Optical coherent detection Brillouin distributed optical fiber sensor based on orthogonal polarization diversity reception

Muping Song (宋牟平), Bin Zhao (赵 斌), and Xianmin Zhang (章献民)

Department of Information and Electronic Engineering, Zhejiang University, Hangzhou 310027

Received January 6, 2005

In Brillouin distributed optical fiber sensor, using optical coherent detection to detect Brillouin scattering optical signal is a good method, but there exists the polarization correlated detection problem. A novel detecting scheme is presented and demonstrated experimentally, which adopts orthogonal polarization diversity reception to resolve the polarization correlated detection problem. A laser is used as pump and reference light sources, a microwave electric-optical modulator (EOM) is adopted to produce frequency shift reference light, a polarization controller is used to control the polarization of the reference light which is changed into two orthogonal polarization for two adjacent acquisition periods. The Brillouin scattering light is coherently detected with the reference light, and the Brillouin scattering optical signal is taken out based on Brillouin frequency shift. After electronic processing, better Brillouin distributed sensing signal is obtained. A 25-km Brillouin distributed optical fiber sensor is achieved.

OCIS codes: 060.2370, 290.5830, 260.5430.

Recently, optical fiber sensors have attracted more and more attention for their advantages such as excellent radiant resistance, immunity to electromagnetic noise, and good chemical stability[1−8]. Distributed optical fiber sensor (DOFS)[2−8] is a very attractive and appealing technique because of its potential for measuring the distributing information along the entire sensing fields. In recent years, the commercial Raman DOFSs have been widely used, while Brillouin distributed optical fiber sensor (B-DOFS)[3−8] attracts a great attention.

In B-DOFS, the key point is how to detect Brillouin scattering optical signal, because the frequency shift between Brillouin scattering light and Rayleigh scattering light is only about 11 GHz (near 1.55 μm) and the Rayleigh scattering light is stronger than Brillouin scattering light, which makes it difficult to distinguish them. Two different techniques for long distance B-DOFS are practical: Brillouin optical time domain analysis (BOTDA)[6] and Brillouin optical time domain reflectometry (BOTDR)[7,8]. BOTDR needs to process light signal only at one end of the fiber, which simplifies the optical measurement system and thus can be widely used. But the spontaneous Brillouin scattering optical signal detected by BOTDR is very weak and the Brillouin frequency shift is small. So an appropriate detection method should be developed. Here we use optical coherent detection method to detect Brillouin scattering optical signal of B-DOFS and solve the problem caused by optical polarization.

Brillouin scattering in fiber can be described as the nonlinear process between pump light and scattering light caused by acoustic waves[9]. The frequency shift between scattering light and pump light, also called Brillouin frequency shift, is given by[9]

$$\nu_{\rm B} = 2nv_{\rm A}/\lambda_{\rm p} \tag{1}$$

with the parameters of the acoustic velocity $v_{\rm A} = 5.96$ km/s, refractive index $n = 1.45$. There is $\nu_{\rm B} \approx 11$ GHz for quartz fiber near $\lambda_{\rm p} = 1.55$ μm. When the fiber suffers a temperature or strain change, the refractive index and acoustic velocity also change, which makes Brillouin frequency shift $\nu_{\rm B}$ become a function of temperature (T) and strain (ε)[3,4]

$$\nu_{\rm B}(T) = \nu_{\rm B}(T_{\rm r})[1 + C_T(T - T_{\rm r})], \tag{2}$$

$$\nu_{\rm B}(\varepsilon) = \nu_{\rm B}(0)[1 + C_\varepsilon \varepsilon], \tag{3}$$

where $T_{\rm r}$ is the reference temperature, $C_T = 9.4 \times 10^{-5}$ K^{-1} and $C_\varepsilon = 4.6$ are the proportional constants. Concerning the single-mode fiber (SMF) under the condition of $T = 300$ K and $\lambda = 1.5$ μm,

$$\delta\nu_{\rm B} = C_{\nu\varepsilon}\delta\varepsilon + C_{\nu T}\delta T, \tag{4}$$

$$C_{\nu T} = 1.10 \pm 0.02 \text{ MHz/K}, \tag{5}$$

$$C_{\nu\varepsilon} = 0.0483 \pm 0.0004 \text{ MHz}/\mu\varepsilon. \tag{6}$$

It is obvious that Brillouin frequency shift is determined by temperature and strain. Thus the temperature and strain distribution along the fiber can be measured by detecting Brillouin frequency shift.

