The Principle and Application of Optical Fiber Sensing Technology: Three Kinds of Distributed Sensing and Fiber Bragg Grating

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Abstract. In modern society, optical fiber plays a significant role in ordinary people’s life. The development of optical fiber communication is so fast while the optical fiber sensing has gained huge achievements although fewer people know about that. In fact, optical fiber sensing technology has become increasingly popular due to its low price and the fact that this method overcomes the problems encountered with traditional sensor, such as in the high-intensity magnetic field. Meanwhile distributed sensing enables the all-day and all-spots monitoring. Based on different principles, distributed optical fiber sensing could be classified into three kinds, which are optical time-domain reflectometry based on Rayleigh scattering, Raman-optical time-domain reflectometry based on Raman Scattering and Brillouin-optical time-domain reflectometry based on Brillouin scattering. These three methods have their own benefits and applications because of their special structures. Fiber Bragg grating can be taken as one kind of optical fiber sensor as well as the grating locates inside the optical fiber. Relying on the diffraction effect, FBG can measure temperature, strain and even pressure sensitivity. The demodulation methods of FBG are various as well. There are about 8 different methods that can meet different requirements, each with its own benefits and defects.

1. Introduction:
Since Professor Charles Kuen Kao came up with his famous paper ‘dielectric-fiber surface waveguides for optical frequencies’, the field of optical fiber began to develop exceedingly. Because of the low prices, small volume and high sensitivity, optical fiber soon became popular. Currently, the most popular optical fiber research mainly focuses on optical fiber communication and optical fiber sensing technology. Optical fiber communication has experienced extraordinary development, especially around the year 2000. Compared with optical fiber sensing, although lots of development exists in this field, this technology is less known than optical fiber communication by public. In this paper, the main purpose is to introduce the definition of optical fiber sensing, different types of optical fiber sensing and the application of this technology.

There are several types of optical fiber sensing. Simply disturbed fiber sensing can be divided into reverse Rayleigh scattering, Raman scattering and Brillouin scattering \cite{2,3}, according to different sensing methods. Moreover, discrete optical fiber sensing could be classified into eight kinds, which is fiber Bragg grating sensing, \cite{6} fiber F-P sensing, FOG, fiber active intracavity gas detection, fiber surface plasma, micro bubble whispering gallery mode sensor, fiber magnetic fluid and OCT. In addition, intellectualized optical fiber sensing is a great way to set up the sensing system. \cite{7}

With the standard of detection being higher, the demand of optical fiber sensing is increasing. People
begin to find a more sensitive way to detect or supervise the condition of some special equipments. Meanwhile, the advantages of optical fiber sensor are shown. Due to the silica material, the thin volume and the high sensitivity of optical fiber, it is proven that optical fiber is a great sensor. The application of optical fiber sensing is wild as well, and has gradually replaced the traditional measurement. There are several main fields which use the optical fiber sensing, like army application, monitoring engine, construction detection, electronic industry, temperature sensor and pressure sensor. Optical fiber sensor is not only highly sensitive, but also comprehensive.

2. Classification of optical fiber sensing technology

In this section we review three kinds of distributed sensors based on optical fiber. Besides the different principle behind these three technologies, they aim to different targets and require different systems to be designed.

The first one, depending on the Rayleigh scattering, is called optical time-domain reflectometry, OTDR. The main principle of OTDR is as follows. A pulse that comes from the Pulsed Laser, meets some odd spot existing in the fiber under test. It arises the Rayleigh scattering, which sends to many directions. At this time, the detector located at the start of the fiber, detects this scattering wave and sends the signal to electronics. Finally this signal is analyzed by the computer. Basing on the former principle, OTDR can help to calculate the distance. The formula is as follows.

\[ D = \frac{(c \times t)}{2n} \]

where D is the distance, c is the speed of light in vacuum, t is the time from sending signal to detecting signal, n is refractive index of the testing optical fiber.

