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Simultaneous temperature sensing using distributed cascading fiber Bragg grating-based single-ended Brillouin optical time-domain analyzer

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Abstract

We report a novel method of simultaneous distributed temperature sensing in optical fibers. The method is based on the cascading fiber Bragg grating (FBG) single-ended Brillouin optical time-domain analyzer (BOTDA). This proposal applies the technology of cascading FBGs to improve the signal-to-noise ratio of the single-ended BOTDA. Experimental results show achievement of a 50 km sensing range with 3 °C temperature resolution and 5 m spatial resolution.

Keywords: fiber optics, fiber optics sensors, stimulated Brillouin scattering, nonlinear optics

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, Brillouin scattering-based optical fiber sensors have brought advantages of electromagnetic immunity, stable chemical properties and radiation interference resistance abilities, increasing their popularity in many engineering applications such as distributed strain and temperature measurement [1–7]. Brillouin scattering-based optical fiber sensors have four main structures, depending on their different functions. These are: Brillouin optical time-domain analyzers (BOTDAs) [8–11]; Brillouin optical time-domain reflectors (BOTDRs) [12, 13]; Brillouin optical frequency-domain analyzers (BOFDAs) [14, 15] and Brillouin optical correlation-domain analyzers (BOCDAs) [16, 17].

At present, most research into long distance optical fiber sensing based on Brillouin scattering is focused on BOTDAs and BOTDRs, and the two techniques are widely used in

applications. BOTDRs based on spontaneous Brillouin scattering have access to only one end of the sensing fiber, but suffer from short sensing distances because of weak spontaneous Brillouin scattering. BOTDAs that are based on stimulated Brillouin scattering (SBS) have the advantage of long sensing distances owing to the relatively intense SBS. However, conventional BOTDA sensors require two light waves propagating in opposite directions through the sensing fiber. This makes sensor installation more complicated or may compromise the use of previously installed optical fibers.

In this paper, we propose a novel approach for simultaneous distributed temperature measurements in optical fibers. Our approach is based on a cascading fiber Bragg grating (FBG) single-ended BOTDA. Experimental results demonstrate that our structure achieves high performance at both temperature and spatial resolutions.

2. Experimental setup

Figure 1 shows the experimental setup of the proposed cascading FBG-based single-ended BOTDA. In this scheme, a



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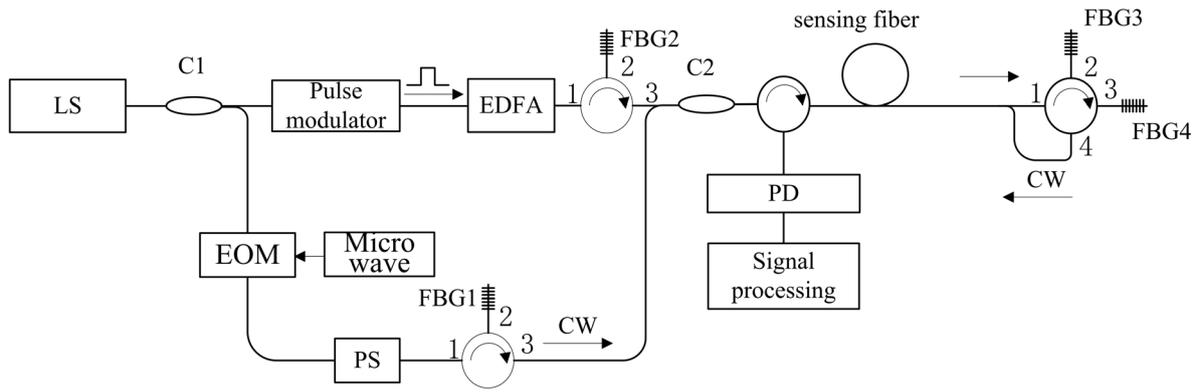


Figure 1. Experimental setup of a 50 km cascading FBG-based single-ended BOTDA.

