Performance Analysis of Temperature and Strain Simultaneous Measurement System Based on Heterodyne Detection of Brillouin Scattering

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Abstract—Microwave heterodyne detection can be used to measure the temperature and strain distribution along a fiber with high accuracy in a Brillouin optical time domain reflectometry (BOTDR) system. This method involves simultaneous measurement of Brillouin scattering and Rayleigh scattering in fiber, and scanning of Brillouin spectrum to obtain the desired information. This paper presents a simultaneous measurement system of temperature and strain based on microwave detection and analyzed the system performances such as measurement accuracy, dynamic range, and spatial resolution theoretically. The analysis shows that the system can achieve a temperature resolution of 1 °C and a strain resolution of 100 με.

Index Terms—Brillouin scattering, heterodyne detection, strain, temperature.

1. Introduction

The distributed fiber-optic sensing technology based on Brillouin scattering is that the continuous distributed information of time and spatial domain can be measured simultaneously by running an optical fiber to each location, which is one of the main methods in the area of distributed sensing technology, thus leading to the extensive attention. Brillouin scattered light is caused by non-linear interaction between the incident light and phonons that are thermally excited within the light propagation medium. And this scattered light is shifted in frequency relative to the pump light called Brillouin frequency shift, which is proportional to temperature and strain applied to the optical fiber, and the authors\[1\] proved that the power of Brillouin scattering light is also proportional to temperature and strain applied to the optical fiber. In this way, it can be measured that the temperature and strain simultaneously use Brillouin frequency shift and power.

Brillouin scattering time-domain distributed fiber-optic sensing technologies are mainly divided into two groups: Brillouin optical-fiber time-domain reflectometry (BOTDR) and Brillouin optical-fiber time-domain analysis (BOTDA). These sensing technologies using optical time-domain reflectometry (OTDR) give a measure of the spatial orientation along the fiber. BOTDA system accesses to both ends of the sensing fiber with probe pulsed light and continuous wave (CW) light. It is possible to measure temperature and strain applied to the optical fiber, provided that the frequency difference between the two lasers is equal to the Brillouin frequency shift (\(v_B\)) at the point, the CW light intensity experiences gain through the stimulated Brillouin scattering process. The both ends input makes the power of Brillouin scattering increase obviously in BOTDA system, but its limitation becomes more apparent in application and execution. BOTDR system accesses to only one end of the fiber with probe pulsed light, and detects the frequency and power of the backscattered light at the same end. Since the spontaneous Brillouin scattering is very weak in BOTDR system, we apply the heterodyne detection method to improve the sensitivity of system.

This paper presents a sensing experiment scheme of simultaneous measurement of temperature and strain based on heterodyne detection of Brillouin scattering and analyzes the performance of the system theoretically. Comparison between our theoretical results and experimental results reported before shows the validity of theoretical analysis.

2. Principle

When light wave transmits in a medium, most of it propagate at original direction, a small portion of it departure from the original direction and bring a scattering. There are three main types of scattering: Rayleigh scattering, Brillouin scattering and Raman scattering, which are caused by different scattering mechanisms. Rayleigh...
scattering is caused by flexibility collision of the incident light and the micro-particles in medium. The frequency of Rayleigh scattered light is the same as the incident frequency, and its intensity is the highest. The initial observation of Brillouin scattering in silica was studied by Krishnan in 1950. It has been shown that the Brillouin backscattered intensity and frequency shift exhibit both temperature and strain dependence [2].

Spontaneous Brillouin scattering which caused by the interaction between an incident light and a thermally excited acoustic waves has a Doppler frequency shift and has maximum scattering in the backwards direction [3]. The changes in Brillouin frequency shift and power due to the temperature and strain, can be represented using the following matrix equation

$$\frac{\delta \nu_p}{P_p} = \begin{bmatrix} C_{\nu T} & C_{\nu C} \end{bmatrix} \frac{\delta T}{\delta \nu_p} \quad \begin{bmatrix} C_{\nu T} & C_{\nu C} \end{bmatrix} \quad \begin{bmatrix} \delta \nu_p \end{bmatrix} \quad \begin{bmatrix} \delta \nu_p \end{bmatrix}$$

where $\delta \nu_p$ is the change of Brillouin frequency shift, $\delta \nu_p/P_p$ is the relative change of Brillouin scattering light power, $\delta T$ and $\delta \nu_p$ are the changes of temperature and strain, $C_{\nu T}$ and $C_{\nu C}$ are the temperature and strain coefficients for frequency shift, and $C_{\nu T}$ and $C_{\nu C}$ are the coefficients for power variation. The coefficients have been reported to be $C_{\nu T} = 1.10 \pm 0.02 \text{ MHz/K}$, $C_{\nu C} = 0.0483 \pm 0.0004 \text{ MHz/\mu e}$, $C_{\nu T} = 0.36 \pm 0.06 \%, t = 7.7 \pm 1.4 \times 10^{-4} \% / \mu e$ when $\lambda_p = 1550 \text{ nm}$ [4]. The two variables of temperature and strain can be resolved by taking the inverse of (1), and the inverse matrix must be non-singular, i.e., $C_{\nu T}C_{\nu C} \neq C_{\nu T}C_{\nu C}$.

