

Experimental Study on Brillouin Optical Fiber Temperature Distributed Sensing System

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Abstract: Based on a temperature measurement principle of Brillouin optical time-domain fiber sensor, an optical fiber temperature distributed sensing system was established. Brillouin frequency shift temperature coefficient of the system is calibrated by measuring the Brillouin frequency shift spectrums of the optical sensing fiber to determine the peak Brillouin frequency shift at different temperatures. With the system temperature coefficient, system experiments on measuring the temperature of 900m optical fiber were carried out. Experimental results show that temperature changes on the sensing optical fiber can be sensitively sensed in the system. And relative errors of these measurements are between 0.017% and 0.279%.

Introduction

In recent years, fiber optical sensors are taken much fancy because of their high sensitivity, anti-electromagnetic interference, anti-radiation, corrosion resistance, environmental adaptability and many other advantages. In the formation of sensor networks for distributed measurement, optical fiber sensors are more suitable for a wide range of measurement areas, especially on monitoring structural health of bridges^[1], tunnels^[2], dams^[3], tall buildings^[4] and other large buildings. Since the Optical Time Domain Reflectometry (OTDR) has been proposed by M K Barnoski and S M Jensen^[5], the research on optical fiber sensor used in distributed measurement are mainly the distributed measurement technologies based on backscattering optical time domain and frequency domain reflection^[6] which have been developing rapidly. A variety of techniques have been proposed to improve the spatial resolution, measurement accuracy and extend the sensing distance for distributed sensing systems, where higher resolution and further transmission distance can be obtained in distributed measurement by using Brillouin scattering, which is one of the hot topics on sensor research.

In 1989, Horiguchi^[7] first proposed Brillouin optical time domain analysis (BOTDA) method. In 1995, Bao Xiaoyi first obtained a spatial resolution of less than 10m in the range of 51km using loss-type BOTDA system^[8]. In 2004, Kishida et al.^[9] proposed using pulsed pre-pulsed (PPP) technique in the BOTDA system to increase the spatial resolution to 10 cm. In the same year, Bao Xiaoyi et al.^[10] achieved the measurement of 1.5cm gap with a strain resolution of 10-30 $\mu\epsilon$ and a temperature resolution of 1- 2 ° C by using polarization-maintaining fiber in the loss-type BOTDA system. Then in 2008, they obtained spatial resolution of the 50cm by using two pump lights with different pulse widths (50ns and 48ns)^[11]. In 2011, Y. Dong et al.^[12] solved the problem of pumping loss in long-distance BOTDA system by using time-division multiplexing technique, and improved the sensing distance of the system to 100km. In 2012, YairPeled and AviMotil^[13] proposed a fast Brillouin Optical Time Domain Analysis (F-BOTDA) test method, which fully realizes the dynamic measurement. In the paper, an optical fiber temperature distributed sensing system was established based on a temperature measurement principle of Brillouin optical time-domain fiber sensor. And the system performance on measuring temperature will be studied in detail.

Temperature measurement principle of Brillouin optical time-domain fiber sensing system

The Brillouin scattering in optical fiber can be described as the scattered light frequency is different from a incident light because of a Doppler effect caused by a refractive index grating moving at the speed of sound, which is formed by acoustic or pressure waves when the incident light passes through an optical fiber. A Brillouin scattering frequency shift is determined by the velocity of sound. The changes of sensing fiber's temperature/strain will affect sound velocity and the Brillouin scattering frequency shift inside the fiber, so the fiber temperature/strain can be measured by measuring the Brillouin frequency shift. According to the conservation of momentum, the back-to-Brillouin scattering frequency shift in the fiber is expressed as ^[14]:

$$\nu_B = 2nV_a/\lambda_0 \quad (1)$$

Where λ_0 is the incident light wavelength, n is the refractive index of the sensing fiber, and V_a is the acoustic velocity in the sensing fiber. From formula (1), the Brillouin frequency shift ν_B is proportional to the acoustic velocity V_a in the fiber. Sound velocities in optical fiber materials is influenced by temperature and strain changes because of its photoelastic properties and thermo optic properties, so temperature and strain changes will cause the changes their Brillouin frequency shifts. A large number of theoretical and experimental studies have shown that under certain conditions, the frequency shift of the Brillouin scattering signal in the fiber is linear with the ambient temperature and the strain of the fiber, and can be expressed by the formula ^[14]:

$$\Delta\nu_B = C_{\nu T} \Delta T + C_{\nu \epsilon} \Delta \epsilon \quad (2)$$

