the possibility of this technique being used in sensing fields. By this method, we have observed fringe output from a 30 cm long sapphire fiber interferometer for the first time.

4.1. Principle of Self-mixing Interferometer

The self-mixing interferometer can be realized by using many kinds of lasers. Typically, semiconductor lasers are preferred due to their low power and small size. The structure of said interferometer is shown in Figure 5, where a photodiode is in the same package as the laser diode. The output light of the laser diode is focused on a reflector which moves along x direction. The light reflected back from the target is fed back into the laser diode. When the target moves a distance of $\lambda/2$, the laser intensity will output a fringe, similar as normal interferometer. This method is called self-mixing interferometry.

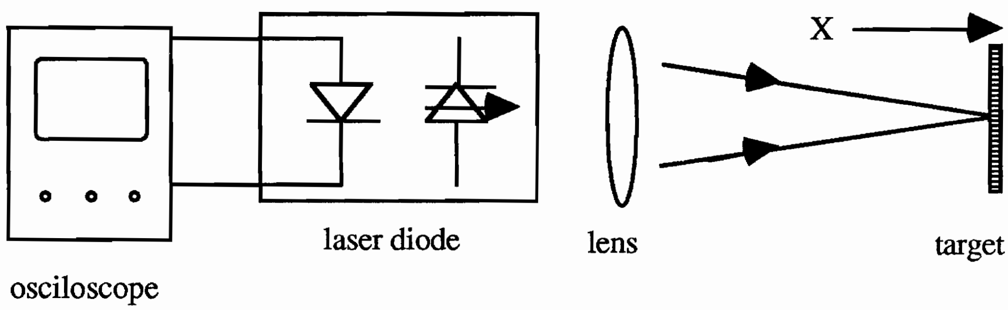


Figure 5. Self-mixing interferometer setup

When an optical fiber is used to conduct light, the feedback light from the far end of the fiber will cause a similar result to that of the free space case above. The visibility of the optical fiber self-mixing interferometer depends on the effective power feedback into the laser cavity rather than the fiber type, and the fringes for a multimode fiber interferometer are very clear. The characteristics of fiber self-mixing interferometer are as follows [1]. The interference can occur whether the fiber is single-mode or multimode fiber; and also when the laser diode is single-mode or multimode laser diode. The fringe visibility is clear even when the fiber length is much beyond the coherence length of the laser diode. The waveform of fringe is asymmetric, something like a sawtooth, and the waveform varies for different directions of motion. This means the direction of movement can be distinguished directly from the fringe waveform. These unique features make the fiber self-mixing interferometer very attractive.

There are many papers discussing feedback effects of the laser diode. Most of these papers are concerned with the noise property of the laser diode related to the optical feedback, which is very important in optical fiber communications. The general results are that the feedback will broaden the laser spectral width and hence reduce the coherent length, except when the feedback is very weak [2][3]. The feedback laser cavity was analyzed with a three mirror Fabry-Perot cavity, which indicated that the feedback effect was the strongest when the mode frequencies of the inner cavity and the external cavity overlapped [4][5]. The waveform asymmetry and modulation depth were also analyzed in reference [5], which showed that the modulation depth was the largest when the current was near the threshold. Reference [1] seems to be the only paper discussing self-mixing interferometer with optical fiber.

All the analysis above assumed that the feedback light was coherent with the light inside the laser cavity. The experimental results showed that the self-mixing coherence still existed when the fiber was 7 km long[6]. It is obvious that the coherence assumption is inadequate in the analysis, and that the active laser cavity plays a very important role in the resulting interference fringes. So let us view this problem in a different way without assuming the coherence.

4.2. Theoretical Analysis

When two light signals with the same wavelength and phase difference superposed, the intensity of the combined signal will exhibit an interference pattern. The interferometer is a decoder for phase modulation signals. The phase modulation is a common assumption in analyzing interferometers. Now let us begin with the assumption of frequency modulation, instead of phase modulation, to see the equivalence between phase modulation assumptions and frequency modulation assumptions in interferometer cases.

In any interferometer there are two light signals. One is the modulated signal and the other is the reference. The reference light can be thought of as both the wavelength and phase reference relative to the modulated signal. Consider the moving mirror of a Michelson interferometer, if the mirror is moving at a velocity of v. The Doppler frequency shift of the reflected light is 2vf/c, where f is the frequency of light and c the velocity of light. Since $2f/c = 2/\lambda$, where λ is the wavelength of light, the Doppler frequency shift is $v/(\lambda/2)$.

When this frequency shifted signal is mixed with reference light, the heterodyne frequency is the Doppler frequency shift whose time period is $\lambda/(2v)$. This means when the mirror moves a displacement of $\lambda/2$, the output of the beat signal will generate one period of waveform or a fringe. In the case of the EFPI sensor, we can also consider the light reflected from the end of moving fiber as frequency modulated, and the light reflected from the end of leading fiber as the reference. And the output fringes can be considered as the beat pattern between the two signals. In this sense, the phase modulation assumption is equivalent to the frequency modulation assumption.

