OPTOELECTRONICS LETTERS Vol.14 No.2, 1 March 2018

A performance enhanced Rayleigh Brillouin optical time domain analysis sensing system[*]

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(Received 7 November 2017; Revised 15 December 2017)

Aiming at the problem of large fading noise in Rayleigh Brillouin optical time domain analysis system, a wavelength scanning technique is proposed to enhance the performance of the temperature sensing system. The principle of the proposed technique to reduce the fading noise is introduced based on the analysis of Rayleigh Brillouin optical time domain analysis system. The experimental results show that the signal-to-noise ratio (*SNR*) at the end of optical fiber with length of 50 m after 17 times wavelength scanning is 5.21 dB higher than that with single wavelength, the Brillouin frequency shift (*BFS*) on the heated fiber with length of 70 m inserted at the center of sensing fiber can be accurately measured as 0.19 MHz, which is equivalent to a measurement accuracy of 0.19 °C. It indicates that the proposed technique can realize high-accuracy temperature measurement and has huge potential in the field of long-distance and high-accuracy sensing.

Document code: A **Article ID:** 1673-1905(2018)02-0084-4
DOI https://doi.org/10.1007/s11801-018-7241-8

In a Brillouin optical time domain analysis (BOTDA) system, a pump wave and a probe wave propagate in opposite directions along optical fiber, and when the frequency of probe wave lies within the Brillouin spectral range, stimulated Brillouin scattering (SBS) interaction occurs, and the probe wave experiences an amplification (or attention)[1]. Although the traditional BOTDA system has the advantages of high signal-to-noise ratio (*SNR*) and long sensing distance, the requirement for two-ended structure makes it inconvenient for large scale structural health monitoring (SHM), in addition to the case that the signal will become unavailable if there is a break on the fiber. To solve the problem, single-ended structure BOTDA systems were proposed[2-7]. M. Nikles et al[2] proposed a single-ended structure BOTDA sensing system by employing the Fresnel reflection of fiber end as probe wave in 1996. After that, some similar structures were proposed and demonstrated experimentally[3-6]. However, the Fresnel reflection at the end of fiber is directly related to the condition of the end face of the fiber, such as the cleanness of the end face and with or without a connector, which has a great influence on the measurement. Therefore, in the harsh environment of SHM, the achievable performance of the Fresnel reflection based single-ended BOTDA system is limited.

In 2011, Q. Cui et al[7] demonstrated a single-ended structure BOTDA sensing system in which the Rayleigh backscattered light in fiber is used as probe light. Rayleigh BOTDA sensing system can be operated even when the sensing fiber gets broken and is not affected by the end face condition of fiber. Therefore, the Rayleigh BOTDA system has the unique advantages of non-destructive measurement, single light source and single-ended work. However, compared with the traditional BOTDA system, the probe light in Rayleigh BOTDA system is much smaller, which leads to small signal and low *SNR*. Among the noises contained in the system, the fading noise is generated by the interference between the Rayleigh backscattered lights in fiber, which is essentially signal-induced noise and can not be effectively reduced by the commonly used signal averaging, thereby causing amplitude fluctuation on the backscattered trace. In order to reduce fading noise, some methods have been proposed in coherent optical time domain reflectometry and coherent optical frequency domain reflectometry[8-16] for characterization and fault location of optical fiber transmission system, but few studies have been done in the field of distributed sensing[17]. Wavelength scanning can reduce the number of scattering signals between which strong phase correlations are retained, so the fading noise can be reduced.

To reduce the fading noise, we propose a wavelength scanning Rayleigh BOTDA temperature sensing system, which can improve the *SNR* and achieve a higher

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[*] This work has been supported by the National Natural Science Foundation of China (No.61377088), the Natural Science Foundation of Hebei Province of China (Nos. E2015502053 and F2015502059), and the Fundamental Research Funds for the Central Universities (No.2016XS104).

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measurement accuracy. The principle of Rayleigh BOTDA system is conducted, the characteristics and reduction method of fading noise are discussed, and an experimental setup for Brillouin signal measurements with Rayleigh BOTDA system using single wavelength or 17 times wavelength scanning is constructed. Finally, we compare the performance of Rayleigh BOTDA systems employing single wavelength and 17 times wavelength scanning.