Optical coherent detection is a good method to measure B-DOFS signal[7,8]. A key point of coherent detection is how to produce two coherent laser lights. There are two normal methods: using acoustic-optics modulation[7] or directly using the same light[8]. Here we use microwave electric-optical modulator (EOM) to produce the required light[5].

Figure 1 shows the basic schematic diagram of the optical coherent detection method for detecting Brillouin scattering optical signal of B-DOFS. In Fig. 1, the frequency of pump light is $\nu_{\rm p}$; the frequency of Brillouin scattering light produced in sensing fiber is $\nu_{\rm p} - \nu_{\rm B}$; the frequency of Rayleigh scattering light is $\nu_{\rm p}$. Reference light is produced by microwave EOM, whose frequency is $\nu_{\rm p} - \nu_{\rm LO}$. The frequency shift between reference light and pump light $\nu_{\rm LO}$ is close to $\nu_{\rm p}$ in order to simplify the heterodyne detection and electronic processing. In the coherent detection, the weak electric field of Brillouin scattering light is superimposed on the strong electric field of reference light, and then converted into photocurrent. Brillouin scattering light produces one part of the photocurrent. The frequency of this part is relatively low and can be described as

$$\nu_{\mathrm{PH-B}} = (\nu_{\mathrm{p}} - \nu_{\mathrm{B}}) - (\nu_{\mathrm{p}} - \nu_{\mathrm{LO}}) = \nu_{\mathrm{LO}} - \nu_{\mathrm{B}}. \quad (7)$$

The frequency of another part of the photocurrent that is produced by Rayleigh scattering light is about 11 GHz and is given by

$$\nu_{\mathrm{PH-R}} = \nu_{\mathrm{p}} - (\nu_{\mathrm{p}} - \nu_{\mathrm{LO}}) = \nu_{\mathrm{LO}}. \quad (8)$$

These two parts are quite different in frequency, so it is easy to separate the Brillouin scattering optical signal form the total photoelectric signal.

In coherent detection, another key point is how to make the polarizations of Brillouin scattering light and reference light match. Because the performance of coherent detection is related to the polarization states of Brillouin scattering light and reference light while the former is unknown in advance, a proper polarization controller (PC) should be developed to eliminate the changes of signal caused by optical polarizations.

The optical coherent detection B-DOFS system used in this letter is shown in Fig. 2. In the system, a distributed feedback laser diode (DFB-LD) is used as optical source, and the light produced by optical source is divided into pump and reference lights by a fiber coupler. The pump light is modulated into optical pulse whose width is 100 ns and repetition frequency is 2 kHz. Then, after being amplified by an erbium-doped fiber amplifier (EDFA) (here we use fiber Bragg grating (FBG) and circulator to filter the amplified spontaneous emission (ASE) noise introduced by EDFA), the pump pulse is launched into a 25-km single-mode fiber via fiber circulator. Reference light is modulated by a microwave EOM, and its polarization is controlled by a PC. The coherent detected signal is mixed with a local 90-MHz signal and then filtered to get the amplitude-modulated baseband signal. Using a high speed (80 MHz) analog/digital (A/D) converter, the baseband signal is converted to digital signal and then accumulated by BOXCAR to obtain a better signal-to-noise ratio (SNR). At last, the sensing signal is transferred to computer.