In the self-mixing interferometer case, the frequency modulation assumption is more convenient to use than the phase modulation assumption to make the experiment results more understandable. Whether the conducting fiber is single-mode or multimode fiber and no matter how long the fiber is, the frequency modulated light feedback into the laser cavity always has a certain frequency shift relative to the light frequency in the laser cavity. Since the two light fields are totally incoherent, the phase relationship between the two light fields is arbitrary so the beat signal can not appear. Aided by the active material in the laser cavity, heterodyne between two incoherent light signal becomes possible. The FSK light absorbed by laser material reduces the threshold at frequencies at two sides of the laser oscillating frequency, and the sideband frequency in turn will make the laser intensity oscillate at beat frequency. A quantum process is needed to treat this method theoretically, and it is too complex to solve.

When a light signal is transmitting through a fiber whose optical path length is modulated by a PZT, the output light is actually a FM signal. As a result, the feedback light of the fiber will introduce a FM noise in the laser diode if an isolator is not used. In the case of the fiber self-mixing interferometer, the influence of fiber will also cause the interference to be unstable. Due to the FM noise caused by the fiber, the fiber self-mixing interferometer is not suitable for static quantity measurement, but it may be a useful tool for AC quantity measurements because of the output digital signal with information concerning the direction of motion. Furthermore, in some spatial cases, where only multimode fiber is available, the self-mixing interferometer becomes the only choice for digital output sensor. On the other hand, the influence of fiber can be used as a sensing mechanism. For example when a single mode fiber coil is used as a acoustic sensor such as in hydrophone application, the modulation on the fiber coil will modulate the intensity of laser output just as in ordinary self-mixing interferometers. The advantages of the self-mixing interferometer approach lies in the fact that the expansion or contraction of fiber is distinguishable, the fiber length is four times less than Michelson interferometer and the cost is low.

4.3. Experiment with Fibers

The original purpose of this study is to demonstrate the possibility of a sapphire fiber interferometer with the self-mixing method, since sapphire fiber is the only fiber for VHT applications. Interference patterns have not been observed before for several decimeters long sapphire fiber, because of the low spatial coherence of the fiber output. Since this technique may be useful in other applications, ordinary single-mode and multimode fibers are also tested.

Figure 6 shows the experimental setup. The mirror was fixed on a speaker which was driven by a signal generator. The beat signal was obtained from the output of a photodiode which was in the same package as the laser diode. The laser diode was a Sharp LT022MC multimode laser diode.

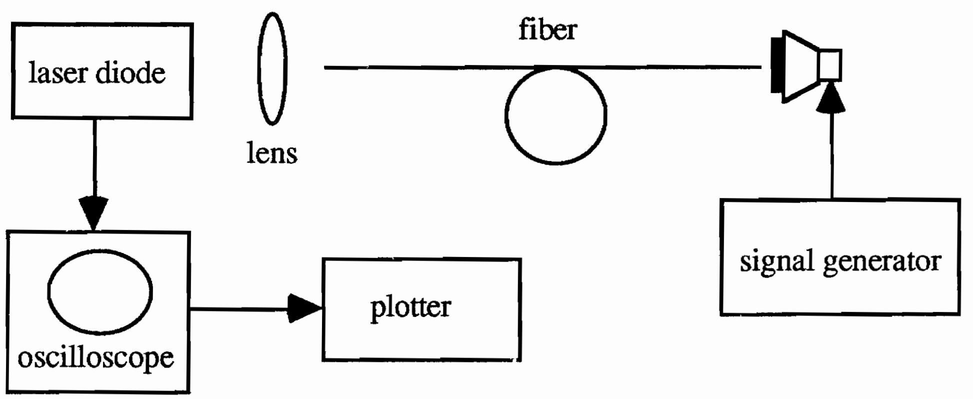


Figure 6. Experiment setup for fiber self-mixing interferometer

The visibility of the fringe pattern is determined by the light power feedback into the laser cavity. In the multimode fiber case, only a small fraction of light can be coupled back into laser cavity due to the mismatch of numerical aperture between the laser output and feedback beams. By choosing a laser diode which matches the multimode fiber output beam, the fringe modulation depth will increase considerably. In our experiment, the single-mode fiber had the biggest modulation depth, and the modulation depth of a 100 μm GI fiber was large enough to show clear fringes. The 50 μm SI multimode fiber interferometer had a modulation depth less than 100 μm GI fiber because of the larger beam parameter mismatch. Similar reasoning applies to sapphire fiber interferometers. The large diameter and NA of the fiber make the feedback light very inefficient, and only a small portion of light can be coupled back into the laser cavity. Thus the modulation depth was low for sapphire fiber interferometer. The fringes were still visible in this case as shown in Figure 7. The length of the sapphire fiber was 30 cm. The performance can be modified by using a better type of laser diode to increase the energy feedback efficiency. On the other hand, the steeper the current-intensity curve of the laser diode, the bigger the visibility of interference pattern.

Figure 8 is waveform of a single-mode fiber interferometer. The fiber length was about two meters. The interference signal was strong in the experiment, and it was clear that the interference waveform was asymmetric for the different directions of displacement of the mirror. The waveform of the 100 μm fiber interferometer is shown in Figure 9. The visibility of multimode fiber was lower than the single-mode fiber case, because less light power could be fed back into the laser cavity. For both the single and multimode fiber cases, half wavelength displacement of the mirror created a fringe output. The displacement of the mirror corresponding to the driving signal had been calibrated by using a two beam interferometer, similar to an EFPI sensor.

