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Techniques of Advanced FBG sensors: fabrication, demodulation, encapsulation and their application in the structural health monitoring of bridges

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Abstract : *FBG(Fiber Bragg Grating) sensors have been more and more accepted by engineers in structural health monitoring(SHM). This paper has given a brief introduction on the practical techniques of fabrication and demodulation on FBG sensors. Aiming at the practical applications in infrastructures, the techniques of FBG encapsulation techniques are developed. And their applications in the structural health monitoring of bridges are conducted. Finally, some problems of FBG sensors when used in practical infrastructures are put forward and the solutions are also suggested.*

Keywords: *FBG sensors, FBG fabrication, demodulation, encapsulation, structural health monitoring, bridge*

INTRODUCTION

Infrastructures, such as long-span bridges, high-rise buildings, large dams, nuclear power stations, offshore-platforms and so on, will inevitably generate damage accumulation and resistance degradation subjected to coupling actions of environmental corrosion, material aging, long-term loading, fatigue and natural disaster hazards during long time service, even collapse (Ou, 1996). There-fore, in order to assure structural safety, integrity, suitability and durability, a lot of infrastructures in service are in great need of intelligent health monitoring systems to evaluate their safety and rehabilitate, further control their damages. Due to the frequent disastrous lessons, more and more infrastructures have been added long-term heath monitoring system during construction (Housner, 1997).

However, infrastructures are large, long span and se rvice for a very long time, so the durability and stability of the health monitoring systems are the 2 core questions. Optical fiber sensor, especially optical FBG (fiber Bragg grating) shows distinguishing advantages: immunity to el ectromagnetic interference and power fluctuation along the optical path, high precision, durability, quasi-distribut ion and absolute measurement, compact size, reduced ca ble requirement and so on. FBG has more and more beco me the most prominent sensors for structural monitoring.

The first report of photosensitivity in optical fiber was attribute to Hill (Hill, 1978). However, the first prac tical grating technique was regarded to be UV grating fabrication(Meltz, 1989). In 1989, Morey disclosed the potential sensing abilities of FBG (Morey,1989). Recently, the Rapid progress has been made in both FBG se nsor system developments and applications in recent year s (Rao,1999; Mufti; 2003, Ou). FBG sensors have been more and more accepted by engineers in structural health monitoring(SHM).

FBG sensors' key research areas include FBG fabrication, FBG demodulation, FBG encapsulation and practical applications. And in order to push forward the applications of FBG sensors, the core problems focus on reliable FBG encapsulated sensors and the multi-channels, high frequency, and high precision demodulation devices (Zhou, 2003). In this paper, a brief introduction on the practical techniques of fabrication and demodulation on FBG sensors is given. Aiming at the practical applications in infrastructures, the techniques of FBG encapsulation techniques are developed. And their applications in the structural health monitoring of bridges are conducted. Finally, some problems of FBG sensors when used in practical infrastructures are put forward and the solutions are also suggested.

FBG FABRICATION

Currently, there are two major methods for fabricating Fiber Bragg Grating: holographic method (Meltz,1989) and phase mask method (Hill,1993). In 1989, G. Meltz used holographic interference setup to write FBG, and the grating was written from the side of fiber. Due to the great potential of FBG's applications,

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more research was conducted on the fabrication methods of FBG. Away from G. Meltz's two UV beams interference, other methods were given to improve the stability during the fabrication process, such as using a prism to split the UV beam and then interference. The advantage of the Holographic method: it is easy to adjust the angle between two beams to create different periods, therefore, to fabricate FBG with difference wavelengths. The disadvantage of this method is that a more stable setup is needed and a good coherence light source is also requested in the meantime.

In 1993, Hill et al gave another easy method to fabricate FBG by phase mask. Phase mask is a piece of diffractive grating with depth modulation on fused silica. The phase mask were designed to suppress 0^{th} order diffraction efficiency(<5%) and increase +/-1^{st} order efficiency (>35%). When a UV beam incident on phase mask, the +/- 1^{st} order beam will credit a interference pattern, this pattern will write the FBG on the fiber. The period on FBG is the half of phase mask. The advantage of Phase Mask method: it is simple with great repeatability as well as the disadvantage of Phase Mask: each mask can only generate one wavelength of FBG.

