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Performance improvement of BOTDR system using wavelength diversity technique

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ABSTRACT

In this paper, a novel technique was proposed to improve the sensing performance by employing wavelength diversity in Brillouin optical time domain reflectometry (BOTDR). This technique enables to maximize the launch pump power to achieve a higher measurement accuracy, without activating the nonlinear effects, which limit the conventional BOTDR performance. Experimentally, we have demonstrated the proposed technique, that provides measurement accuracy improvement of 3.6 times at far end of the sensing fibre compared to the conventional BOTDR system.

Keywords: Brillouin scattering, Brillouin optical time domain reflectometry (BOTDR), wavelength diversity.

1. INTRODUCTION

Brillouin optical time domain reflectometry (BOTDR) [1] can be used for simultaneous measurement of strain and temperature based on spontaneous Brillouin scattering. On the other hand, Brillouin optical time domain analysis (BOTDA) [2] is introduced based on stimulated Brillouin scattering (SBS). The BOTDA system requires access to the both ends of the sensing fibre with complex system implementation. Whereas, the BOTDR features with simple implementation schemes and only requires access to the single end of the sensing fibre.

In Brillouin based distributed fibre sensors, the strain and temperature measurement accuracies are determined by the signal-to-noise ratio (SNR) at a given location. The SNR depends on the injected pump power, sensing fibre length and total fibre attenuation. In the conventional BOTDR, the SNR can be improved by increasing the input pump power and local oscillator reference signal power. However, the local oscillator signal power is strong enough, thus the SNR is no longer dependant on the reference signal power [3]. On the other hand, the launching pump power in the BOTDR system is limited by the non-negligible nonlinearities in the sensing fibre, typically called SBS [4]. The accuracy of strain/temperature measurements will be degraded by the occurrence of unwanted nonlinearities. If the launch power is above the threshold power, the nonlinear effects will distort the backscattered traces and pump depletion, hence reduces the system performance. Several techniques have been proposed to improve the SNR of the BOTDR, such as Raman amplification [5] and pulse coding [6] techniques.

In this paper, we propose a novel technique with simple implementation of wavelength diversity BOTDR, in which multiple wavelengths are injected into the sensing fibre to improve the SNR, thus achieving a higher measurement accuracy. The multiple wavelength pumps significantly increase the total launched pump power into the sensing fibre beyond the nonlinear threshold level without activating any nonlinear effects. Since, the nonlinear threshold power limit is based on the peak power per wavelength [3]. In order to evaluate the performance of the proposed system, the temperature effects have been measured and compared with those from the conventional BOTDR.

2. PRINCIPLE OF PROPOSED WAVELENGTH DIVERSITY TECHNIQUE

The concept of the conventional BOTDR and our proposed wavelength diversity technique incorporated in the conventional BOTDR are illustrated in Fig. 1 and Fig. 2, respectively. Fig. 1, illustrates the operating principle of conventional BOTDR using a single wavelength. In Fig. 2 of our proposed wavelength diversity technique, three equal pump wavelengths ($N=3$, where N is the number of wavelengths) with the corresponding frequencies of ν_1, ν_2, ν_3 have been considered for generating multiple pump wavelength instead of a single wavelength in the conventional BOTDR system. As shown in Fig.2, the three pump pulses generate three Brillouin gain spectra (BGS), which interact with the corresponding local oscillator signals and each pump wavelength has the same frequency separation ($\Delta\nu$) of 5 GHz as shown in Fig. 2(b). Therefore, at the receiver, the measured Brillouin gain amplitude (which is proportional to the sensor

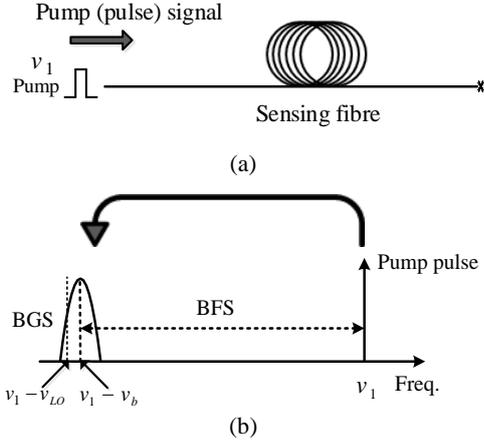


Figure 1. Conventional BOTDR ($N=1$) (a) operating principle (b) Brillouin gain spectrum