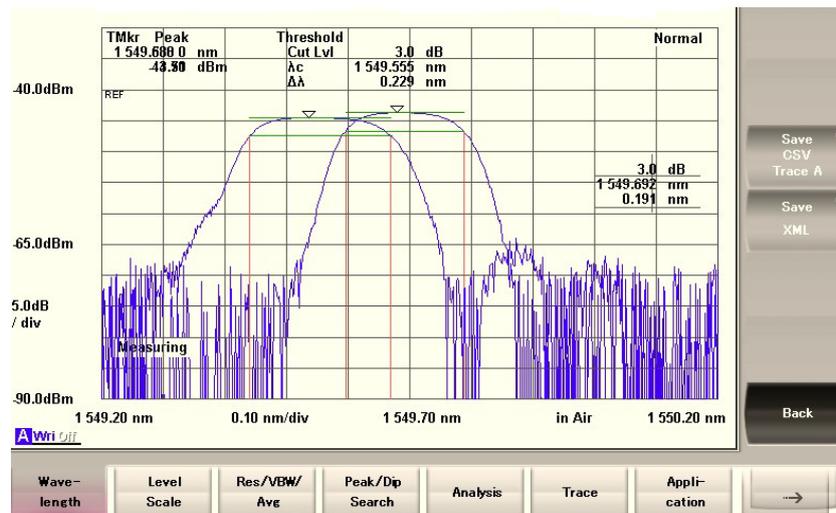


Figure 2. The measured spectra of FBG3 and FBG4.

tunable narrow linewidth (~ 100 kHz) laser source (Agilent HP 81682A) was used as the light source (LS), which operates at a wavelength of 1549.500 nm and with a maximum output power of 16 dBm. The pump pulse duration is 50 ns, which corresponds to a 5 m spatial resolution. The output of the LS is split into two branches using a 50:50 polarization-maintaining coupler (C1). One of the branches is modulated by a pulse modulator to generate pump pulses. The pulse modulator is controlled by an electro-optic modulator (EOM) with a high extinction ratio of 50 dB and an acousto-optic modulator. An erbium-doped fiber amplifier (EDFA) is used to amplify the pump pulses' peak power to 20 dBm. Then, an FBG filter (FBG2) is employed to filter out the amplified spontaneous emission noise emitted from the EDFA. In the other branch, a continuous counter-propagating Stokes wave is generated by the EOM, driven by a microwave generator to generate a two probe sideband signal (suppressed carrier) with 11 GHz frequency shift around the laser wavelength. Two probe sidebands are fixed to the same power level, -20.3 dBm, to prevent nonlocal effects. A polarization scrambler (PS) is used to depolarize the probe signal and to avoid polarization-induced fluctuations in the Brillouin gain. FBG1 is used to select the low-frequency probe sideband only (Stokes frequency). The two optical beams are together launched into the front-end of

the fiber via a coupler (C2), and transmitted to the sensing fiber through a circulator.

In the receiver block, the signals pass through the circulator (port 1) and are directed into a cascading tunable narrowband FBG filter, which is combined with the FBG3 (port 2) filter (centered at 1549.555 nm, with a 3 dB bandwidth of ~ 0.229 nm) and the FBG4 (port 3) filter (centered at 1549.500 nm, with a 3 dB bandwidth of ~ 0.191 nm). The measured spectra of FBG3 and FBG4 are shown in figure 2. The LS operates at the wavelength of 1549.500 nm, and the pump light's wavelength is in FBG3's 3 dB bandwidth. Probe light is driven by a microwave generator with 11 GHz frequency shift around the laser wavelength. Therefore, its wavelength is in FBG4's 3 dB bandwidth. Then, the cascading tunable narrowband FBGs filter the reflection of the pump light and reflect the probe light (port 4). Compared with a single FBG, these two cascading FBGs have a narrower bandwidth in order to filter the reflection of the pump light more efficiently and improve the accuracy of measurement. Finally, the probe light after SBS along the sensing fiber is received by a photoelectric detector with 2 GHz sampling, and processed by a fast signal processing system to obtain the distribution of the Brillouin frequency shift (BFS) and the temperature information along the fiber.

3. Experimental results and discussion

In order to verify the performance of the proposed novel method, we design a proof-of-concept experiment setup (shown in figure 1 and explained in the previous section). A 50 km long sensing fiber is used in the experiments. The testing section (about 20 m) of the sensing fiber at the far end is put in hot water (60 °C temperature) in an ambient temperature-controlled climatic chamber at 24 °C. The cascading FBGs are placed at the end of the ~50 km sensing fiber. The pump pulses' peak power is set at 20 dBm to avoid modulation instability.

