Abstract of Dissertation

Title of Dissertation:

High performance reflectometry and dynamic grating-based distributed fiber-optic sensor using synthesis of optical coherence function

(光波コヒーレンス関数の合成法による高性能リフレクトメトリとダイナミックグレーティングを用いた分布型光ファイバセンサ)

Name of Author:　樊　昕昱　(Xinyu FAN)

Distributed fiber-optic sensors, which are possible to determine the value of a wanted measurand continuously as a function of position along the length of optical fiber, have attracted great interest since their potential applications in many fields such as smart structures and smart materials.　The capability of these fiber sensors to measure many parameters such as strain, temperature, pressure, etc. makes them powerful tools for civil engineering.　Meanwhile, the capability of measuring backscattered lightbeams makes them powerful tools for diagnosing optical devices and systems.　In this thesis, we researched distributed fiber-optic sensors for these two kinds of applications by using an original technique developed in our laboratory with the name of synthesis of optical coherence function (SOCF).

In a Michelson interferometer, lightbeam from the light source is separated, reflected, and then combined together.　Lightbeams from the two arms interfere each other and the visibility of the interference pattern is called the coherence function.　Actually, it is the Fourier transform of the light source's spectrum.　It is possible to manipulate the spectrum by modulating the light source to obtain the coherence function which we want.　Using a stepwise modulation or sinusoidal modulation of optical frequency of light source, delta function-like coherence peak is synthesized.　The technique of SOCF is to synthesize and scan the coherence

peak along the position by changing the modulation parameters. Based upon this principle, various distributed fiber-optic sensors have been developed.

Several schemes of distributed and multiplexed sensing techniques for measuring strain and temperature have been proposed and demonstrated till now. One is based on stimulated Brillouin scattering processes, such as Brillouin optical time-domain analysis (BOTDA) and Brillouin optical coherence-domain analysis (BOCDA). As another scheme, the fiber Bragg grating (FBG)-based strain sensors, is also very attractive and many schemes for multiplexing the FBGs have been investigated. The FBG-based sensors, however, are only quasi-distributed because they can only supply sensing data at discrete points. In this thesis, a novel mechanism based on another kind of grating, a dynamic grating in a polarization-maintaining erbium-doped fiber (PM-EDF), is proposed. In this scheme, the dynamic grating is localized and scanned along the fiber by the technique of SOCF to realize fully distributed sensing.

When two counter-propagating coherent light beams (referred to as writing beams hereafter) are launched into a pumped erbium-doped fiber (EDF), they interfere to each other and create a periodical gain structure per the phenomenon of gain saturation, producing a dynamic grating in the EDF. A third beam launched into the fiber (referred to as reading beam hereafter) is reflected by the dynamic grating when its optical frequency (wavelength) is the same as the writing beams'. If the dynamic grating is written in PM-EDF along one primary polarization axis and read along the other primary polarization axis, the detected Bragg reflection frequency is different from the frequency of the writing beams due to the birefringence. When a strain is applied to the fiber, the birefringence changes in proportion to the strain. As a result, the detected Bragg reflection frequency shifts in proportion to the strain. By using the technique of SOCF, the dynamic grating is formed in a localized region, and the position of the region can be controlled to scan along the fiber. If the dynamic grating is not formed at the part of the fiber where the strain is applied, the strain does not have any effect on the Bragg reflection frequency. In this way, we can determine the strain location by sweeping the localized dynamic grating along the PM-EDF.

We established a theoretical model of the dynamic grating and performed numerical simulations based on the model. Our results showed that considerably high reflectivity could be obtained if the dynamic grating is properly designed with suitable parameters. It is also predicted by simulation that the performance of strain-sensitivity and temperature-sensitivity comparable or even better than SBS-based technology can be expected with the proposed scheme.