FBG DEMODULATION

Commercial interrogators for multiple Bragg grating sensors fall into two main categories: time division multiplexing (TDM) and wavelength division multiplexing (WDM). TMD discriminates between many sensors on a single optical fiber by gauging the time required for a pulse of light to return to the detection system. In TDM, all sensors are nominally written at the same wavelength. Each is of low reflectivity thus allowing some light to pass down the fiber to illuminate sensors downstream. As environmental conditions change, the time signature of each sensor changes. TDM instruments translate these time shifts into changes in the parameter of interest, e.g., strain. TDM systems must be designed to balance the sensor-sampling rate with the distance of the sensor from the light source and detection system. Distance between sensors must typically be greater than a few meters to allow the instrument to clearly distinguish between adjacent sensors

The most popular approach is WDM. WDM systems discriminate individual sensors by wavelength. That is, several sensors may have nominal center wavelengths separated by a few nanometers. Each sensor is tracked simultaneously as its center wavelength changes due to environmental changes like strain, temperature or pressure.

Most WDM systems are designed using one of two basic configurations: broadband source and swept detector (BSSD) and laser source and broadband detector (LSBD). BSSD systems generally use an ASE, LED or SLED source coupled with a tunable filter and broadband detector. The filter is simultaneously calibrated so that the wavelength-insensitive detector "knows" which wavelength it is receiving at any given time. The result is a robust, relatively inexpensive interrogator that can handle from about 5 to 30 sensors on a single fiber. The sensor limit is a function of the relatively low power of the light source and sources of loss present in a particular application (e.g., connectors, bend losses). Even with these sensor-number limitations, hundreds of these systems (like the Micron Optics Fiber Bragg Grating Interrogation System, FBG-IS sm220) have been deployed around the world in civil, oil and aerospace applications – as well as in dozens of universities for education and research.

The second approach, laser source and broadband detector (LSBD), overcomes the sensor limitation with much more optical power. Typically, laser-based interrogators can illuminate more than 100 sensors per channel. The limiting factor determining the maximum number of sensors is usually wavelength range. This is the "window" in which sensors can be placed. Each sensor needs room to move up and down in wavelength as its environment changes. So each sensor uses up a bit of the available window. Typically, sensors are design with a wavelength spacing of 2 to 3nm and sensing instruments provide a total wavelength range of 20 to 50nm.

Another consideration for both BSSD and LSBD systems is what type of information is gathered about each sensor. The simpler approach is to use zero-crossing circuitry to find the peak of a reflected sensor signal. Movement of the peak's central wavelength corresponds to a change in strain or temperature at the sensor. This is important information, but it says little about the shape of the reflected signal. The basic tradeoff is one of cost and speed. Full spectrum instruments tend to be slower and more expensive. But these concessions may be worth it to get a more complete picture of what's happening at each sensor. This is especially true when new high-volume applications are being developed and where sensor selection must be optimized.

WDM systems often need to operate in harsh conditions. For example, an open control room on an oil platform or an un-air-conditioned enclosure at the base of a bridge piling. Temperature and humidity, shock and vibration, can vary wildly. So to keep measurements accurate and repeatable, simultaneous calibration is employed. This means that with each sweep of the laser, or each scan of the detector, a wavelength calibration is performed in parallel with the interrogation of the sensor arrays. A fiber ring laser developed by Micron sweep a 50nm wavelength range in 2 milliseconds, interrogating all sensors in that range. These fast, high-powered, swept lasers are at the heart of today's leading optical sensor interrogation systems – and at the heart of each laser is a Fiber Fabry-Perot Tunable Filter (FFP-TF).

Micron Optics' tunable filters provide superior performance across a broad spectrum of parameters. FFP-TF technology has taken the Fabry-Perot principles and developed proprietary innovations to build its fiber Fabry-Perot tunable filter. The FFP-TF consists of an elegant, simple etalon design with just fiber and mirrors. The Fabry-Perot Interferometer is widely accepted as having the highest optical resolution existing today. Micron Optics' technology is the first to fully capitalize on this approach. FFP-TF technology incorporates critical design innovations that allow fiber Fabry-Perot filters to cleanly follow the Airy function from the top of its low-loss peak down to the bottom of its stop band - all controlled smoothly and precisely across a broad temperature range.

Micron Optics' FFP-TF technology is the base for the highest performance optical performance monitor available today, monitoring up to 400 channels in the C band alone. The high resolution, deep dynamic range and continuous smooth tuning combine together to allow dense channel analysis. For example, the optical performance monitor Finesse 2000 filters have a contrast factor of 62 dB.

The Micron Optics si425 Swept Laser Interrogator provides rapid, accurate measurements on hundreds of optical sensors in real time. Powered by a high output power 250Hz swept laser, the si425 can interrogate up to 512 optical sensors simultaneously, with 1 pm resolution and 10 pm repeatability over time and temperature. The si425 can be controlled and monitored remotely through a complete set of TCP-IP controls and commands. Four on-screen operational modes can be used to monitor optical sensors using the front panel controls and display. With a measurement dynamic range of 25dB, the si425 is expandable from 1 to 4 channels.