The inverse equation is given by

$$\begin{bmatrix} \delta T \\delta \nu_p \end{bmatrix} = \frac{1}{\begin{bmatrix} C_{\nu T} & C_{\nu C} \end{bmatrix} \begin{bmatrix} C_{\nu C} & -C_{\nu T} \end{bmatrix}} \begin{bmatrix} \delta \nu_p \\delta \nu_p \end{bmatrix}$$

The variation of Brillouin power in an optical fiber is not only due to the variation of temperature and strain applied to the fiber, but also due to transmission attenuation, microbending and splice loss of the fiber. In order to overcome this, it is necessary to have a measure of the fundamental fiber attenuation. As the intensity of Rayleigh backscatter signal is insensitive to temperature and strain variation, the intensity ratio of the Rayleigh scattering to Brillouin scattering which is known as the Landau Placzek variation, the intensity ratio of the Rayleigh scattering to backscatter signal is insensitive to temperature and strain fundamental fiber attenuation. As the intensity of Rayleigh overcomes this, it is necessary to have a measure of the applied to the fiber, but also due to transmission attenuation, not only due to the variation of temperature and strain.

Therefore, the following level correction is performed in order to amend $\delta \nu_p/P_p$ by compensating the scattered light power with a reference fiber section where the temperature and strain are already known. The scattered light power ratio at the reference fiber section is defined as

$$C_{RB} = \frac{P_p(ref)}{P_p(ref)}$$

then amended relative variation of Brillouin power is given by

$$\frac{\delta P_p(z)}{P_p(z)C_{RB}} = \frac{(P_p(z) - P_p(z)C_{RB})}{P_p(z)C_{RB}}.$$

In (3), $P_p(ref)$ and $P_p(ref)$ are the Brillouin scattered light power and the Rayleigh scattered light power in the reference section. In (4), $P_p(z)$ and $P_p(z)$ are the Brillouin scattered light power and the Rayleigh scattered light power for location $z$ in the sensing fiber. $\delta \nu_p$ obtained by BOTDR and $\delta \nu_p/P_p$ obtained by (4) are substituted into (2), and $\delta T$ and $\delta \nu_p$ can be solved by resolving (2). The temperature and strain of the reference section are substituted into (5) and (6), we obtain

$$T(z) = T(ref) + \delta T,$$

$$\nu(z) = \nu(ref) + \delta \nu_p.$$  

where $T(z)$ and $\nu(z)$ are the temperature and strain of location $z$ in the sensing fiber.

3. Microwave Heterodyne Detection

BOTDR Sensor System Based on LPR

The experimental configuration for the microwave heterodyne detection BOTDR sensor system based on LPR is shown in Fig. 1. The system could measure the Brillouin scattered light and the Rayleigh scattered light in the same sensing route. The impact of the fiber attenuation, microbending and splice loss on system performance could be eliminated by calculating the ratio of the Rayleigh and Brillouin backscattered intensity. First of all, BOTDR need fine temperature and strain coefficients calibration of Brillouin frequency and intensity in sensing fiber. In one setting, in order to obtain higher Brillouin scattering efficiency, a narrowband source was utilized for the Brillouin measurement. Excellent frequency stability was ensured by deriving both the sensing pulses and the local oscillator with coupler 1 (C1) from the same seed laser. One part of the laser was modulated from continuous wave to pulse light by electro-optic modulator (EOM). The pulses were amplified via the erbium-doped fiber amplifier, EDFA1, and then passed through an in-fiber Bragg grating (FBG1) via a circulator to reduce the amplified spontaneous emission (ASE) noise from EDFA1 and launched into the sensing fiber via circulator 2 (C2). The backscattered traces were preamplified using EDFA2. Both the Rayleigh backscatter and the ASE from EDFA2 were then filtered out by reflection from FBG2 via circulator 3 (C3). The amplified, filtered backscatter was mixed with the local oscillator via a 3 dB coupler and then detected using a photodetector 1 (PD1). In order to match the polarization of the two beams to reduce the polarization noise on the signal, a polarization controller was used in the local oscillator arm.
The output signals from PD_1 were only difference frequency signals (that is, Brillouin signals), DC and the second harmonic components were filtered out by PD_2. The generated beat signal was around 11 GHz, corresponding to the Brillouin frequency shift which was too high to process accurately. A frequency down-converter would be required to obtain down-converted IF signal, and then utilizing data acquisition and processing unit to process the signal.