The experiment showed that the self-mixing interferometer can more easily obtain interference patterns than an ordinary interferometer. A digital readout sensor is possible under VHT conditions with sapphire fiber. In this technique the light source may be a low cost multimode laser diode, the fiber length can be much longer than the coherence length of the laser, and the direction of movement can be decided from the asymmetric interference pattern. Since the change of fiber length is equivalent to the mirror movement, it would be interesting to apply this technique in applications such as a hydrophone with single-mode fiber coil. Compared with the Michelson type hydrophone, the self-mixing interferometric hydrophone has the following advantages. It needs only one fourth the fiber length to achieve the same sensitivity as the hydrophone of Michelson type. The asymmetry of

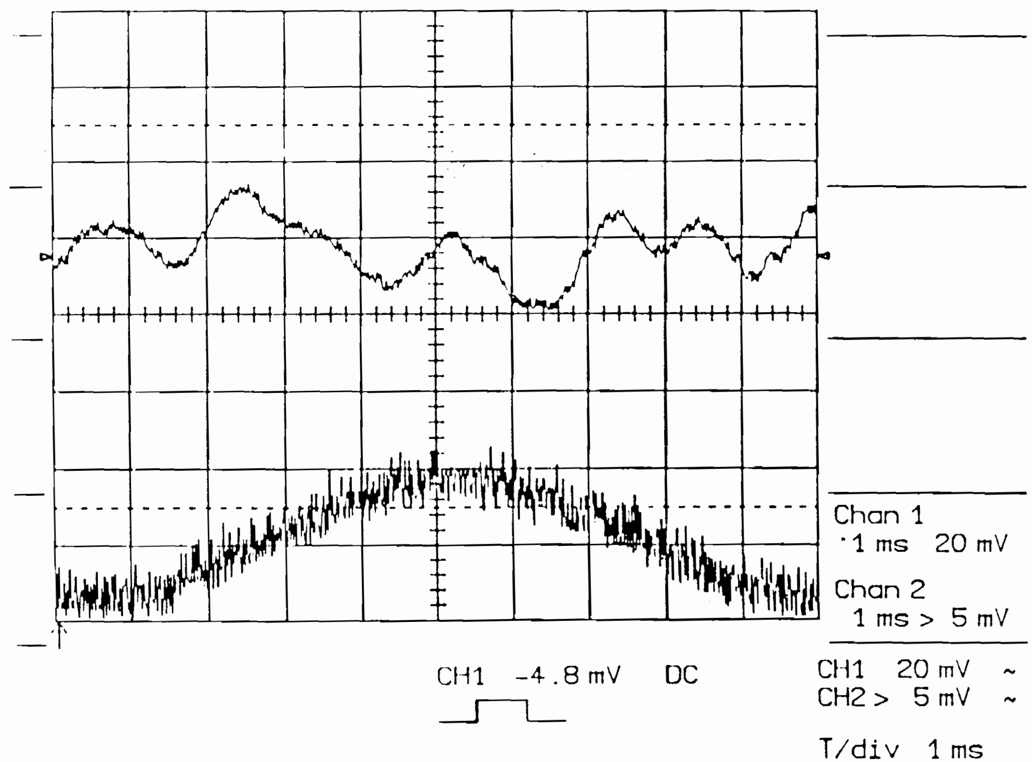


Figure 7. Output fringes from a self-mixing interferometer built with a 30 cm long sapphire fiber. The lower waveform is the driven signal for the speaker.