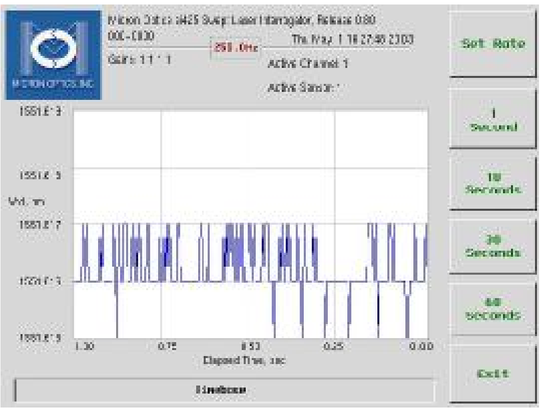

Figure 1. Sensor Wavelength View

Figure 1 shows measurements of a single FBG in the Sensor Wavelength View of the si425. Note that the measurements over the time interval of a minute show repeatability of 1 pm. In the Sensor Wavelength View, the user can select both the data acquisition rate of the si425 as well as the time base over which data is displayed to the screen.

Figure 2 shows the Table View of the si425. Here, the wavelengths of all measured sensors are displayed simultaneously. The first column shows the sensor number for each channel, and can be scrolled using the up and down keys of the front panel keypad. The next four columns show the present sensors by channel, with a total number of sensors in parentheses in the header.

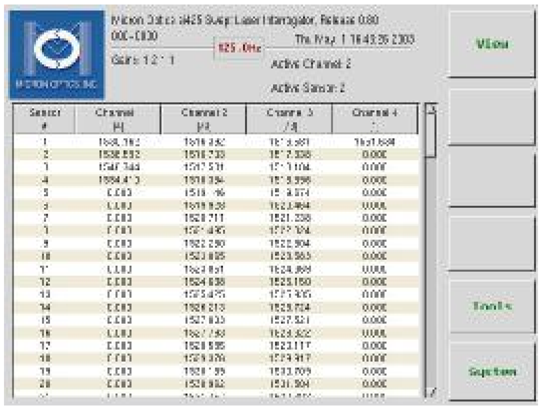

Figure 2. si425 Table View

FBG ENCAPSULATION

Due to fragility of bare FBG, it is hard to directly apply bare FBGs in infrastructures without any protection, so it is necessary to develop encapsulation techniques for bare FBG strain sensors. Two kinds of encapsulation techniques are developed for bare FBG strain sensors and one for FBG temperature sensors, depicted as Figure 3~5.

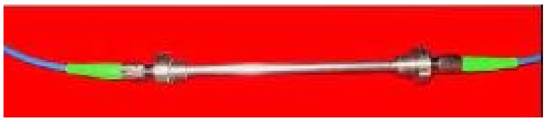

Figure 3. Sketch for mental capillary encapsulation for FBG strain sensor

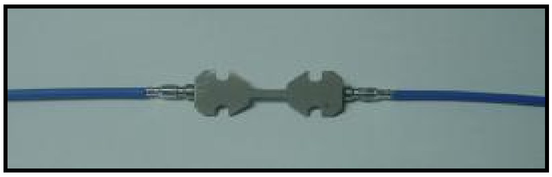

Figure 4. Sketch for mental slice encapsulation for FBG strain sensor

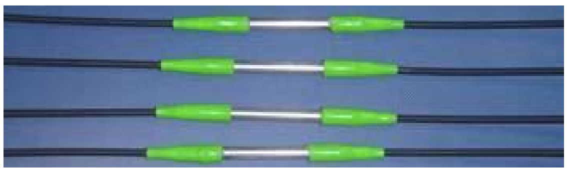

Figure 5. Sketch for steel capillary encapsulation for FBG temperature sensor

Capillary encapsulation FBG strain sensor can be conveniently used in concrete structures. The mental holder ring is used to keep the FBGs deformation consistent with the concrete structures, and the stretched optical fiber is ready for temperature compensation connector.

Slice base encapsulation FBG strain sensor is FBG encapsulated in slice base by glue, which can be conveniently used on the surface of mental and concrete structures.

Due to that the encapsulation layers will change the sensitivity of the original FBGs, the encapsulated FBG sensors must be calibrated before they are applied in practical structures.

FRP is now more and more accepted as a kind of important construction material. To make full use of FRP's strength properties and FBG's sensing properties, Prof. OU (2002) has developed the fabrication technique of FRP-OFBGs bars and gotten the products, shown as Figures 4 and 5. FRP bar embedded with OFBGs can not affect its mechanical properties because OFBG diameter is by far smaller compared with FRP bars diameter.