![Fig. 1. Experimental configuration for the microwave heterodyne detection BOTDR sensor system based on LPR.](image)

In the second setting, with the fiber optic switch, the source was broadband, and here the Rayleigh power would be measured in direct detection. The broadband laser light was modulated to pulsed light by the EOM. The pulsed light launched into the sensing fiber with the same route of the Brillouin measurement. A 95/5 fiber coupler was utilized as a tap for 5% of the backscattered signal which was detected by PD_2, and then the signal was to be processed utilizing the data acquisition and processing unit.

The system adopted Brillouin spectrum scanning to measure the Brillouin frequency and intensity. Moreover, the temperature and strain applied to the fiber would be measured simultaneously. When the beat frequency of the electrical local oscillator (ELO) was equal to the central frequency of band-pass filter and Brillouin signal, the measured components of the Brillouin spectrum passed through the low-pass filter of the frequency down-converter. After each set of spectra was obtained, the frequency shift and power of Brillouin backscatter was determined for each point of interest along the fiber. This was done by fitting each individual spectrum to a Lorentzian curve. For the Lorentzian spectral profile, the Brillouin intensity is proportional to peak power multiplied by linewidth and the Brillouin frequency shift is determined by the central frequency of the spectrum.

### 4. System Performance Analysis

#### 4.1 Measurement Accuracy

In BOTDR system, the Brillouin spectrum can be measured at any location along an optical fiber. This spectrum is well approximated by a Lorentzian curve with the parameters Brillouin shift $v_B$ and Brillouin line width $\Delta v_B$. Measurement accuracy is defined as the capability of detecting the very weak Brillouin backscattered signal, that is, the changes in value of temperature or strain applied to sensing fiber were limited by the change of photocurrent signal which was equal to the total noise current RMS. The accuracy of $v_B$ measurement directly influences that of the temperature or strain measurement, since temperature or strain changes are derived from the change of $v_B$ in the optical fiber [6]. Linewidth and signal-to-noise ratio (SNR) considerations determine the measurement accuracy of $v_B$ which is given by

$$\delta v_B = \frac{\Delta v_B}{\sqrt{2(SNR)^{1/4}}}.$$  

When the laser linewidth $\Delta v_L$ is appreciable, $\Delta v_L + \Delta v_B$ replaces $\Delta v_B$ in (7). The minimum detectable changes in temperature and strain are given as follows:

$$\left\{ \begin{array}{l}
\delta T = \frac{\Delta v_B}{\sqrt{2C_T(SNR)^{1/4}}} \\
\delta e = \frac{\Delta v_B}{\sqrt{2C_e(SNR)^{1/4}}}
\end{array} \right.$$  

#### 4.2 Dynamic Range

The dynamic range (Dr) of BOTDR is defined as the furthest range who can reach. The Dr of BOTDR can be derived in a similar way to that for conventional OTDR [6], which is given by

$$Dr = \frac{1}{2} \left( \frac{P_p + R_B + T_s - L_c - P_d + \frac{SNIR}{2}}{SNIR} \right)$$  

where $P_p$ is input peak power of the pulse (dBm), $R_B$ is Brillouin backscattering factor (dB), $T_s$ is Brillouin scattering selection ratio (dB), $L_c$ is directional coupler loss (dB), $P_d$ is minimum detectable power of receiver (dB), $SNIR$ is improvement in signal-to-noise ratio by averaging (dB), $SNIR_c$ is signal-to-noise ratio required for temperature/strain measurement (dB). Brillouin backscattering factor $R_B$ is given by

$$R_B = 10 \log (0.58 \alpha f \lambda W)$$  

where $W$ is the launched pulse width, $\alpha$ is the backscatter capture fraction, and $f_B$ is the Brillouin scattering coefficient. $S$ and $\alpha$ are given by

$$S = (\lambda/n)^2/(4\pi A)$$  

$$\alpha = \frac{1}{2} \left( \frac{P_p + R_B + T_s - L_c - P_d + \frac{SNIR}{2}}{SNIR} \right)$$  

$$\left\{ \begin{array}{l}
\delta T = \frac{\Delta v_B}{\sqrt{2C_T(SNR)^{1/4}}} \\
\delta e = \frac{\Delta v_B}{\sqrt{2C_e(SNR)^{1/4}}}
\end{array} \right.$$  