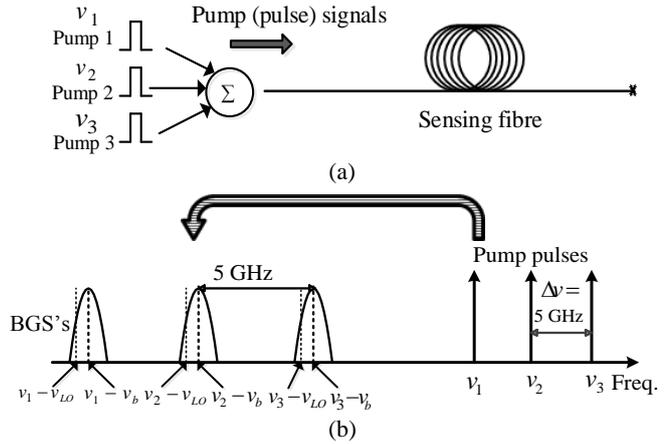


Figure 2. Proposed wavelength diversity BOTDR ($N=3$) (a) operating principle (b) Brillouin gain spectra

amplitude response improvement [7]) will be N (three) times larger than that of the conventional BOTDR, thus the SNR can be increased significantly.

In our proposed technique, the following factors should be taken into account: (i) the number of pump wavelengths are limited by the four-wave mixing (FWM) [8], where FWM will increase significantly with higher number of pump wavelengths, due to small and equal frequency separation. (ii) on the other hand, the use of large frequency separation results a spectrum broadening and an in-effective interference between the BGSs. Although, in our proposed technique, the Brillouin frequency shift (BFS) dependence on pump wavelength is 7.02 MHz/nm [7], the broadening due to the different BGSs of pump wavelengths is basically symmetrical and the centre frequency of overlapped BGS remains unchanged due to the small differences of the pump wavelengths (less than 0.1 nm). The peak BFS and peak Brillouin power can be easily obtained by the Lorentz curve fitting. The SNR of the wavelength diversity BOTDR with N wavelengths can be expressed as follows [8],

$$\text{SNR}_N = \frac{2R_D^2 P_{T_B} P_{T_{LO}}}{(4K_B T / R_L) + (2qR_D P_{T_{LO}} I_d B) + \langle i_{E-noise}^2 \rangle} \quad (1)$$

where R_D is the photodetector responsivity, P_{T_B} is the total peak power of the backscattered Brillouin gain spectra $P_{T_{LO}}$ is the total local oscillator power. In the above denominator, the first term $(4K_B T / R_L)$ and the second term $(2qR_D P_{T_{LO}} I_d B)$ denote the thermal noise and shot noise of the photodetector (PD), respectively. K_B is the Boltzmann constant, T is the photodetector operating temperature in Kelvin, R_L is the load resistance, q is the elementary charge, I_d is the dark current of the photodetector, B is the electrical bandwidth of the photodetector and the term $\langle i_{E-noise}^2 \rangle$ is the power of the electrical noise. Furthermore, in Eq. (1), the P_{T_B} and $P_{T_{LO}}$ can be expressed as,

$$P_{T_B} = \sum_{i=1}^N P_B(i) \text{ and } P_{T_{LO}} = \sum_{i=1}^N P_{LO}(i) \quad (2)$$

$P_B(i)$ is the peak power of the Brillouin gain spectrum of i^{th} pump wavelength and $P_{LO}(i)$ is the peak power of i^{th} local oscillator, respectively. In the proposed technique, each pump wavelength has the same level of power, which is below the SBS threshold. In this technique, the total injected pump power increases significantly without activating nonlinear effects, because the total pump power is spectrally distributed over three wavelengths.

3. PROPOSED SYSTEM EXPERIMENTAL SETUP AND RESULTS DISCUSSION

The experimental setup for the proposed system is illustrated in Fig. 3. Acquisition procedure and data processing remain identical to those of the conventional BOTDR. The major advantage of the proposed technique is that it requires only one laser source to generate three pump wavelengths with simple implementation. A tunable laser source (AQ2200-131) at 1550 nm with a 12 dBm output power is used as a laser source. The single wavelength laser output is modulated by a