Reflection from dynamic grating in pumped EDF is successfully detected and a 10% reflectivity is obtained. The bandwidth of the reflection spectrum is in inverse proportion to the fiber length. By modulating the optical frequency of the writing beams with sinusoidal wave, we successfully localized the

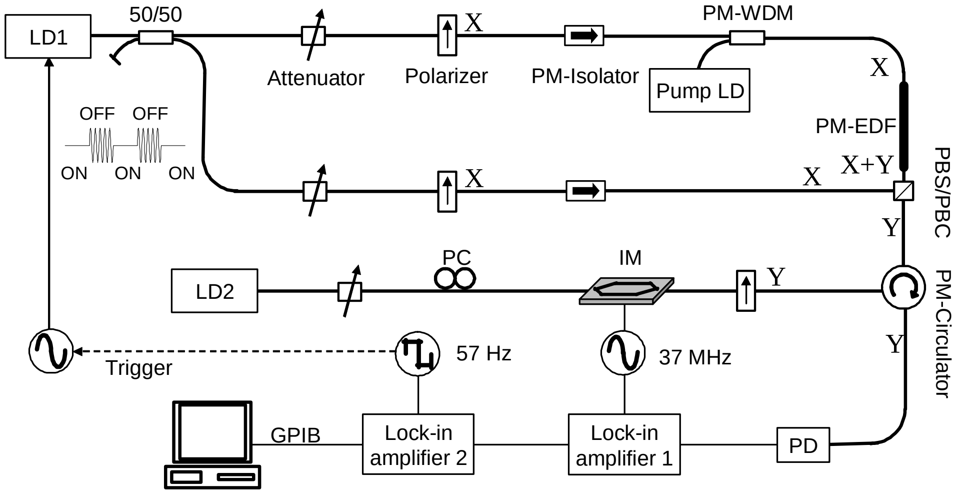


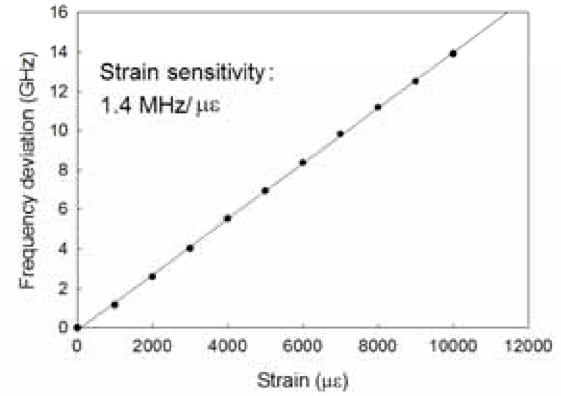
Fig. 1. Experimental setup to detect reflection from dynamic grating in PM-EDF.

dynamic grating in EDF in a region corresponding to the position of the coherence peak where the interference of the writing beams take place. By adjusting the modulation amplitude of the frequency modulation to control the width of the coherence peak, the reflection bandwidth of the dynamic grating is adjusted successfully.

In the experiment of dynamic grating in PM-EDF, noises make it very difficult to observe the reflection spectrum of the dynamic grating. In order to get rid of these strong noises, a dual-stage synchronous signal processing method is developed. We design a scheme to switch the dynamic grating ON and OFF. In the ON-state, the dynamic grating is formed, and in the OFF-state is not. Then the difference between the two states is purely related to the reflection at the dynamic grating; all other reflections and beatings, which are common between the both states, are canceled out. Experimental setup is shown in Fig.1.

With this method, we observed the reflection from the dynamic grating in PM-EDF successfully. After we applied strain and changed temperature, our experimental results show a strain-sensitivity of 1.4 MHz/με (shown in Fig. 2) and temperature-sensitivity of 60 MHz/^{o}C (shown in Fig. 3), which are 28 and 60 times higher than those of SBS technique, respectively. Also, when the PM-EDF is longer than 8 cm for strain sensing, or longer than 4 cm for temperature sensing, respectively, the dynamic grating method has a better strain- resolution and temperature- resolution than SBS method.