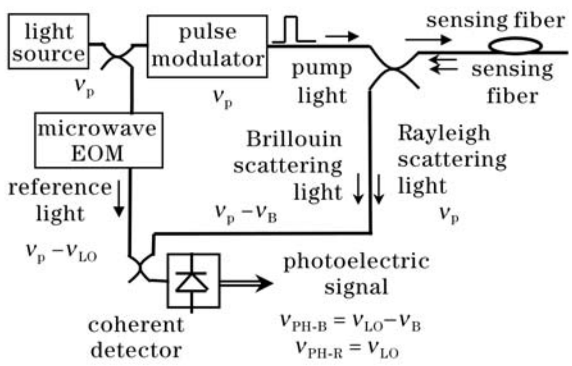

Fig. 1. The scheme of optical coherent detection method for B-DOFS.

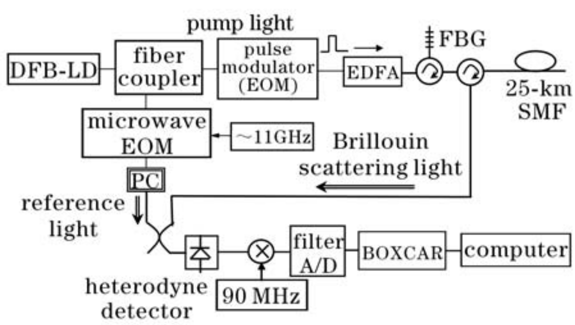

Fig. 2. The experiment system scheme for optical coherent detection B-DOFS.

In the coherent detection B-DOFS system, there exists the polarization-correlated problem. In Fig. 3, the left side shows two orthogonal linear polarization light and the PC used here consists of two $\lambda/4$ plates that are electrically controlled, and the right side illustrates Brillouin scattering optical signal. The polarizations of Brillouin scattering light and reference light are characterized as follows.

1) The reference light before processed by PC is nearly steady linear polarization. After being processed, it is changed into two orthogonal polarizations in two adjacent acquisition periods.

2) Under the control of periodic pump light pulse, the Brillouin scattering optical signal is also periodic and its polarization state changes randomly along the fiber. In one sample period, different sample points of scattering light represent random polarization states, which depends on the initial polarization state of input light, characteristics of sensing fiber and environments, so they are unknown in advance.

3) In different sample periods (2 kHz), the polarization state of same points can be regard as nearly the same.

Therefore, the polarization state of Brillouin scattering light at every point alters randomly, and the polarization tracing technique used in optical communication is not appropriate for B-DOFS, because the normal PC response is too slow (our demanding response speed is faster than the sample frequency — 80 MHz). The method of using randomizing reference light and local light polarization states to eliminate polarization-correlated problem was proposed by Kurashima *et al.*[7]. Here we call the method orthogonal polarization diversity reception.

Concerning that Brillouin scattering optical signal is periodic, the polarization states of different points in one

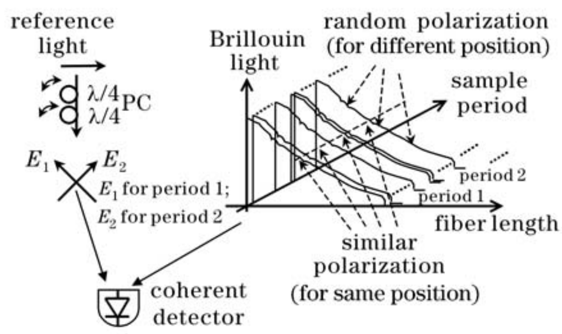

Fig. 3. The polarization features of B-DOFS using optical coherent detection method.

sample period are different, while the polarization states of same points in different sample periods are nearly the same. So Brillouin scattering light is given by

$$\vec{E}_{\mathrm{B}}(z) = E_{\mathrm{B}x}(z)\vec{e}_x + E_{\mathrm{B}y}(z)\vec{e}_y. \tag{9}$$