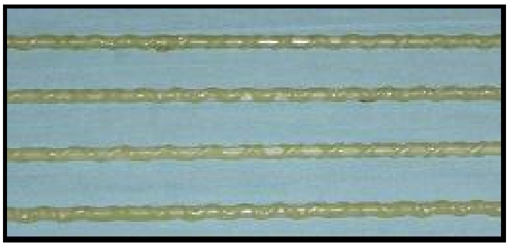

Figure 6. OFBG-GFRP bars

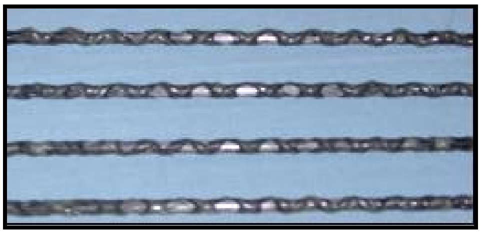

Figure 7. OFBG-GFRP bars

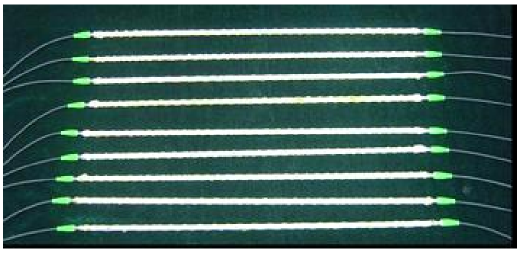

Figure 8. FRP-OFBG sensors

PRACTICAL APPLICATION OF FBG SENSORS

Due to that the bridges is the key part of transportation, lots of large-span bridges are under construction in developing countries as well as China. In order to avoid disastrous tragedy to happen and with the development of structural health monitoring, the bridge owners realize the importance of adding structural health monitoring system to the bridges under construction. OU (2003) have developed several structural health monitoring systems based on FBG sensors to be applied in the several large-span bridges, shown as figure 9~15, to monitor the performance of the bridges under construction and in service.

Figure 9. Fulan river bridge in Heilongjiang

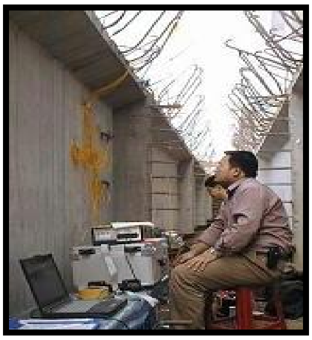

Figure 10. Niutoushan Bridge in Heilongjiang

Figure 11. Songhuajiang River Bridge in Heilongjiang Province

Figure 12. Dongying Yellow River Bridge in Shandong Province

Figure 13. Binzhou Yellow River Bridge in Shandong Province

Figure 14. Maocaojie Bridge in Hunan Province

Figure 15. Luoguo Bridge
in Panzhihua of Sichuan Province

PROBLEMS OF FBG SENSORS IN STRUCTURAL HEALTH MONITORING

Structural Health Monitoring (SHM) has currently become the highlight of researches and applications in civil engineering. And its core is damage detection and identification. As is known, it is a challenge to perform accurate damage analysis, especially the damage location, via global information. Local damage monitoring seems paramount. Generally speaking, local damage behaves as crack, fatigue, slip, debonding, stiffness loss, effective force-resistance area loss, and so on. Strain is an alternative parameter which can be used to describe deformation, study the crack opening and even detect the slip and bonding, so high-quality strain sensor has always been pursued by the structural researchers.

As a new kind of sensor for structural health monitoring system, application of strain and temperature sensors based on FBG is still a challenge for the construction technicians. Following problems are needed to be considered carefully before the projects are carried out: 1) Temperature compensation for FBG strain sensors; 2) How to build the data collection system when we have to face the embarrassment that we have no choice but to cut down the number of FBG sensors along one cable, even sometimes one sensor on one cable, which makes us not able to make full use of the advantages of FBG. Perhaps we have to keep the balance of number of FBG sensors and the limited FBG interrogator system; 3) How to avoid the damage of the FBG sensors and cables during constructions; 4) How to get the true strain state of the practical object when we use the packaged FBG sensors; 5) How to make the FBG monitoring system become the important part of the Structural Health Monitoring System. With the development of FBG interrogators, we believe that FBG sensors will be accepted more and more in civil Engineering.

REMARKS

FBG sensors' key research areas include FBG fabrication, FBG demodulation, FBG encapsulation and practical applications. The core problems focus on reliable FBG encapsulated sensors and the multi-channels, high frequency, and high precision demodulation devices.

FBG sensors show distinguishing advantages : immunity to electromagnetic interference and power fluctuation along the optical path, high precision, durability, quasi-distribution and absolute measurement, compact size, reduced cable requirement and so on. With the development of FBG fabrication, FBG demodulation, FBG encapsulation and practical applications, FBG sensors have been accepted by engineering for Structural Health Monitoring.

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