For the distributed sensing experiment, the improvement of signal to noise ratio (SNR) becomes very important since the dynamic grating is shortened during the application of SOCF. In experiments, noises come from mainly the environmental low frequency perturbation to the PM-EDF. Since those noises



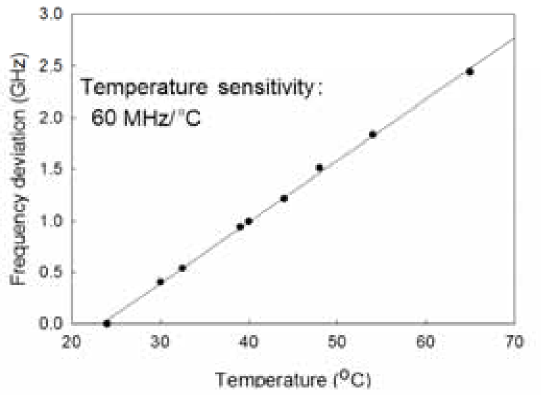


Fig. 2. Strain dependence of Bragg frequency shift of the reflection peak.

Fig. 3. Temperature dependence of Bragg frequency shift of the reflection peak.

decrease sharply at higher frequency, to increase the ON-OFF frequency is an effective method to decrease noise and improve SNR. On the other hand, the switching ON and OFF of the dynamic grating should be slow to have enough time to set up the grating. Therefore, the increase of ON-OFF frequency decreases the signal. Obviously, with increasing the ON-OFF frequency, signal and noise decrease at the same time. Experimental results show that the ON-OFF frequency has an optimum value at 200~600 Hz for a best SNR.

In the distributed sensing experiment, we also switch the dynamic grating ON and OFF. The ON-state is realized by modulating the optical frequency of LD in sinusoidal wave around 17 MHz to localize the dynamic grating and sweep it along the fiber, while the OFF-state is realized by modulating in sinusoidal wave at 47 kHz to make the two writing beams not interfere inside the PM-EDF. Our experimental results show a strain-sensitivity of 1.4 MHz/με and a spatial resolution of 20 cm (shown in Fig. 4 and Fig. 5). It is expected that the spatial resolution can be improved by improving the SNR of the reflection from the dynamic grating.

Our researches focus not only on the distributed fiber-optic sensors for smart material and smart structures, but also on these for diagnosing optical devices and systems.

Troubleshooting the fiber optic assembly modules is a long-time headache in the fiber optic manufacturing industry. In such an application, a 0.1-dB-order reflectance resolution is necessary to distinguish an out-of-spec fusion splice. Nowadays, there are several available optical reflectometry techniques such as optical time domain reflectometry (OTDR), optical frequency domain reflectometry (OFDR), and so on. OTDR technique has a wide spatial resolution typically about 10 m, which cannot be used to diagnose an optical fiber assembly module. OFDR technique seems promising in terms of spatial resolution, but their reflectance resolution is not satisfactory yet. Wavelength domain averaging method is

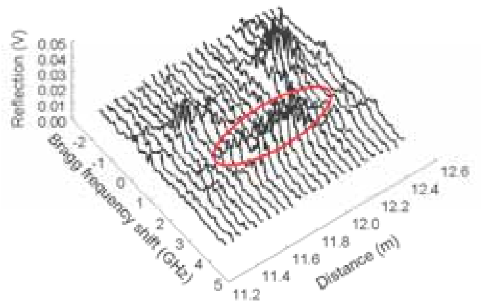


Fig. 4. Reflection spectrum of the dynamic grating localized at strained section.