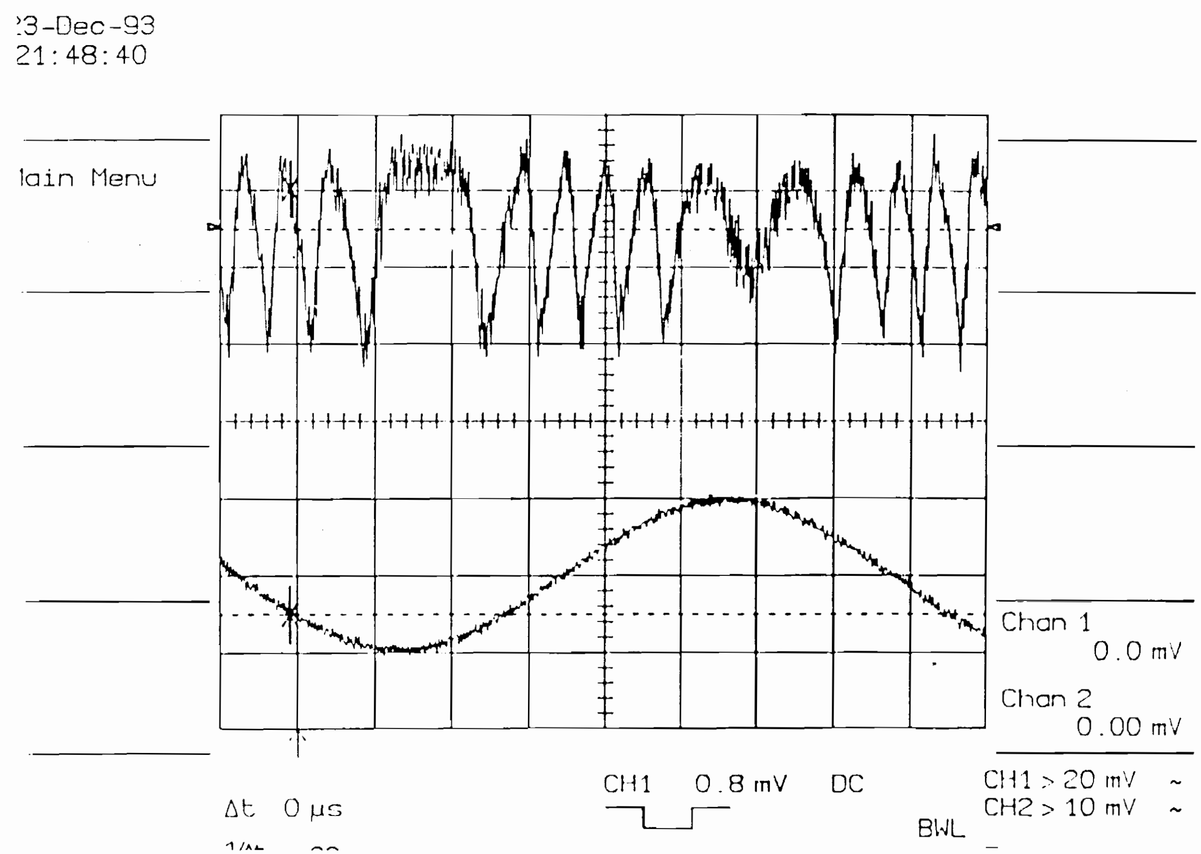


Figure 8. Output fringes from a two meters long single-mode fiber self-mixing interferometer.

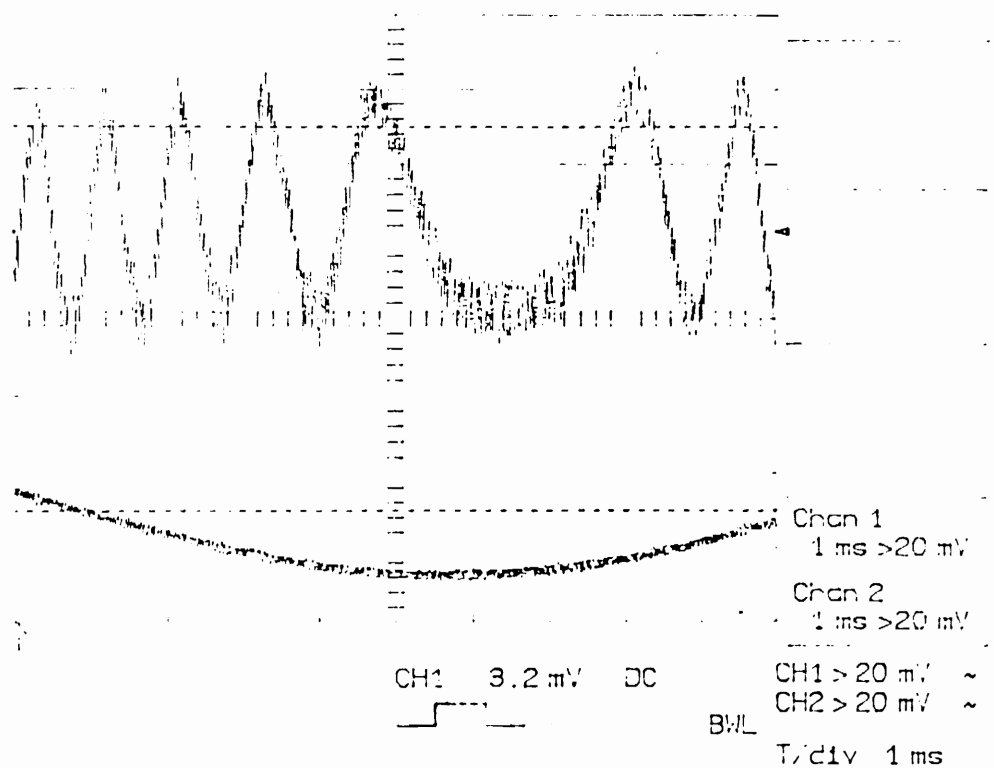


Figure 9. Output signal from a one meter long 100 mm diameter GI fiber self-mixing interferometer.

interference waveform also enables the possibility of direction decision, which means the sensor is more reliable than ordinary interferometers.

V. Moiré Interferometer

Although the self-mixing interferometry is an interesting method, and the sapphire fiber based interferometer can be realized, the influence of fiber disturbance makes the signal very noisy. It is very difficult to use this method to measure DC quantities, because the final extensometer for VHT displacement measurement should have 0.2% accuracy with a quarter inch dynamic range. Since Phase I of this project was based on single-mode fiber EFPI sensor, all receiver and data processing units for Phase II of the project should be the same to make them in accord with each other. So the sensor for Phase II should be a digital output sensor. To overcome the limits of conventional interferometers, a promising digital output extensometer based on Moiré interferometry is introduced here for VHT applications.

5.1. Principle of Moiré Interferometer

The principle of Moiré interferometry is rather simple. Consider two gratings with the same grating constant d. When their grooves are put together in a line, thick fringes appear. This is the Moiré effect. The fringe is called a Moiré fringe with a fringe width of $d/\sin\phi$, where ϕ is the angle between directions of the grating grooves of the two gratings [7]. The smaller the angle, the wider the fringe. When one of the grating moves a distance of d relative to the other grating, the Moiré fringe will shift a fringe period. So the Moiré fringe can be thought of as an enlarged image of the grating. A displacement of d in grating will result in a shift of $d/\sin\phi$ for Moiré fringe. There is no need of coherence for light source, so any kind of light source can be used. The spacing between the two gratings is an important factor. In order to get sufficient fringe contrast, the spacing should be small. For 100 lines/mm grating, the spacing should be less than 100 microns.