The principle of Rayleigh BOTDA system is illustrated in Fig.1. The continuous Stokes light and the pulsed light enter into the sensing fiber in sequence. Here, the Rayleigh backscattering light produced by continuous Stokes light acts as the probe light, while the pulsed light acts as the pump light. The probe light and pump light excite the SBS interaction in the sensing fiber when the frequency of probe light falls into the Brillouin gain spectrum, and maximum SBS interaction occurs when the optical frequency difference between probe light and pump light is equal to the Brillouin frequency shift (*BFS*) v_B of fiber. The frequency of probe light is down-shifted from the frequency of pump light by v_m that is tunable in the vicinity of the *BFS*, and the probe light acting as the Stokes wave experiences an SBS gain. The Rayleigh backscattering light signal carrying the SBS information can be represented as

$$E_R(t)=E_R\cos\left[2\pi v_R t+\varphi_R(t)\right]H_{SBS}(v,z), \tag{1}$$

where E_R is the optical field intensity of the Rayleigh backscattering light produced by continuous Stokes light, v_R is the frequency of Rayleigh backscattering light, $\varphi_R(t)$ is the phase of Rayleigh backscattering light at time t, and $H_{SBS}(v, z)$ is the SBS transfer function.

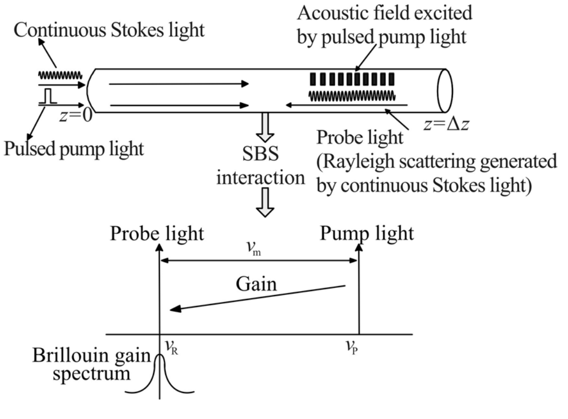


Fig.1 Schematic diagram of Rayleigh BOTDA system

A photodetector (PD) is used to detect the probe light, and the produced photocurrent of it can be expressed as

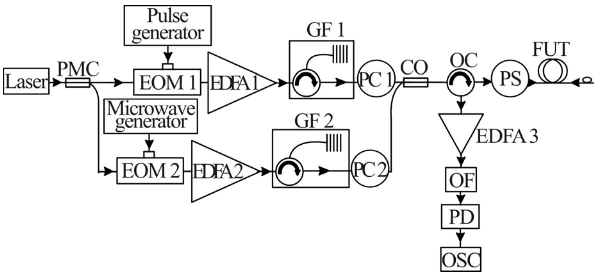
$$i=R\left|E_R(t)\right|^2\approx\frac{1}{2}E_R^2H_{SBS}^2(v,z), \tag{2}$$

where R is the responsivity of PD.

Fading noise mostly results from the interference between the Rayleigh backscattered lights in fiber, including coherent Rayleigh noise (CRN) and polarization fading noise. In Rayleigh BOTDA system, the degree of polarization of Rayleigh backscattering light is one-third of that of the incoming light, which indicates that the Rayleigh backscattering light is partially depolarized in low birefringent fibers[7], thus the polarization fading noise can be neglected approximately in the system. Moreover, due to the SBS amplification on probe light, CRN is more serious in Rayleigh BOTDA system than that in other BOTDA systems, which can decrease the overall *SNR* and thus poses a serious limitation on the achievable measurement accuracy, so it is an urgent problem to reduce the influence of CRN in the sensing system.

Unlike receiver noises, CRN can not be reduced by signal averaging that is commonly used in the reduction of shot noise and thermal noise. CRN is inherent to Rayleigh backscattered radiation and is determined by the relative phase relations of a huge number of backscattered light waves at different locations in the fiber[14]. When the wavelength of laser is changed, an independent backscattered signal with different phase relations is obtained. Thus, by changing enough wavelengths of laser, a large number of independent signals can be generated, which can reduce the number of scattering signals between which strong phase correlations are still retained. So the fading noise can be reduced by scanning the optical wavelength of the laser source.