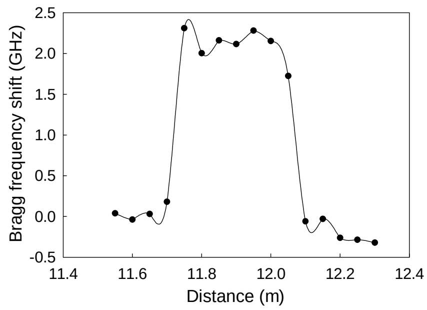


Fig. 5. Bragg frequency shift when sweeping the coherence peak along the fiber.

possible to enhance the reflectance resolution of OFDR. However, hundreds of profiles need to be used for averaging to achieve a sufficient reflectance resolution. Therefore, the speed becomes a critical problem, which refrains from the application in the manufacturing industry. In this thesis, for the purpose of this application, we propose and demonstrate a novel high-accuracy high-speed reflectometry technique based on SOCF technique, in which wavelength domain averaging is used in combination with the SOCF to enhance the reflectance resolution.

Fading noise caused by interference of different reflection and Rayleigh backscatter (RBS) signals decreases the accuracy of distributed measurement of reflection. To reduce fading noise, averaging must be performed for a large number of independent backscatter signals which are sampled at different wavelengths. By applying the wavelength domain averaging, the phase correlations between lightwaves backscattered at different positions are changed and correlation peaks are formed. Strong correlations of the scatter elements appear periodically at a length of L, which is called correlative range. After applying the wavelength domain averaging, these scatter elements, which are not correlative, do not interfere each other and induce the fading noise, while those correlative elements influence the fading noise. The distribution of probability function changes and becomes closer to the average intensity. As a result, the reflectance resolution is improved.

What a continuous wavelength averaging method differ from a conventional discrete wavelength averaging method first is the correlative range. The latter is in inverse proportional to the numbers of wavelength steps while the former is nearly infinity if applying a slow wavelength sweep for averaging. Another advantage of using the continuous wavelength averaging method is about the signal processing issue. The averaging of continuous wavelength sweep can be performed automatically by electronic circuits with simply selecting the integration time after receiving signals from photodiode. This process is much short in time compared to the numerical processing in discrete averaging method.

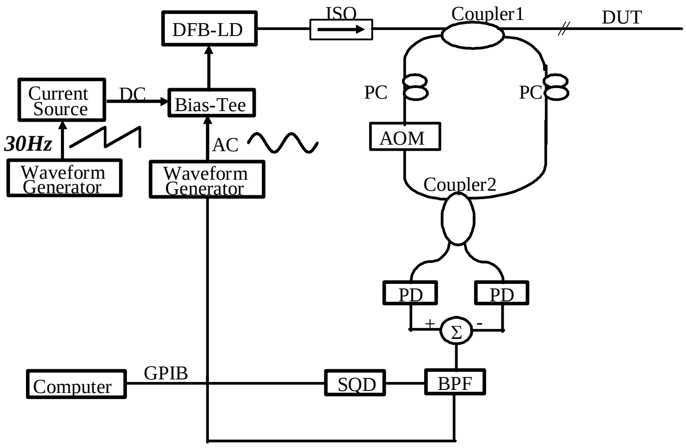


Fig. 6. Experimental setup for high-accuracy high-speed adaptive reflectometry.

As sweeping the center wavelength, there is a problem of carrier frequency shift. There are two methods available to solve this problem. The first one is to use an electrical filter with large bandwidth to cover the entire frequency shifts, with a degeneration of the sensitivity and the dynamic range of the measurement. The other one is to use a narrow-bandwidth filter with the center frequency changing adaptively along with the detecting position. This method is suitable for SOCF technique since SOCF is a peak- sweeping technique that we know the position to detect. When we perform the peak- sweeping along the device under test (DUT), the center frequency of the filter should change to the peak- position- dependent carrier frequency adaptively. The experimental setup is given in Fig. 6.

After using the SOCF with wavelength domain averaging method to reduce the fading noise, the reflectance-resolution of 0.022 dB is realized. Dynamic range improvement of ~20 dB is also realized because of the adaptive changing of the electrical filter center frequency. Owing to the integrated modulation, the measurement time improved to less than 1 minute for the measurement of 50 m DUT with the resolution of 10 cm.