Figure 10 shows the Moiré interferometric displacement sensor setup. The leading fibers are sapphire fibers and the gratings are made of high temperature material by the etching method. The rail of scale grating is made of sapphire rod and tube. All the sapphire tubes, fibers and index grating are fixed on the sensor base. The scale grating is moved by the moving block.

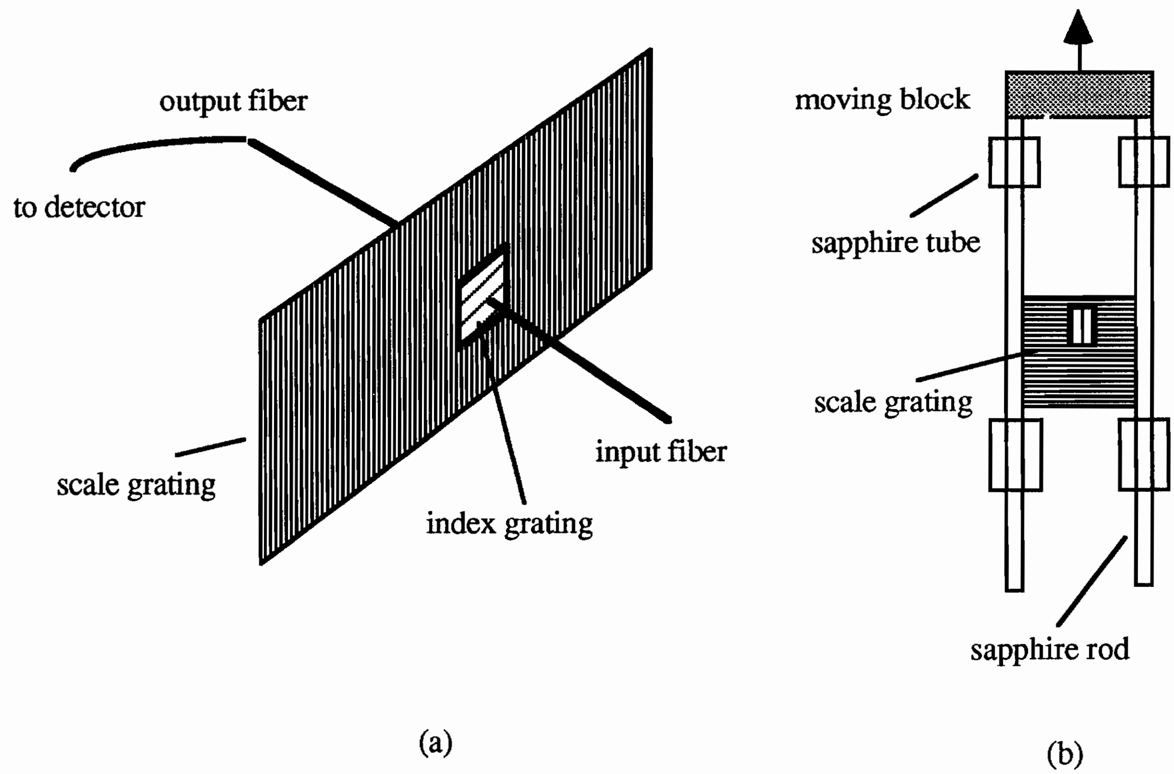


Figure 10. Moire interferometric displacement sensor structure. Sapphire fiber is used as leading fiber and fixed on the sensor base with the index graing together shown in (a), the structure of moving rail of scale grating is shown in (b).

The direction of moving can be distinguished by adding another receiving fiber which is separated from the first one by a distance of a quarter of Moiré fringe period. So the signals from the two receiving fiber have $\pi/2$ phase difference. The direction of displacement can be obtained from the two quadrate signals by well developed techniques.

5.2. High Temperature Extensometer by Moiré Interferometry

The Moiré interferometry is a well developed technique and widely used in computer controlled machinery for position sensing. The implementation of this technique into high temperature displacement measurement was demonstrated in 1991 [8]. But the temperature in that experiment only reached several hundreds degrees. In order to apply this technique to a very high temperature condition, we need to manufacture gratings on a high temperature optical substrate. The rail of the moving grating also needs to be modified, because it is not easy to guarantee the spacing between the two gratings within the desired certain accuracy.

The structure in the Figure 10 above is just an original prototype. There are many different structures of Moiré interferometer that can operate in either transmission mode or reflection mode. Since in very high temperature conditions, no reliable reflection coating is available now, the sensor should be designed to operate in the transmission mode instead of the reflection mode. Although high temperature moving rails can be realized, other methods are also proposed here as additional possibilities for building a Moiré interferometer.