In BOTDA sensors, the Brillouin effect is the nonlinear scattering of incident light by the acoustic phonons of the optical fiber, and the spectrum of the scattered light contains key information about strain and temperature along the sensing fiber [18]. SBS is a nonreciprocal process of energy transfer from the high-power pump to the probe wave when the BFS is equal to the frequency difference between pump and probe wave [19]. The velocity of the acoustic wave determines the BFS. Temperature or strain may change the velocity of the acoustic wave. The BFS is in proportion to the strain or temperature. The linear relationships between BFS and strain or temperature are given as:

$$\nu_B(\varepsilon) = \nu_B(\varepsilon_r) [1 + C_\varepsilon(\varepsilon - \varepsilon_r)] \quad (1)$$

$$\nu_B(\Omega) = \nu_B(\Omega_r) [1 + C_\Omega(\Omega - \Omega_r)] \quad (2)$$

where ε_r is the reference strain, Ω_r is the reference temperature, C_ε is the strain coefficient, C_Ω is the temperature coefficient, $\nu_B(\varepsilon_r)$ is the Brillouin frequency of the reference strain, $\nu_B(\varepsilon)$ is the BFS induced by strain, $\nu_B(\Omega_r)$ is the Brillouin frequency of the reference temperature, and $\nu_B(\Omega)$ is the BFS induced by temperature. The two above equations can also be expressed as:

$$\Delta\nu = C_{\nu\varepsilon}\Delta\varepsilon + C_{\nu\Omega}\Delta\Omega \quad (3)$$

where $C_{\nu\varepsilon}$ is the frequency shift coefficient of strain (approximately 0.0483 MHz/ $\mu\varepsilon$), $C_{\nu\Omega}$ is the frequency shift coefficient of temperature (approximately 1.10 MHz K⁻¹), $\Delta\varepsilon$ is the variation of the strain, and $\Delta\Omega$ is the variation of the temperature. From equations (1)–(3), it is shown that temperature and strain have a similar effect on the BFS.

Figure 3 shows the measured BFS profile along the 50 km sensing fiber. The resulting trace is obtained after averaging 4000 times at different distances. The modulation frequency is 10.796–10.868 GHz and a 12 MHz scanning step is applied. The continuous pump power depletion over the fiber is negligible in the measurement scenario. Therefore, the BFS along the fiber can be obtained under good evaluation conditions. By fitting the measured Brillouin gain spectrum (BGS) at each position along the fiber with Lorentzian curves, the BFS along the fiber can be obtained. The measured relative backscattered power versus distance is shown in figure 4. The frequency shift is 10.796 GHz. The curve shows the results after 4000 times of cumulative average processing. The detecting signal from the beginning to 50 km is the SBS along the sensing fiber, and the rest of the curve represents the noise. We can see

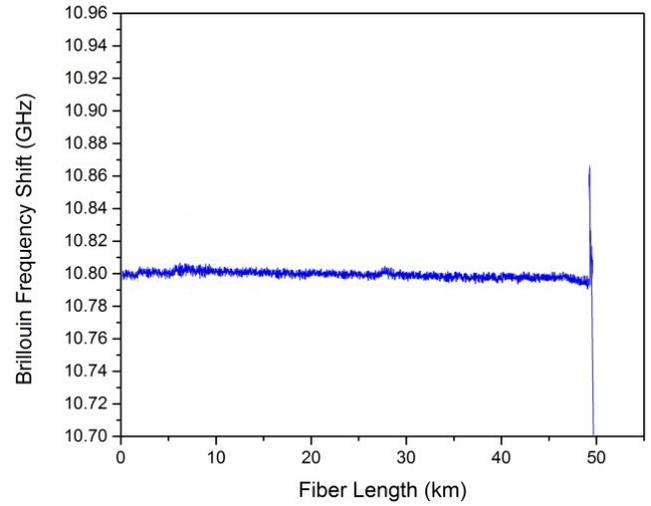


Figure 3. The measured BFS versus the fiber length.

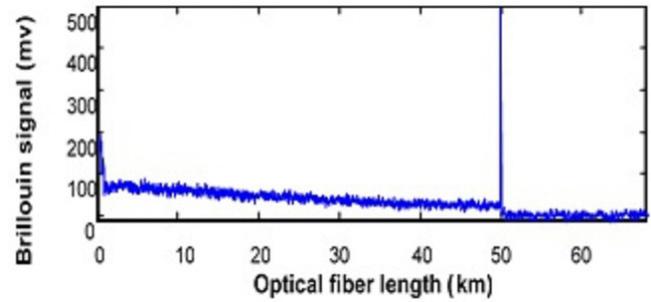


Figure 4. The Brillouin signal when the modulation frequency is at 10.796 GHz.

that the peak dynamic range of the system is about 500 mV, which corresponds to a sensing length of ~50.0 km.