If the polarization of reference light keeps only in x or y direction, only part of the scattering light can be detected and this causes the polarization-correlated problem. Here the polarization of reference light is changed into two orthogonal polarizations for two adjacent acquisition periods, as shown in Fig. 3, and these two lights have the same amplitude

$$\vec{E}_{\mathrm{LO}}(t) = E_{\mathrm{LO}}(t)\vec{e}_x + E_{\mathrm{LO}}(t+\Delta t)\vec{e}_y. \tag{10}$$

Δt is the interval of a sample period. After reference light is superimposed on Brillouin scattering light and the signals sampled in two adjacent periods are accumulated, the detected signal is given by

$$P_o = \eta\,(E_{\mathrm{B}x} + E_{\mathrm{B}y})\,E_{\mathrm{LO}}, \tag{11}$$

where η is the coefficient of optical-electric conversion.

By detecting all parts of Brillouin scattering light that distribute in two orthogonal directions, the alterations of detected signal caused by the polarization-correlated problem are eliminated.

Using orthogonal polarization diversity reception, we designed a model system of B-DOFS. It is as big as a normal personal computer, connecting with a monitor on one side and 25-km single-mode sensing fiber on the other side.

In order to illustrate the performance of orthogonal polarization diversity reception, we kept the frequency of microwave EOM unchanged to detect the Brillouin scattering light at 10.83 GHz. The detected signal (accumulated and averaged 4000 times) of B-DOFS without using orthogonal polarization diversity reception is shown in Fig. 4. It is shown that the detected signal contains drastic fluctuations. These fluctuations were introduced by polarization-correlated problem, because the processing of accumulation reduced the effect of random noise. The evidence was that the intensity of detected signal changed a lot when the polarization of reference light was altered by PC. The fluctuations caused by non-matching polarization affect the acquisition of sensing information greatly.

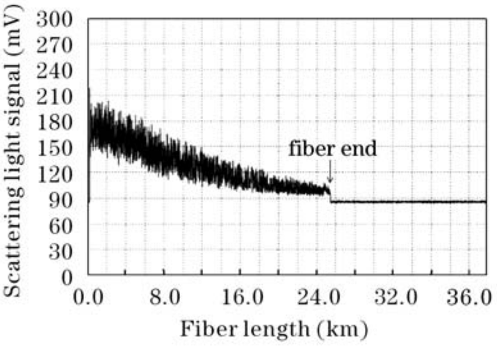

Fig. 4. The detected signal of B-DOFS without using orthogonal polarization diversity reception.

Then we used orthogonal polarization diversity reception to detect Brillouin scattering light. The detected signal of B-DOFS using orthogonal polarization diversity reception is illustrated in Fig. 5. In contrast to the signal in Fig. 4, fluctuations have been well restrained. When altering the frequency shift of reference light, the Brillouin scattering optical signal between 10.81—10.91 GHz could be got, as shown in Fig. 6. It is shown that the intensity of Brillouin scattering optical signal drops exponentially along the sensing fiber, while the frequency profile changes like a Lorentz curve[9] and the peaks of Brillouin scattering optical signal appear near 10.83 GHz.

According to the relationship between Brillouin frequency shift and temperature, the temperature distribution along the 25-km sensing fiber was obtained, as shown in Fig. 7. The environment temperature was 20 °C, two sections of the fiber near the end were immerged in warm water. As the inset in Fig. 7 shows, the 15-m-long

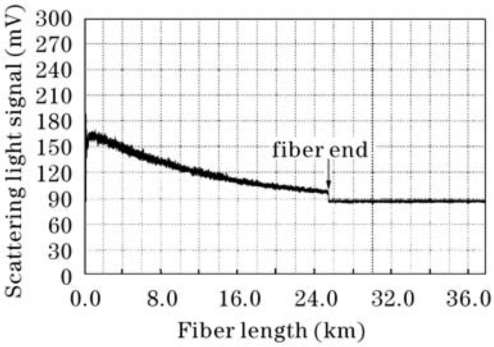

Fig. 5. The detected signal of B-DOFS with using orthogonal polarization diversity reception.