The structure of the modified transmission mode Moiré interferometer is shown in Figure 11. It uses a lens to image the intensity pattern of index grating on the scale grating. The output will be a Moiré fringe output. This is only a prototype structure. Since in this

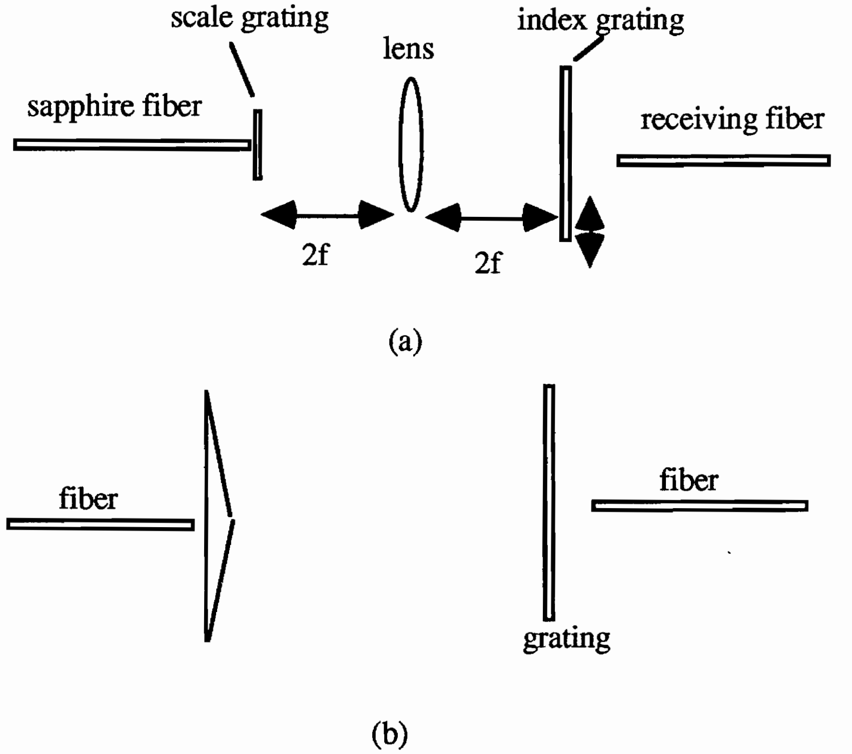


Figure 11. Modified transmission mode Moire interferometer.

structure the quality of the lens must be very good in order to obtain a good intensity image pattern on the index grating surface, it would be better to use an asymmetry structure where the grating constant of scale grating is larger than the index grating. The lens will produce a reduced size image of the scale grating on the surface of the index grating and make the bright-dark spacing period of the image be of similar size to that of the index grating. The structure in (b) uses an interference pattern to illuminate the index grating to obtain a moiré fringe output. A laser is needed as the light source.

Compared with other interferometric optical extensometer (for example EFPI), the Moiré fringe type extensometer has the following advantages.

(a). Since meter long instrument gratings are available with more than 1000 lines per millimeter, the dynamic range and accuracy of displacement measurement can be very large.

(b). A displacement of one grating constant will cause the thick Moiré fringe to move one period, which means by selecting the grating constant, sensors with different kinds of sensitivity can be realized. This makes the design of the sensor very flexible for different applications.

(c). The light source and the lead-in fiber can be any kind. This eliminates laser noise background and lowers the cost by getting rid of the expensive diode laser control system.

(d). It is convenient to realize direction decision by using quadrate technique.

(e). It is consistent with the technique of fringe counting developed in Phase I of the project.

The disadvantage of this sensor is its complexity and volume compared with the EFPI sensor. For our purpose, a ten millimeter long and 5 millimeter wide scale grating with 100 lines/mm is needed, so the size of the sensing part is acceptable in certain cases. The average cost of the grating will be low since only a small piece is needed. This method is a promising candidate for high temperature extensometer structure.

VI. Coherence Matching Interferometer

Methods of coherence matching are promising techniques since they enable the implementation of absolute interferometry. Low coherence light sources such as LEDs or SLDs are used instead of lasers, and the coherence matching technique is provided for signal decoding. The coherence matching method can be realized by introducing a reference fiber into the interferometer to make a coherence of two light signal matching, or by using a second interferometer to match the signal. All of these methods can be easily understood by analyzing a Michelson interferometer. The EFPI sensor may be interpreted as a two beam reflection interferometer, similar to the Michelson interferometer, so coherence matching techniques for Michelson interferometers can also be applied for building absolute EFPI. Two typical structures for absolute Michelson interferometer are shown in Figure 11. A similar structure has been used in coherence multiplexing technique [9], but for different purposes. The original structure of this project by Fizeau interferometer is also a similar approach to the structure (b), which is a modified form. Structure (a) is proposed by Li et al to provide an alternative way to realize the aim of coherence matching. The difficulties related to structure (a) come when the leading fibers are long or when the fibers have a very large numerical aperture, both the path length and the polarization states are too difficult to be perfectly matched. Common path structure of type (b) combines the advantage of the structure in reference [9] with the Fizeau interferometer decoder in the original proposal of this project. Eventually absolute displacement measurement with sapphire fiber may become possible.

Figure 11 shows the two structures for absolute interferometer demodulation. These two structures may be called absolute coherence matching and relative coherence matching structures. The output light from the sensing interferometer in the absolute matching structure (a) combines with the light reflected from the reference fiber, if the two light signals have traveled the same path length, they will interfere with each other. Relative coherence matching structure (b) is an alternative way to realize the coherence matching, where the second Michelson interferometer or EFPI acts as the conjugate counterpart of the sensing interferometer and is introduced to match the coherence.