The experimental setup of wavelength scanning Rayleigh BOTDA sensing system is shown in Fig.2. The laser with a linewidth of ~100 Hz and an output power of 16 dBm operates at 1 549.66—1 549.82 nm. The output of laser source is divided into two branches by a 20:80 polarization-maintaining coupler (PMC). The upper branch with 20% output is modulated into pulsed pump light by an electro-optic modulator 1 (EOM1) with high extinction ratio of 40 dB, controlled by a pulse generator. Then the pump pulses are amplified by an Erbium doped fiber amplifier 1 (EDFA1), and a Bragg grating filter1 (GF1) with a central wavelength of 1 549.686 nm and a bandwidth of 0.236 nm is used to filter out the amplified spontaneous emission noise (ASEN). The lower branch with 80% output is modulated into two sidebands (Stokes and anti-Stokes light) of continuous light by EOM2 that is operated in the suppressed carrier regime and driven by a microwave generator, and the modulating frequency of EOM2 is in the vicinity of the *BFS* of the fiber under test (FUT). These two modulated sidebands are amplified by EDFA2, and a GF2 with a central wavelength of 1 549.889 nm and a bandwidth of 0.35 nm is used to filter out the anti-Stokes light and ASEN. The polarization controller 1 (PC1) and PC2 inserted into the two branches are respectively used to adjust the light polarization to ensure the minimum polarization fading before the pump pulse and continuous Stokes light are entered into the optical coupler (CO). Then the CO's output is inputted into the FUT through an optical circulator (OC), and a polarization scrambler (PS) is employed to reduce the polarization fading of SBS before the pump pulse and continuous Stokes light are launched into the FUT. The backscattered Stokes component is amplified by EDFA3 to a desired power and extracted by an optical filter (OF) with tunable wavelength and bandwidth. Then the Stokes component is detected by a direct current (DC)-1 GHz PD and displayed by a 1 GHz oscilloscope (OSC).



PMC: polarization-maintaining coupler; EOM: electro-optic modulator; EDFA: erbium doped fiber amplifier; GF: Bragg grating filter; PC: polarization controller; CO: optical coupler; OC: optical circulator; PS: polarization scrambler; FUT: fiber under test; OF: optical filter; PD: photodetector; OSC: oscilloscope

Fig.2 Experimental setup for wavelength scanning Rayleigh BOTDA sensing system

In the experiment, the FUT is a standard single-mode fiber (SMF) G.652D with a total length of about 1.97 km. Thereinto, 70-m-long SMF is spliced at the center of 1.9-km-long SMF and placed in a thermostatic water bath with a temperature of 50 °C, and a knot is tied up at the end of the fiber in order to minimize the impact of Fresnel reflection. At the room temperature of 38.8 °C, the *BFS* of fiber is measured to be about 10.852 GHz. The pump pulse is with a width of 130 ns and a power of 23 dBm, and the continuous Stokes light is set to be 6 dBm. The frequency of microwave generator is changed from 10.800 GHz to 10.910 GHz with a step of 5 MHz, and the sampled Rayleigh backscattered signals is averaged 65 536 times to improve the *SNR*.

In the experiment, the wavelength of the laser is operated in the range from 1 549.66 nm to 1 549.82 nm, and is scanned with an interval of 0.01 nm, so that 17 backscattered signals with different wavelengths can be achieved.

As mentioned above, fading noise mostly results from the interference between the Rayleigh backscattered lights in fiber. The obtained three dimension (3D) amplitude spectrum with single wavelength and the averaged 3D spectrum at 17 scanned wavelengths in Rayleigh BOTDA system are shown in Fig.3. It can be seen from Fig.3 that the amplitude fluctuation with 17 times wavelength scanning is much smaller than that with single wavelength. In order to illustrate the increase of *SNR* with wavelength scanning, the Brillouin amplitude distribution at the frequency of 10.850 GHz with wavelength scanning number of *n* (*n*=1, ..., 17) are analyzed.

In order to clarify the relationship between the number of wavelength scanning and system *SNR*, the *SNR* is obtained by the linear fitting of the measured Brillouin time domain signals on the 50-m-long fiber near the fiber end at the frequency of 10.850 GHz. The *SNR* values under *n* (*n*=1, ..., 17) times wavelength scanning are showed in Fig.4. In Fig.4, the *SNR* is firstly increased rapidly with the increase of wavelength scanning number, and then it is slowly increased when the number of wavelength scanning increases to 6. It can be obtained that the root mean square error values with 17 times wavelength scanning and single wavelength are 0.000 943 and 0.003 124, respectively. According to the *SNR* formula $R_{SN}=V^2/\sigma^2$ in which V is the signal voltage and σ is the standard deviation of noise, the *SNR* with 17 times wavelength scanning is 5.21 dB higher than that with single wavelength.