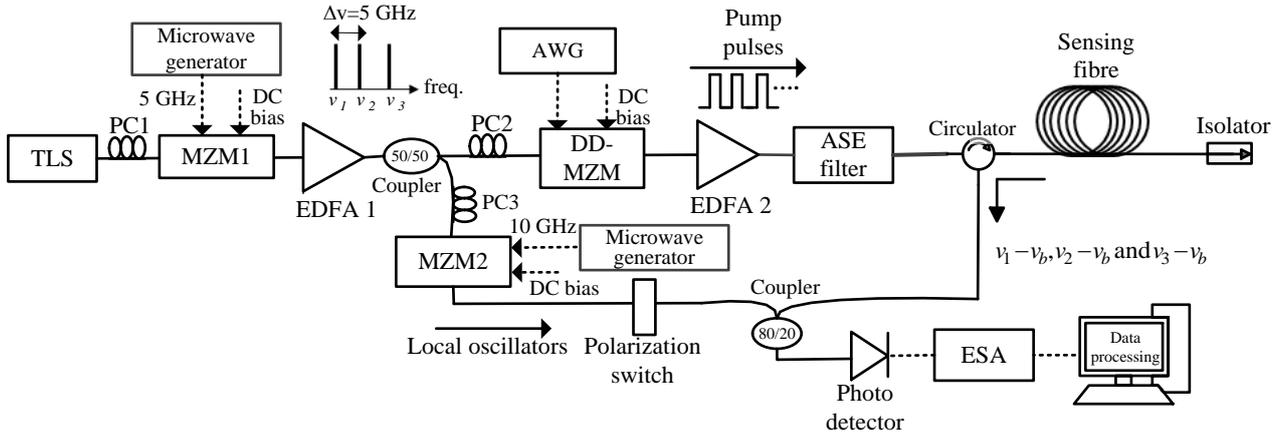


Figure 3. Experimental setup of wavelength diversity BOTDR ($N=3$)

(TLS=tunable laser source, PC= polarization controller, MZM=mach-zehnder modulator, EDFA=erbium doped fibre amplifier, DD-MZM=dual drive-MZM, AWG=arbitrary waveform generator, ASE=amplified spontaneous emission, ESA=electrical spectrum analyzer)

Mach-Zehnder modulator (MZM 1, MXAN-LN-20) driven by an external microwave signal generator at 5 GHz. Tuning the DC bias of the modulator, the three pump wavelengths (carrier and two sidebands) have been set to an equal peak power. The three pump wavelengths were split into two propagation paths using 50/50 coupler, the upper branch signal used for pump and the lower branch signal used for local oscillator signal. The polarization controller (PC) is employed at the input of each MZM to achieve the maximum optical power at the output of the MZMs. The upper branch signal is modulated with a dual-drive MZM (DD-MZM, Covega-40086) to obtain high extinction ratio pump pulses using an arbitrary waveform generator. Subsequently, the output signal is amplified by an erbium doped fibre amplifier (EDFA). The amplified spontaneous emission (ASE) filter is used to eliminate the ASE noise from the EDFA. The peak power of each three pump wavelength same as the single wavelength peak power. The pulse width and peak power of each pump pulse are 100 ns and 17 dBm, respectively. The local oscillator signal modulated by MZM 2, whose frequency was downshifted and upshifted by 10 GHz from the original frequency and the resultant signal consists of six sidebands. A polarization switch was used to compensate the polarization sensitivity. The circulator collects the back scattered signal and beat with the six local oscillator signals, respectively. The beat signal is detected by the PD and analyzed by electrical spectrum analyzer (ESA) in a zero-span mode. The electrical signals from the PD consist summed contribution of BGSs generated by the three pump wavelengths.

The peak frequency Brillouin power traces obtained by the conventional BOTDR and proposed wavelength diversity BOTDR are illustrated in Fig. 4. The improved SNR is 3.92 dB using the proposed technique at the far end of the sensing fibre. The measured BFS distribution along the 10 km sensing fibre in both the systems are shown in the inset of Fig. 4. For both the cases, 2000 trace averages are used with same measurement time. By calculating the standard

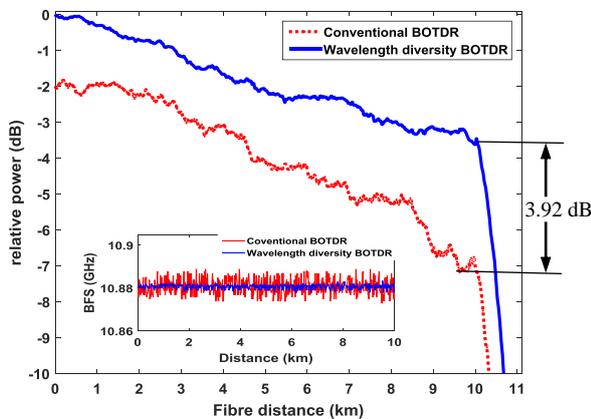


Figure 4. Comparison of peak Brillouin power traces of conventional BOTDR and wavelength diversity BOTDR

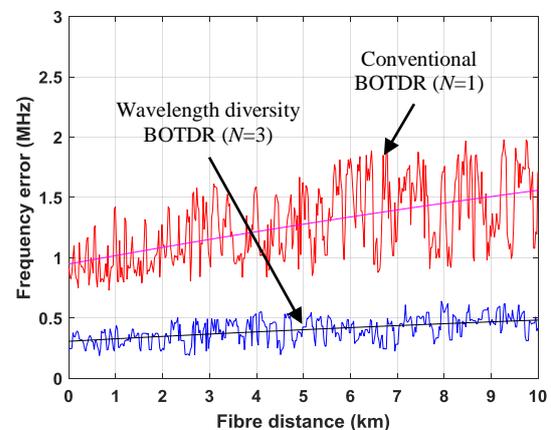


Figure 5. Brillouin frequency error vs. sensing fibre distance of conventional BOTDR and wavelength diversity BOTDR