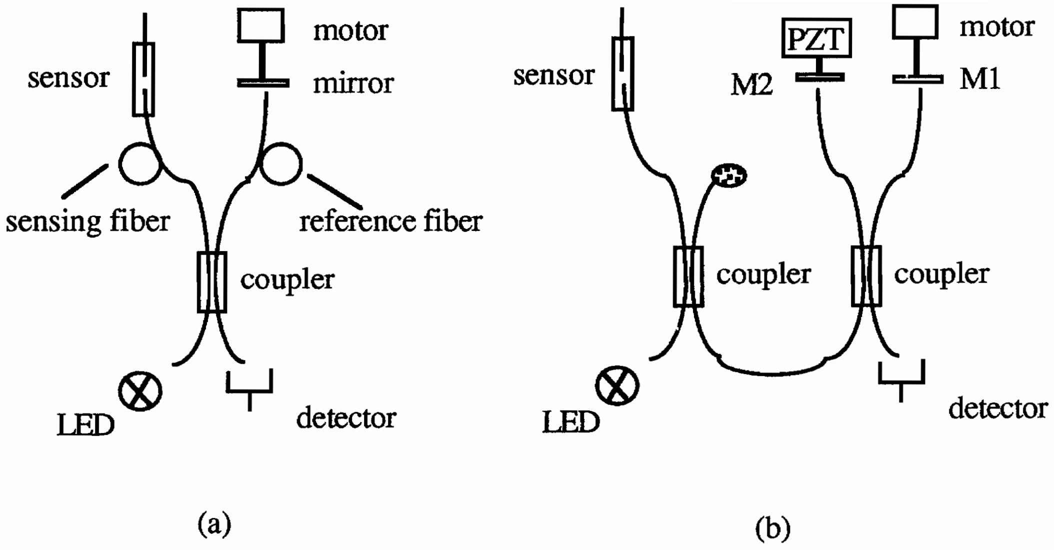


Figure 11. Equal-path coherence matching interferometer by (a) reference fiber and (b) Michelson interferometer.

The use of two mirrors structure instead of a single EFPI as the decoding interferometer can make the demodulation more flexible. One of the mirrors is driven by a motor while the other mirror is driven by a PZT. Since the coherence length of the light source is short (20 microns for example), only when the path length difference in the demodulation interferometer equals the length of path difference inside the sensing interferometer, will the interference fringes appear. The PZT is driven by a certain AC signal, and when the path difference between the two mirrors M1 and M2 equal the spacing inside EFPI sensor or the path difference of any other kind of Michelson interferometers, there will be interference fringes at the detector. Let the signal from the detector pass through a high pass filter, and feed back to control the motor to maximize the AC component of the interference signal as a servo system.

The use of a PZT to sweep the spacing over a small range can make the position decision more accurate and provide a directional signal to control the motor in order to make the mirror follow the changes of spacing inside the sensor. Aided by a servo system, the sensor can realize real time dynamic measurement, provided the speed of movement is not too big to be followed by the feedback loop. From this point, we can also say that the respond speed of this absolute EFPI is increased by adopting a PZT modulator..

When the leading fiber of the sensor is a multimode fiber, the mode dispersion lowers the coherence of the output light, and the interference becomes weak since mode coupling will take place. When sapphire fiber is used to build the interferometer, not only will the large mode dispersion degrade the operation, but also the high birefringence of the fiber makes the structure (a) difficult to operate, especially when the leading fibers are long. Since the birefringence of fiber is both temperature and bending sensitive, it is difficult to make the light from two different paths have the same polarization state in order to get good interference. The low coherence nature of the output light needs very precise optical alignment of the mirrors and fiber endfaces inside the sensor. The Michelson interferometer type decoder (b) can also be built using a prism instead of a fiber coupler. The advantage of structure (b) is that the reflected light from two endfaces travels through the same path to the receiver, the information of the path difference will be recovered better and information will be insensitive to disturbances on the fiber. The other advantages of structure (b) are higher response speed and shorter fiber. The main difficulty of the sapphire fiber absolute EFPI sensor is the need for accurate alignment. Two mirrors and endfaces of sapphire fiber must be aligned very accurately in order to obtain interference. How well the coherence matching method works in sapphire fiber case need further experimentation to investigate. Generally speaking, the longer the sapphire fiber, the more difficult it is to get interference, because small misalignment will greatly influence the output of the demodulation interferometer.

In addition to high temperature applications, the coherence matching methods can easily be implemented into many other sensing systems. Generally speaking, the absolute interferometer sensors in Figure 11 can be an EFPI or any other kind of two beam interferometers such as Michelson or Mach-Zehnder interferometers. Since absolute type matching technique has difficulty in remote sensing applications, relative matching technique becomes more important in that area. The multiplexing for two-beam interferometers is simple and straight forward. Figure 12 shows several possible structures utilizing the relative coherence matching technique, where the path difference in each sensor is separated and set to values isolated from each other. The reflection type interferometers such as Michelson interferometer or EFPI can be multiplexed by either cascade or parallel connection as shown in (a) and (b); while the transmission type Mach-Zehnder interferometer can be multiplexed in a totally different way (c).