Where $\Delta\nu_B$ is Brillouin frequency shift; ΔT is temperature change; $\Delta \epsilon$ is strain change; $C_{\nu T}$ is Brillouin frequency shift temperature coefficient; $C_{\nu \epsilon}$ is Brillouin frequency shift strain coefficient. Using the formula (2), by measuring the frequency shift and intensity of the Brillouin scattered light along the length of the fiber, the temperature/strain distribution information of the fiber can be obtained, and the measured Brillouin optical time domain analysis the principle of the sensing system is shown in Fig1.

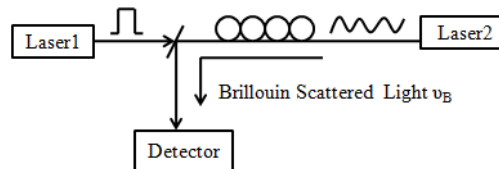


Fig. 1 Principle of BOTDA fibre sensing system

As shown in Fig 1., a pair of pump light and a continuous probe light are respectively injected at both ends of the optical fiber. When the frequency difference between the pumping light and the probe light is equal to the Brillouin frequency shift in a certain region of the fiber, the Brillouin scattered light is coherent with the continuous probe light in this region, and the Brillouin optical amplification occurs, and the optical power of the Brillouin scattering light reaches the maximum. The optical power coupled from one end of the optical fiber is detected by a detector and whether or not stimulated Brillouin scattering occurs could be judged. When stimulated Brillouin scattering is produced by the pulsed light and the continuous light, the continuous light at that position would be gained or attenuated. The power variation of the continuous light at different positions is detected in the time domain. The Brillouin gain spectrum on the whole fiber can be obtained when the optical frequency difference of two beams are changed near the Brillouin frequency shift. Due to the linear relationship between Brillouin frequency shift and temperature/strain, the distributed temperature/strain sensing can be realized by measuring the center frequency of the gain spectrum.

Optical fiber temperature distributed sensing system

According to temperature measurement principle of Brillouin optical time-domain fiber sensing system, an optical fiber temperature distributed sensing system using a narrow linewidth laser with a wavelength 1550.12nm and a power 10mW is shown in Fig.2.