Fig. 1. Experimental configuration for the microwave heterodyne detection BOTDR sensor system based on LPR.
of the Brillouin spectrum is 

\[ \alpha_B = \frac{(8/3)\alpha^3}{\lambda^4} kT n^2 p_{12}^2 / \rho \rho_{12}^2 \]  

(12)

where \( \lambda \) is the optical wavelength, \( n \) is the refractive index of the fiber, \( A \) is the effective cross section of the fiber, \( k \) is Boltzmann’s constant, \( T \) is the absolute temperature, \( p_{12} \) is the photoelastic tensor component, \( \rho \) is the density, and \( V_o \) is the acoustic velocity. The \( S \) and \( \alpha_B \) of silica glass can be calculated as \( 1.4 \times 10^{-3} \, \text{m}^{-1} \) and \( 1.22 \times 10^{-8} \, \text{m}^{-1} \) at a wavelength of 1550 nm with \( n = 1.47 \), \( \lambda = 6.36 \times 10^{-11} \, \text{m}^2 \), \( T = 298 \, \text{K} \) and \( \rho = 2.22 \times 10^3 \, \text{kg/m}^3 \). \( T_s \) is defined as the ratio between the maximum Brillouin signal power that passes through the electrical bandpass filter whose bandwidth is \( B \) and the total Brillouin signal power. When the linewidth of the Brillouin spectrum is \( \Delta B \), \( T_s \) is given by

\[ T_s = 10 \log \left[ \frac{2}{\pi} \tan^{-1} \left( \frac{2B}{\Delta B} \right) \right] \]  

(13)

The maximum input power \( P_{in} \) is limited by optical nonlinear effects such as stimulated Brillouin scattering, four wave mixing and self phase modulation, and ranges from 20 dBm to 25 dBm. If the quantum noise of the receiver is much bigger than the thermal noise, its sensitivity will be improved towards the ultimate quantum limit, and the minimum detectable power will be \(-90 \, \text{dBm} \) for \( B = 1 \, \text{MHz} \). Thus, when \( W = 10 \, \text{ns}, B = 1 \, \text{MHz} \) and \( \Delta B = 30 \, \text{MHz}, R_B \) and \( T_s \) are calculated as approximately \(-87.7 \, \text{dB} \) and \(-13.7 \, \text{dB} \), by utilizing (10) and (13), respectively. Signal integrations of 40000 times give a SNIR of 46 dB, a temperature resolution of 1 °C requires a SNR of 51.4 dB, and a strain resolution of 100 \( \mu \text{e} \) requires a SNR of 25.7 dB. Assuming that \( L_C = 5 \, \text{dB}, P_{in} = 90 \, \text{dBm} \) and \( P_{in} = 24 \, \text{dBm} \), the system can provide a dynamic range of 5.45 dB with a temperature resolution of 1 °C and a strain resolution of 100 \( \mu \text{e} \).

4.3 Spatial Resolution

Spatial resolution (\( \delta_z \)) is defined as the smallest distinguished space along the length of optic fiber when measuring the distributed temperature or strain. \( \delta_z \) in BOTDR system usually depends on the incident pulse width \( W \) and is determined by [6]

\[ \delta_z = \frac{\lambda}{2} \]  

(14)

where \( \lambda \) is the light velocity in the fiber. Equation (14) shows that the pulse width should be as short as possible to obtain good spatial resolution. However, in view of the mechanism of the Brillouin scattering, when the pulse width is less than or close to the phonon lifetime, the Brillouin scattering power decline and the Brillouin spectrum linewidth broaden sharply, which will debase the measurement accuracy obviously. A pulse width of 10 ns is utilized, and the corresponding spatial resolution is 1 m.

5. Conclusions

This paper has introduced the principle of BOTDR system that utilized microwave heterodyne detection based on LPR, and has designed a distributed fiber temperature and strain sensor. Moreover, the paper has deduced the theoretic expression of simultaneous measurement of temperature and strain. The performance of the sensor has been analyzed thoroughly, and the measurement accuracy, dynamic range and spatial resolution of the sensor have been formulated and numerically evaluated. The sensor could obtain a temperature resolution of 1 °C and a strain resolution of 100 \( \mu \text{e} \), which benefits from the advantages inherent to both microwave heterodyne detection and Brillouin spectrum scanning in electric domain.

References