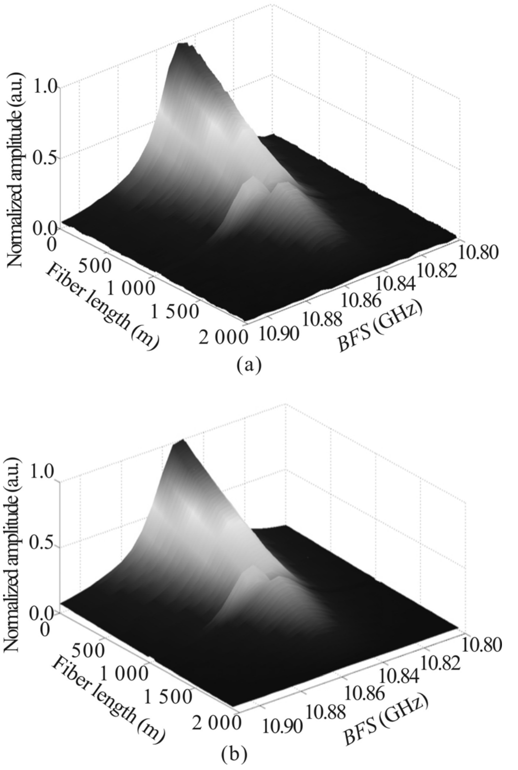


Fig.3 3D amplitude spectra in Rayleigh BOTDA system with (a) single wavelength and (b) 17 times wavelength scanning

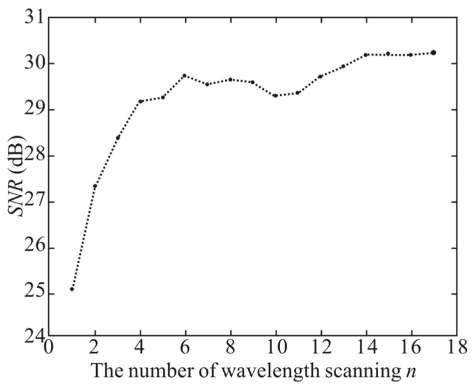
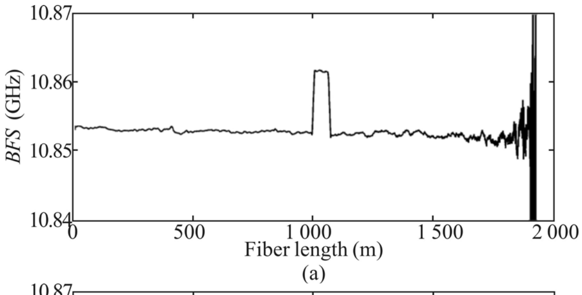
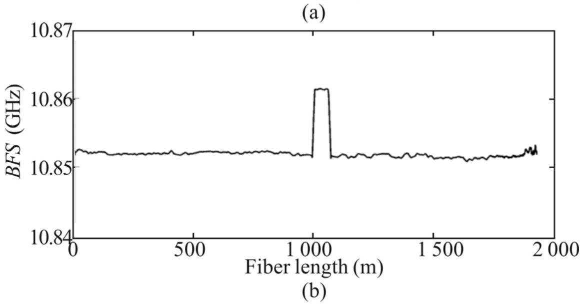


Fig.4 *SNR* versus the number of wavelength scanning *n* (*n*=1, ..., 17)

According to the analysis of the obtained Brillouin time domain signal, the *SNR*s near the end of optical fiber with length of 50 m under *n* (*n*=1, ..., 17) times wavelength scanning are obtained. To further illustrate the performance of the sensing system, *BFS* distribution along the entire sensing fiber with single wavelength and 17 times wavelength scanning are acquired by fitting the measured spectra with a Lorentzian curve, as shown in Fig.5. It can be clearly seen that the *BFS* distribution has a large deviation near the fiber end in single wavelength system. However, through 17 times wavelength scanning, the *BFS* can be accurately measured, as shown in Fig.5(b). Taking the fluctuation of *BFS* on the heated section as the temperature measurement accuracy, the temperature measurement accuracy can be enhanced from 0.34 °C to 0.19 °C, because the frequency fluctuation on the 50-m-long fiber of the heated section is reduced from 0.34 MHz to 0.19 MHz when single wavelength and 17 times wavelength scanning are used in sequence. It can be concluded that wavelength scanning sensing system can effectively enhance the *SNR* and improve the measurement accuracy.



(a)



(b)

Fig.5 *BFS* distribution along the sensing fiber in Rayleigh BOTDA system with (a) single wavelength and (b) 17 times wavelength scanning

In order to reduce the fading noise and enhance the system's performance, a Rayleigh BOTDA sensing system using wavelength scanning is proposed. We analyze and compare the Brillouin time domain signals near the fiber end and the *BFS* distributions along the whole fiber under wavelength scanning. The results show that the *SNR* with 17 times wavelength scanning is 5.21 dB higher than that with single wavelength, and the *BFS* distribution along the sensing fiber can be accurately measured with 17 times wavelength scanning. Through 17 times wavelength scanning, the temperature measurement accuracy can be enhanced to 0.19 °C, which indicates that the proposed technique can realize high-accuracy temperature sensing. Thus, the proposed technique can improve the *SNR* and achieve high-accuracy temperature measurement, which may lead to a performance-enhanced distributed sensor and new applications.

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