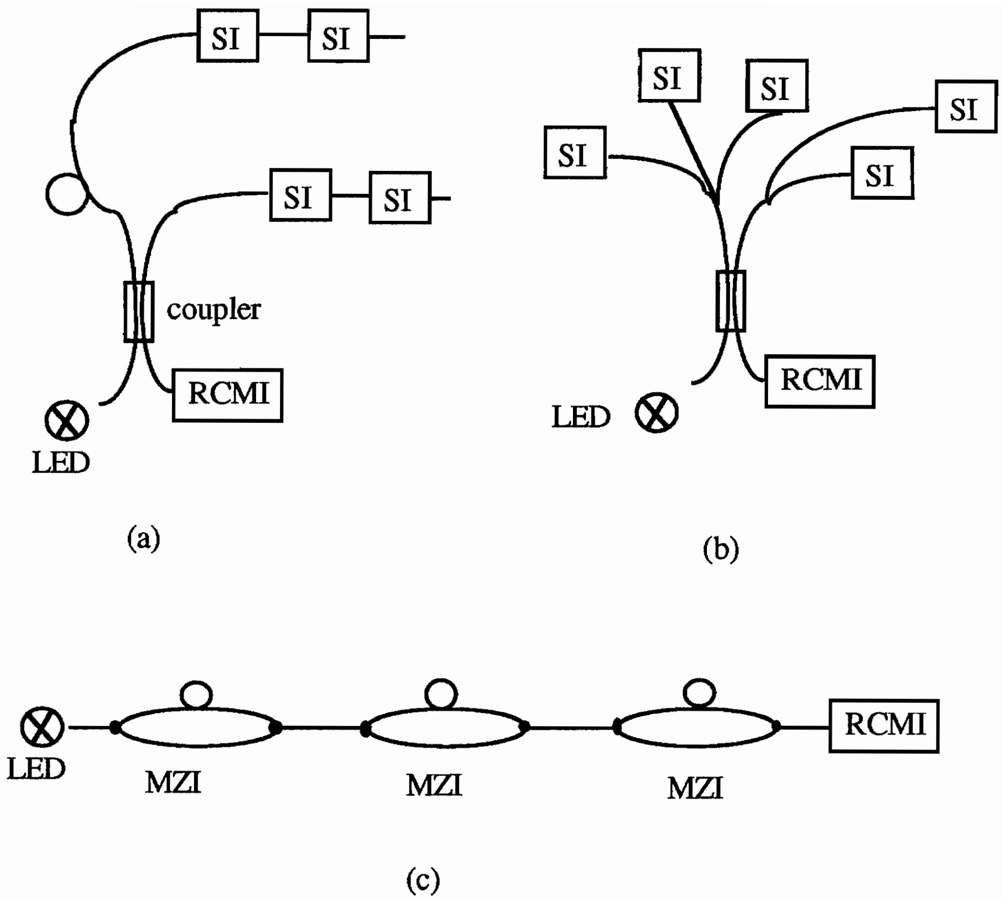


Figure 12. Structures for multiplexing absolute interferometer by relative coherence matching technique: cascade connection of reflection type two-beam interferometer (a); parallel connection (b); transmission type (c). Here RCMI-relative coherence matching decoding interferometer; SI-sensing interferometer; MZI-Mach-Zender Interferometer.

Initially it seems that modulation by different sensors has cross-correlation in structure (c), and the signal sets are not orthogonal. By theoretical analysis, it is found that the signals can be uncorrelated and independent, and the multiplexing system is naturally a code division spread spectrum system and the second decode interferometer is the correlation receiver in communication terms. Unlike the first two multiplexing system where only a small fraction of total received light is related to each sensor, all light power contains the information of each sensor in the third structure and so the visibility of the output fringes will be the same as that of the unmultiplexed single sensor system. This is the greatest advantage of this multiplexing structure.

VI. Conclusion

New sapphire fiber based sensor structures for high temperature strain measurement are proposed and studied in this report. The self-mixing interferometry has been studied and tested. The advantage of this technique is the source coherence insensitivity and direction distinguishment capability. Fringes of the self-mixing interferometer built with standard multimode fiber and sapphire fiber were observed. The application of this technique to static strain measurement seems difficult to stabilize, whereas its implementation to acoustic sensing with single-mode fiber coil as the sensing component will be very interesting. The approach by Moiré interferometry and equal-path coherence matching interferometer are two promising methods for high temperature displacement measurement. The advantages of the Moiré interferometer are source coherence independence and large measurement range. The advantage of coherence matching absolute interferometer is its simplicity in sensor structure. The structures of coherence matching methods and multiplexing techniques are generalized. From this research, we can conclude that the sapphire fiber based high temperature extensometer may be realized by different methods.

References

[1]. W. M. Wang, W. J. O. Boyle, K. T. V. Grattan, and A. W. Palmer, Appl. Opt., Vol.32, No.9, pp1551-1558, 1993

[2]. A. Olsson and C. L. Tang, IEEE J. Quantum Elctron., Vol.QE-17, No.8, pp1320-1323, 1981

[3]. Daan Lenstra, Bastiaan H. Verbeek, and Arie J. Den Boef, IEEE J. Quantum Electron., Vol. QE-21, No.6, pp674-679, 1985

[4]. Roy Lang, and Kohroh Kobayashi, IEEE J. Quantum Electron., Vol. QE-16, No.3, pp347-355, 1980

[5]. Peter J. de Groot, Gregg M. Gallatin, and Steven H. Macomber, Appl. Opt., Vol.27, N0.21, pp4475-4480, 1988

[6]. G. P. Agrawal, N. A. Olsson, and N. K.Dutta, Appl. Phys. Lett., Vol.45, pp597-599, 1984

[7]. M. C. Hutley, "Diffraction Gratings", Academic Press, 1990

[8]. Jean Ebbeni, SPIE Vol.1504, pp268-272, 1991

[9].Valeria Gusmeroli, IEEE J. Lightwave Technology, Vol.11, No.10, pp1681-1686, 1993