Hence, any odd spot or certain required spot can be detected by this method. This kind of sensor can detect the losses in the transmission of optical fiber lines, losses in different parts of the system and connecting points. In addition, OTDR can be used to detect the distance between two connecting points, the distance between odd spot and detecting system and the distance between connecting point and odd spot. Moreover, OTED could be used to detect the return loss of certain point or certain routes.

Additionally, there is another kind of OTDR named Phase-OTDR, which is applied in the areas of security perimeter. When there is an intruder stepping on the buried fiber, it causes the change in the backscattered power that one can use this technology to find out the intruder.

The second optical sensor is based on Raman Scattering. The principle of Raman Scattering is as follows. When the laser pulse from the laser reaches the optical fiber, it generates two scattered light. One light’s wavelength is longer than the Raleigh named Stokes light. Meanwhile, the other light’s wavelength is shorter named Anti-Stokes light. The relationship between Anti-Stokes light and temperature can be illustrated by the following formula.

\[ R(T) = \frac{I_{AS}}{I_S} = \left( \frac{\lambda_{AS}}{\lambda_S} \right)^4 e^{-\frac{hc}{\lambda \nu_0 kT}} \]

where H is Planck constant; c is speed of light in vacuum; \( \nu_0 \) is frequency of incident light; k is boltzmann constant; T is absolute temperature.

Anti-Stokes light is sensitive to temperature; hence this scattered light can be used as temperature sensor. The detection is located at the start of the optical fiber, which can detect the backward Anti-Stokes light. Then, one can analyze this signal through computer and achieve the temperature of the optical fiber. This is so-called Raman-OTDR.

The application of Raman-OTDR is enormous. As a distributed temperature sensor, it can be used in industry of fossil fuels to supervise the leak of oil and the temperature under oil well. Furthermore, in the field of electric power industry, Raman-OTDR can detect the temperature of electric line, which is hard for the traditional sensor to make all-weather detection. Raman OTDR can be used to search for temperature in tunnels or dangerous areas. All these applications of Raman-OTDR will bring a better supervision than traditional equipment.

The third optical sensor is BOTDR, which is based on Brillouin scattering. The shaking present in
the medium will cause the density of medium to rise and fall periodically along with the time and nearby space, with the result that a sound field will be formed. Therefore, the incident light will react with the acoustic wave and generate scattering light. It’s also known as Brillouin scattering. [5]

BOTDR can be used to measure the change of temperature and strain by analyzing the frequency change of backward Brillouin scattering light.

![Fig. 1 Schematic of the BOTDR system](image1)

The system in figure 1 is BOTDR, although it requires only one side on the optical fiber, the signal and noise-signal ratio of this method is low.

![Fig. 2 Schematic of the BOTDA system](image2)

The method showed in figure 2 is called BOTDA, which requires two ends of optical fiber to increase the signal and has an acceptable noise-signal ratio. The process of BOTDA is as follows. Adjust the frequency of the pump light and probe light to near Brillouin frequency, which is about 10.8GHz. Then, scan the difference of these two lights in the field of Brillouin. Aiming at every difference, record this amplifying signal and use several signals to remove noise. After that, the data we got is a two-dimensional array, one dimension refers to distance and the other one refers to difference in frequency. Finally, data processing can be used to achieve Brillouin spectrum of each spot on the optical fiber.

In summary, OTDR is based on Rayleigh scattering and can be used to detect odd spot and broken spot. Raman-OTDR can be used to supervise the temperature of the optical fiber. BOTDA system is based on Brillouin scattering and can detect strain feature.