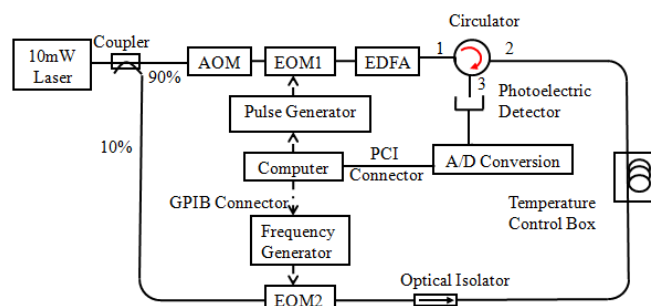


Fig. 2 Diagram of optical fiber temperature distributed sensing system

Work process of experimental system: a light from the laser is divided into two beams of 9:1 by a polarization coupler, which enter the AOM+electro-optic modulator EOM1 and EOM2, respectively. A computer is a control center for the system. On the one hand, by controlling the pulse generator to trigger EOM1 to modulate that 90% laser beam, a pulsed pump light is generated. The pulsed pump light is then amplified by an erbium-doped fiber amplifier to ensure adequate pump energy. The amplified pulsed pump light is sent into the sensing fiber through 1 end of a circulator. At the same time, the rising edge of the pulse signal from the pulse generator acts as the start time of the trigger clock to trigger a data acquisition card for a multi-step signal acquisition. After the clock period is passed, the pulse generator triggers next pulse signal and simultaneously trigger the data acquisition card to carry on another multi-step signal acquisition. According to the time that signals go and back from sampling points, the corresponding position information can be obtained by using the propagation speed of light in the optical fiber. On the other hand, by setting the frequency shift to control frequency generator to trigger EOM2 to modulate that 10% laser beam, a continuous probe light is generated, whose frequency has a certain frequency difference compared with the frequency of the pump light. The probe light is sent to the other end of the sensing fiber through an optical isolator. When it meets Brillouin scattering light with same frequency generated by the pump light, an amplified probe light will be formed at the point where they meet. The stimulated amplifying Brillouin signals is output through 3 end of the circulator and sent into the photoelectric conversion circuit for conversion and amplification filtering, then into a high-speed A/D data acquisition card built-in the computer for analog-digital conversion. The final data are saved and kept in the computer. From these data Brillouin frequency shift along the fiber can be obtained.

System experiments and results

The fiber used in experiments was a 900-meter Corning SMF-28 common-mode single-mode fiber, whose Brillouin frequency shift is about 11GHz when its temperature is 20 °C. Temperature coefficient of Brillouin frequency shift for the system in formula (3) needs to be calibrated according to actual situations of the system before applying it for temperature measurements.

Calibration of System Temperature Coefficient

The temperature coefficient of Brillouin frequency shift can be determined by Brillouin frequency shift at different temperatures in some spot or region in the fiber. The heating section of the fiber is taken as the research object. The longer the heating section, the easier experimental measurements. Temperatures of the optical fiber is controlled by a temperature control box, so put all the 900m fiber into the control box would be much easy for experiments. In the system an optical power meter could

be directly connected to the end of the circulator 3 to measure the optical power of stimulated Brillouin scattered signals. Frequency values of the frequency generator could be adjusted within a certain range. During the frequency scanning process output power of the stimulated Brillouin scattering signals at the end of the circulator 3 are recorded. Measured Brillouin spectrum intensity at 55 °C is shown in Fig.3. Using nonlinear least squares method normalizing the Lorentz curve where boundary conditions are Lorentz parameters for a typical single-mode fiber, a smooth curve is obtained in Fig. 3. From Fig. 3 it can be seen that the peak Brillouin frequency shift is 10.992 GHz and its Lorentz line width is 30 MHz.

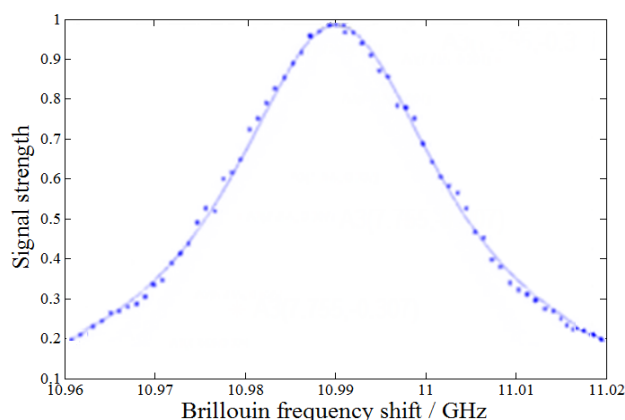


Fig.3 Lorentz curve of Brillouin spectrum at 55 °C.

In the same way, Brillouin spectra were measured at 35 °C, 45 °C, 50 °C, 55 °C, and 60 °C. The corresponding experimental data were also normalized by Lorentz fitting. Their peak Brillouin frequency shifts and Lorentz line widths are shown in Table 1.

Table1 Parameters of Brillouin spectrum at different temperatures

Temperature [°C]	Frequency shift [MHz]	Brillouin line width [MHz]
35	10971	30
40	10975	31
45	10981	30
50	10986	30
55	10992	30
60	10999	31

It can be seen from Table 1 that these peak Brillouin frequency shifts increase when temperatures rise, but their Lorentz line widths of Brillouin spectrum intensity distribution curves are basically same. Their Brillouin frequency shift peaks versus temperatures are plotted and fitted linearly shown in Fig. 4.