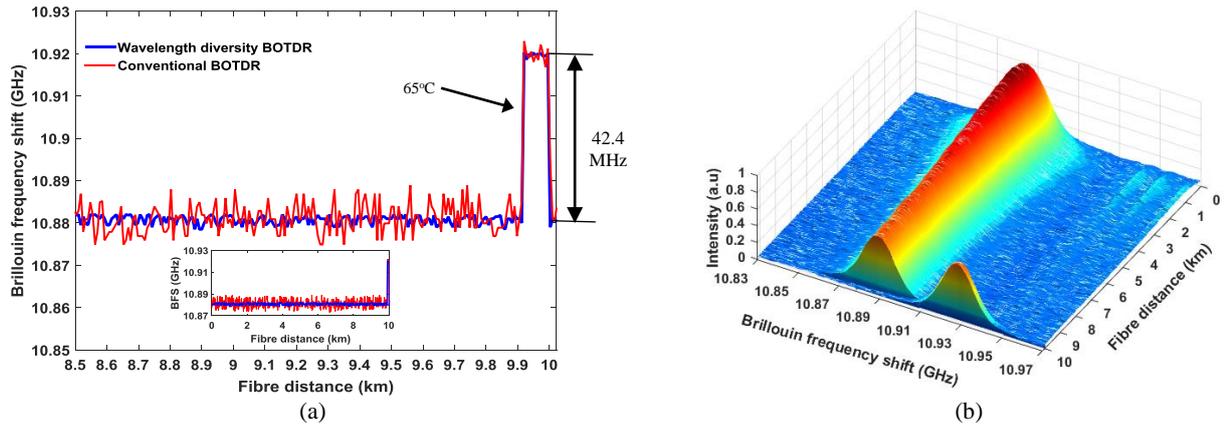


Figure 6. Temperature evaluation in both the systems (a) temperature induced BFSs of 100 m fibre at far end of the fibre (b) Three-dimensional spectrum of proposed wavelength diversity BOTDR

deviation of the measured BFSs at each fibre location, the BFS error along the fibre distance can be obtained, as shown in Fig. 5. As described in [7], the BFS error can be obtained from: $\sigma_v = \sqrt{0.75 \cdot \delta \cdot \Delta\nu_B} / \text{SNR}$, (where δ is the sweep frequency step, 1 MHz and $\Delta\nu_B$ is the Brillouin linewidth, ~ 25 MHz), describes the growth of BFS error is exponentially increases with reducing SNR along the fibre distance. As shown in Fig. 5, at the far end of the fibre, the BFS error of the conventional BOTDR and wavelength diversity BOTDR are 0.45 MHz and 1.52 MHz, respectively.

In order to experimentally evaluate the sensing performance of the proposed system, a 100 m fibre at the far end of the sensing fibre placed in an oven. The rest of the fibre was kept at room temperature (25°C) and strain free. At 65°C , the obtained BFS distributions for both the conventional and wavelength diversity BOTDR are illustrated in Fig. 6(a). In order to obtain three-dimensional spectral mapping, the frequencies were swept from 10.83 GHz to 10.97 GHz, with a frequency step of 1 MHz with 2000 trace averages. The obtained spectrum is shown in Fig. 6(b). The standard deviations of the measured BFSs of 100 m heated section obtained using the conventional BOTDR and wavelength diversity BOTDR are 0.47 and 1.5 MHz, respectively. Therefore, the accuracies of the temperature measurement are 0.39°C and 1.4°C , respectively (the calibration temperature coefficient of the fibre is $1.07 \text{ MHz}/^\circ\text{C}$). This corresponds to the 3.6 times increased measurement accuracy for the proposed technique compared to the conventional BOTDR, which is in a good agreement with an improved SNR of 3.92 dB using the proposed technique [7].

4. CONCLUSION

We proposed and experimentally demonstrated SNR enhancement in a BOTDR system using a wavelength diversity technique. The proposed technique maximizes the launching pump power, hence achieve an improved SNR, while avoiding the unwanted nonlinear effects, which limits the performance of the conventional BOTDR. The wavelength diversity BOTDR is able to provide an enhanced SNR up to 3.92 dB and improved measurement accuracy which is 3.6 times better than that of the conventional BOTDR. In addition, the proposed technique can be effectively combined with other sophisticated pulse coding techniques for further sensor performance improvement.

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