The OTDR, Raman-OTDR and BOTDA have many applications all over the world. In the Brandebourg of German, the temperature sensor which is made of optical fiber is buried under the oil and gas pipeline from Ludesdorf to Heckelberg about 55 kilometers. The optical fiber sensor provides good monitoring of the oil leak. On the border between France and Switzerland, Professor Kronenberg installed optical fiber sensor on the Emosson Dam to measure the crack on the dam. The results from optical fiber are similar to those from traditional Rod extensometer meanwhile results from optical fiber are more accurate and sensitive. In China, optical fiber sensor is applied during the construction of Haicang Bridge, which is the second biggest three-span continuous fully-floating steel box girder suspension bridge. Optical fiber is buried along the whole bridge, not only through the fiber to detect cracks on the bridge, but also to help monitor vehicle flowrate.

In the supervision of offshore platform, distributed sensor shows significant benefits. Point sensor has limited measurement points and blind zone. Whereas, distributed sensor can measure all aspects. Some BOTDR has achieved ultra-long distance and ultra-high spatial resolution distributed Brillouin fiber sensing. Time division multiplexing can overcome the modulation instability and pump-out phenomenon to achieve ultra-long-distance sensing. A new technology named DPP-BOTDA can even achieve the centimeter-scale hot spot detection. This technology could also be used in the on-line monitoring of large generator stator. Normally, the high magnetic field intensity limits the performance of normal detector, while optical fiber can avoid this limitation due to the fact that the material of fiber is silica, which suffers no impact from magnetic field.
3. Fiber Bragg Grating Sensors

3.1 Sensing principle of FBG
The basic principle of this technology is that there are several special regions on optical fiber. These areas are made into grating regions with periodic distribution of refractive index. When the incident light encounters this region, it causes Bragg scattering. Some parts of incident are reflected and this part of light is called Bragg reflected light. The frequency of Bragg reflected light is connected with period of grating and refractive index of fiber core, which is sensitive to the change of temperature and strain.

\[ \Delta \lambda_B = 2 \Delta n_{eff} \Lambda + 2 n_{eff} \Delta \Lambda \]  

By analyzing this light, one can get the temperature and strain condition of the optical fiber. The advantage of this method is that several different periods of grating can be set up on the same fiber, so that one fiber can gather many FBGs.

The certainty of FBG measurement is high with strain measurements up to 1με and temperature measurement up to 0.1℃. Moreover, response time is short. Single FBG’s response time will be less than 0.01s. In addition, measuring range is great. Strain measurement can surpass 10000με.

FBG can detect temperature, strain and pressure sensitivity. First, FBG can be used to measure temperature. The influence from temperature is caused by thermal expansion effect and thermo-optic effect. The period of grating will be changed by thermal expansion effect. Thermo-optic effect will cause the change of refractive index. Therefore, the wavelength of Bragg reflected light can be influenced by the temperature.

Secondly, strain can be detected by FBG as well. The influence from strain is caused by the change of fiber’s period and elasto-optical effect. Strain brings effect on the change of pitch, thus we can define the effective elastic-optical coefficient based on the change of refractive index. As a result, according to Hooke law, the frequency shift can be expressed.

Furthermore, pressure sensitivity can be measured by FBG. The pressure brings effect on the fiber, which is caused by the change of fiber’s period and elasto-optical effect as well. Due to difference in the doping composition and doping content of different optical fiber, the pressure sensitivity of different FBG varies enormously.

3.2 Demodulation method
Eight demodulation methods are shown in the following form, which shows both the merits and drawbacks of different methods.[9]

| Demodulation method                     | Advantage                                      | Disadvantage                                      |
|----------------------------------------|-----------------------------------------------|---------------------------------------------------|
| Matched fiber grating filter           | The reflected mode is simple and low price.   | The reflected mode has low noise-signal ratio.     |
|                                        | The transmission mode has high availability of signal light and resolution ratio is relatively high. | The transmission mode’s traction control is complex and the nonlinear mistake is large. |
| Tunable fiber F-P filter                | Tunable range of FFP is wide and it could realize multifilter and demodulation in static strain and dynamic strain. | Expensive. High loss during filtering.             |
| Use a high refraction Sagnac loop mirror as edge filter | It could measure both static strain and dynamic strain. | Low resolution ratio.                             |
| Tunable narrow-band light               | High resolution ratio and noise-signal ratio  | Poor stability and tunable band would limit the number of FBG and using areas. |

[9]
Loop cavity optical fiber  |  Suitable for wavelength division multiplexing and demodulation strain of array  |  Low resolution ratio

Nonequilibrium M-Z interference  |  High resolution ratio in measuring dynamic parameter  |  Static parameter measurement should cooperate with a reference grating in stable environment.