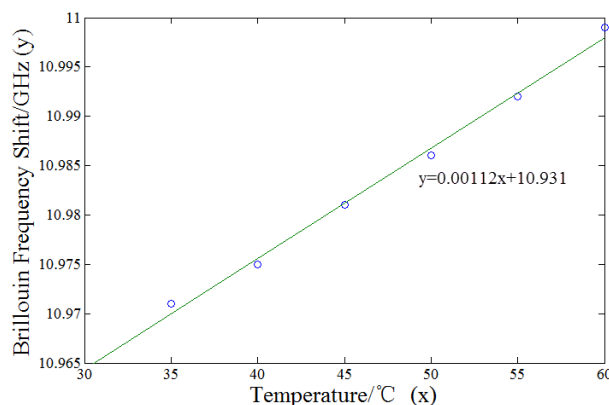


Fig.4 Relationship between Brillouin frequencies shift and temperatures

From Fig. 4, it can be seen that Brillouin frequency shift peaks have a good linear relationship with temperatures. The slope of the fitted line is 1.12MHz/ °C for the experimental system. Namely, the system temperature coefficient of Brillouin frequency shift is 1.12MHz/ °C. When Brillouin frequency shift at 55 °C is taken as a reference point, the fitted straight line can be written as:

$$\nu_B = 10.992[1 + 1.01 \times 10^{-4} (T - 55)] \quad (3)$$

By the relationship between temperatures and frequency shifts provided by equation (3), the temperature information of the fibre on its some section could be obtained by demodulating the frequency shift information at the section.

Temperature Measurement Experiments and Analysis

After the calibration of the system temperature coefficient, temperature measurement experiments are carried out. A fiber about 20m long from 192m to 212m is placed in a temperature control box, and the rest is exposed to the air.

Set the temperature of the control box 55 °C and set the range of scanning and acquisition frequency between 10.955GHz ~ 11.015GHz. Keep 30 min for sufficient heating the fiber. Then data of stimulated Brillouin scattering signal are acquired and stored in the computer. These data were processed to obtain Brillouin scattering spectrums at each point on the whole fiber length. According to the Brillouin scattering spectrum of the sensing fiber at each point, the peak Brillouin frequency shift at the point is obtained. and the temperature of the point is obtained according to the relationship formula (3). The measurement is repeated 5 times. Experimental measurement data and relative error values are shown in Table 2.

Table 2 Optical fiber temperature measurement results

Temperature control box settings [°C]	Times	Temperature value[°C]	Average value[°C]	Relative error[%]
55	NO.1	54.9791	55.0315	0.057
	NO.2	54.9980		
	NO.3	55.0458		
	NO.4	55.0980		
	NO.5	55.0367		

Temperatures of the control box are set in the range of 35 °C ~ 60 °C with heating gradient 5 °C. In order to fully heat the fiber, each stage temperature is kept stable for 30 min before doing above temperature test. A measurement at each temperature is repeated many times for average. Temperature measurement results are shown in Table 3. And the relative errors of these measurements are also given in the table.

Table 3 Measurement results at different optical fiber temperatures

Temperature control box settings [°C]	Average value [°C]	Relative error[%]
35	34.8774	0.350
40	39.8884	0.279
45	45.0075	0.017
50	49.9120	0.176
55	55.0315	0.057
60	59.8675	0.103

In Table 3, average temperatures of the sensing fiber measured by the system is basically the same as heating temperatures given by the control box. And the relative errors of these measurements are between 0.017% and 0.279%.

Conclusions

According to the temperature measurement principle of Brillouin optical time-domain fiber sensor, an optical fiber temperature distributed sensing system is established. The minimum spatial resolution of Brillouin optical time domain analysis sensing system is 1m in theory. Using a narrow pulse source with pulse width 10ns and an acquisition card with 500MHz frequency, the build experimental system would meet the theoretical requirements in the system spatial resolution. Based on the calibration of the temperature coefficient of the experimental system with the 900m sensing fiber, preliminary experiments measuring the temperatures of the optical fiber were carried out. Experimental results show that temperature changes on the sensing optical fiber can be sensitively sensed in the system. And relative errors of these measurements are between 0.017% and 0.279%.

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