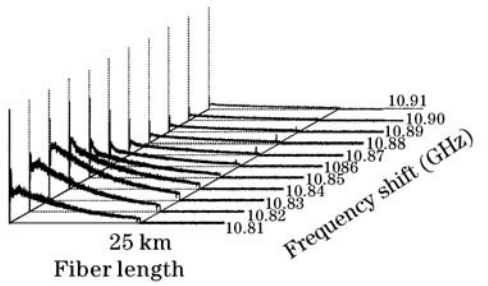

Fig. 6. The 'panorama' of the Brillouin scattering signal.

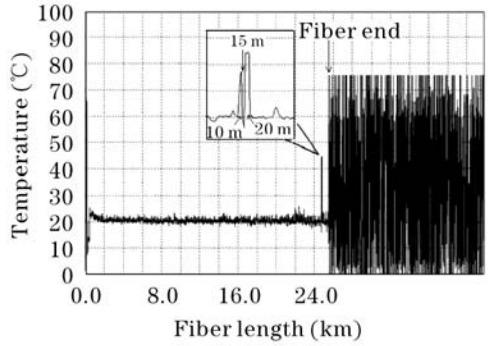

Fig. 7. The temperature curve of 25-km sensing fiber based on analyzing the Brillouin scattering optical signal.

section is at the temperature of 35 °C and the 20-m-long section at 45 °C, while the 15-m-long section in the middle is at the environment temperature. It can be seen that these three sections of fiber under test can be distinguished easily, which means that distributing sensing has been realized. The fluctuations of temperature was introduced by the strain existing in fiber and the detection noise.

In conclusion, the polarization-correlated problem in optical coherent detection B-DOFS is resolved by a novel detecting scheme called orthogonal polarization diversity reception. A PC is used to control the polarization of the reference light produced by EOM, which is changed into two orthogonal polarizations for two adjacent acquisition periods. Then the Brillouin scattering light is heterodyne detected with the reference light. A polarization controlled Brillouin distributed optical fiber sensing signal is obtained and a 25-km Brillouin distributed optical fiber temperature sensor is achieved. Orthogonal polarization diversity reception is easy to realize because it only needs a PC with low response speed. It is appropriate for the detection of optical signal that is weak and changes periodically.

This work was supported by the Zhejiang Provincial Natural Science Foundation of China under Grant No. 603127. M. Song's e-mail address is songmp@zju.edu.cn.

References

1. W. G. Zhang, Y. G. Liu, Y. Wang, G. Y. Kai, Q. D. Zhao, and X. Y. Dong, Chin. J. Lasers (in Chinese) **30,** 71 (2003).
2. W. Wang, B. Q. Zhou, Z. X. Zhang, X. B. Wu, N. Guo, X. D. Yu, Q. L. Wang, Acta Opt. Sin. (in Chinese) **19,** 100 (1999).
3. T. Kurashima, T. Horiguchi, H. Ohno, and H. Izumita, in *Proceedings of ECOC'98* 149 (1998).
4. H. Naruse, M. Tateda, H. Ohno, and A. Shimada, in *15th Optical Fiber Sensors Conference Technical Digest (OFS 2002)* 305 (2002).
5. M. P. Song, Acta Opt. Sin. (in Chinese) **24,** 1111 (2004).
6. X. Bao, J. Dhliwayo, N. Heron, D. J. Webb, and D. A. Jackson, J. Lightwave Technol. **13,** 1340 (1995).
7. T. Kurashima, M. Tateda, T. Horiguchi, and Y. Koyamada, IEEE Photon. Technol. Lett. **9,** 360 (1997).
8. S. M. Maughan, IEEE Photon. Technol. Lett. **13,** 511 (2001).
9. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, San Diego, 1989) pp.263—288.