Nonequilibrium scanning Michelson interference  |  Are capable to query and demodulate signal in fiber grating system  |  Analyze regular of phase variation with time during dynamic measurement.

3.3 Application of FBG

Depending on the benefits that FBG has, such as small volume, light weight, low insertion loss, stability and great compatibility with fiber, the application of FBG is various. In the field of civil engineering, FBG can be used to detect the structure of bridge, dam and steel structure. In the field of space industry, FBG can provide the reference of pressure, temperature, shaking and fuel quality on airplane. In the field of shipping, it can evaluate the damage on body and make in-time warning. In the field of electricity, it can overcome the high-intensity magnetic field and realize temperature measurement of the generating equipment. In the field of petrochemical industry, the safety quality of optical fiber can be suitable for supervising on the temperature of oil deposit and fuel level. In the field of nuclear, it can supervise the scrap station, the construction condition of nuclear reactor. In the research of intelligence material, by using the FBG, it could form a system similar to nerve in human body and served as monitor.

4. Conclusion

In summary, the application of optical fiber is increasing due to the fact that this technology has lots of benefits. The traditional sensor’s disadvantages are avoided by optical fiber sensor, such as the application of detection in high-intensity magnetic field. Moreover, the distributed sensing system based on fiber sensor can reach all-time measurement and supervise everywhere. In addition, the price of fiber is low and the total cost of fiber sensing system is relatively low compared with other methods. This technology has attracted the attention of lots of scientists and the future development in this field will be increasingly fast.

References

[1] Wang B Z, Jiang C, Zhou D W, Dong Y K, Advances of key technologies in long-range distributed Brillouin optical fiber sensing[J], Opto-Electronic Engineering, 2018, 45(9): 170484
[2] Fan B, Xu P B, Dong Y K, Strain measurement of gold-coated fiber by using Brillouin optical time domain analysis[J], ACTA OPTICA SINICA, 2019,39(02):0219002
[3] Liu Y F, Lv Z W, Dong Y K, Li Q, Research on stimulated Brillouin scattering suppression based on multi-frequency phase modulation[J], Chinese Optical Letters, Vol.7, No.1, 2009
[4] Hou J F, Pei L, Li Z X, Liu C, Development and Application of Optical Fiber Sensing Technology[J], ELECTRO-OPTIC TECHNOLOGY APPLICATION, Vol.27, No.1, 2012
[5] Horiguchi T, Tateda M. BOTDA-Nondestructive Measurement of Single-Mode Optical Fiber Attenuation Characteristics using Brillouin Interaction: Theory[J], Journal of Lightwave Technology, 1989, 7(8): 1170-1176.
[6] Comanici M I , Kung P , Development of a long-gauge distributed vibration sensor[C]// Electrical Insulation Conference. IEEE, 2014.
[7] Liu T G, Yu Z, Jiang J F, Liu K, Zhang X Z, Ding Z Y, Wang S, Research Progress on key Technologies of discrete and distributed Optical Fiber Sensing[J], Acta Phys. Sin. Vol.66, No.7(2017) 070705
[8] Yang K, Hao Y Q, Ye Q, Cai H W, Qu R H, Ice-coating monitoring research on aerial cables with BOTDR sensing system[J], LASER JOURNAL, Vol. 39, No. 8, 2018

[9] Fu X N, Niu J J, Chen J. GUANGDIAN JIANCE JISHU YU XITONG SHEJI[M]. Publishing House of Electronics Industry, 2010.