Owing to the linear relationship between the BFS and temperature or strain, the temperature and strain information along the optical fiber can be used to make long range and distributed measurements. The interaction between Stokes light and pump light follows the two steady-state coupled intensity SBS equations:

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha I_s \quad (4)$$

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha I_p \quad (5)$$

where I_s is the Stokes light intensity, I_p is the pump light intensity, α is the fiber loss coefficient, and g_B is the Brillouin gain coefficient, which is related to the optical fiber material and the BFS:

$$g_B(f_m, z) = \frac{\gamma(z) g_{B0}}{1 + \left[\frac{f_m - \nu_B(z)}{\Delta\nu_B/2} \right]^2} \quad (6)$$

where g_{B0} is the peak value, $\nu_B(z)$ is the local BFS, f_m is the frequency offset, $\Delta\nu_B$ is the full-width at half-maximum of the BGS, and $\gamma(z)$ is the polarization factor which depends on the polarization state of the two beams.

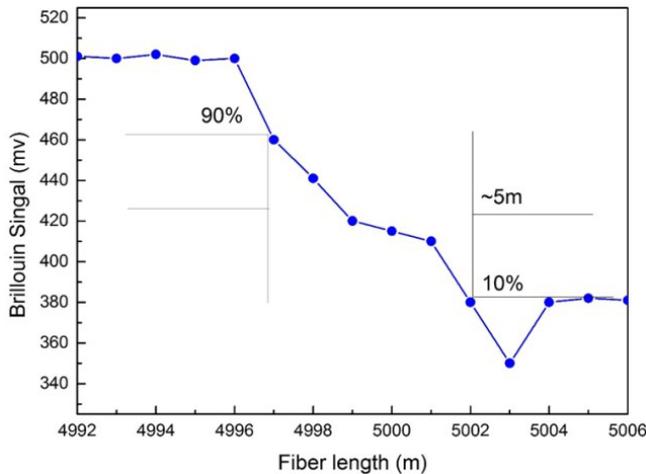


Figure 5. BFS versus distance near the end of the fiber.

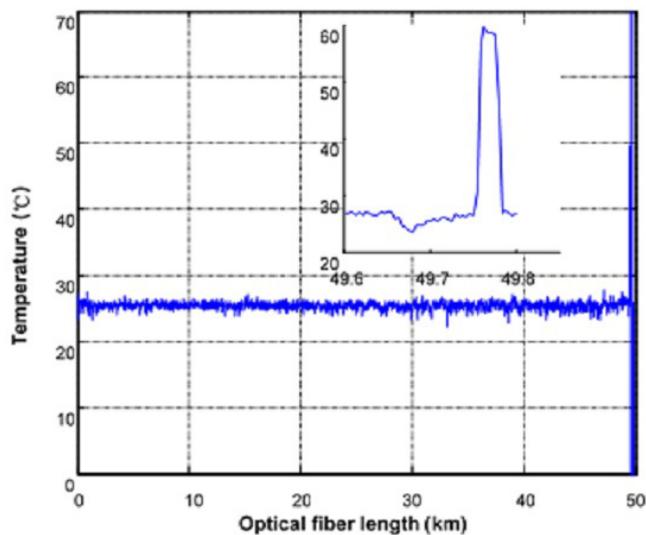


Figure 6. Temperature curve of the 50 km sensing fiber.

A 5 m spatial resolution is achieved, which is defined as 10%–90% of the rise/fall transition region edge on the Brillouin photon counts. As shown in figure 5, the experimental spatial resolution is 5 m under the 50.0 km sensing length, which is in consonance with the 50 ns pulse width we used.

The measured dependence of fiber length on temperature is shown in figure 6. In the calculation of temperature, we use temperature sensor DS18B20 to measure at a room temperature of 24 °C as the sensor fiber BFS reference; the temperature fluctuations do not exceed 3 °C. The results show that the proposed cascading FBG-based single-ended BOTDA sensor can be effectively applied to temperature-distributed measurements. The signal-to-noise ratio can be improved by increasing the number of times of cumulative average, but the measurement time would be relatively longer.

4. Conclusion

In conclusion, we have proposed and experimentally demonstrated a new method of simultaneous distributed temperature sensing in optical fiber sensors. Compared with the traditional BOTDA, the fabrication of the fiber sensor was simplified. Benefiting from the proposed optical structure, the proposed scheme achieves 5 m spatial resolution and 3 °C temperature resolution over a 50 km fiber. The sensing length can be further extended if the probe pulse power increases to the allowable power without causing nonlinear effects in the fiber, and the spatial resolution can be further improved by using a narrower probe pulse.

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