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Simplified single-end Rayleigh and Brillouin hybrid distributed fiber-optic sensing system

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Dear editor,

Distributed fiber-optic sensing (DFOS) technology has been widespread applications in many fields. It is mainly realized by analyzing three kinds of backscattering in optical fibers: Rayleigh, Brillouin, and Raman [1]. Conventionally, the sensing system can only measure one type of parameter: a static one like temperature and strain or a dynamic one like vibration. However, for several applications, such as railway safety monitoring systems, both static and dynamic parameters must be measured simultaneously not only for early warning applications but also for collecting static signals to perform long-term analysis.

In this study, we proposed a simplified hybrid DFOS sensing system based on a single-end Brillouin optical time domain analyzer (BOTDA) and phase-sensitive optical time domain reflectometry (φ-OTDR) to simultaneously measure dynamic [2] and static parameters [3]. The proposed system uses the Rayleigh backscattering (RBS) signal of the probe pulse rather than Fresnel reflection at the fiber end as the probe lightwave. It brings a good result that the system can work successfully even if the sensing fiber breaks. In this system, a pulse pair is injected into the sensing fiber, as the pump pulse of BOTDA follows the probe pulse of φ-OTDR. The continuous RBS lightwave of φ-OTDR will be amplified by the Brillouin pump pulse via stimulated Brillouin scattering (SBS) process when the detuning frequency satisfies the Brillouin frequency shift (BFS) of the sensing fiber. The BFS of fiber is proportional to temperature and strain. The phase of the RBS lightwave can be demodulated to obtain the vibration information, whereas the amplitude of the RBS lightwave is related to static parameters such as temperature and strain. Therefore, vibration information measured by φ-OTDR and static signal measured by BOTDA can be received simultaneously using one signal receiving module. The RBS signal is coherently detected with the help of a polarization diversity scheme (PDS) to remove the effect of polarization fading. The influence of φ-OTDR fading in BOTDA is mitigated using an effective averaging method. The dynamic and static parameters can be measured simultaneously by demodulating the differential phase and the intensity of the RBS lightwave, respectively.

Experimental setup. Figure 1(a) depicts the experimental setup. A narrow-linewidth laser is employed as the light source. The first branch generates the Brillouin pump pulse. An intensity modulator (IM) and an optical bandpass filter (OBPF) are used to produce a frequency-shift around the BFS of sensing fibers. The IM is driven by a voltage-controlled oscillator (VCO). An injection locking module is then used to compensate for the insertion loss of the IM and the OBPF while maintaining the power of the output lightwave stable. A polarization scrambler (PS) is used to mitigate the polarization effect on the stimulated Brillouin scattering process. The second branch generates the probe pulse for φ-OTDR. The two pulses are formed using different acousto-optic modulators (AOMs) and are combined with a 50:50 coupler. An erbium-doped fiber amplifier is used for amplifying the pulses.

The RBS lightwave beats with the local lightwave of the third branch in a PDS, which can almost remove the effect of polarization fading along the sensing fiber. The lightwave of the two different polarization states is converted into electrical signals after being received by two balanced photodetectors (BPDs). The signals are first electrically filtered using electric filters and then recorded by an oscilloscope at a sampling rate of 250 MS/s.

During the experiment, an arbitrary waveform generator (AWG) was used to drive VCO and two AOMs with different frequencies: 200 MHz for AOM1 (used for Brillouin pump pulse) and 80 MHz for AOM2 (used for Rayleigh probe pulse).

The first 9175 m of sensing fiber was coiled around a standard bobbin and placed on the desk at room temperature, the second 5 m was wrapped around a piezoelectric transducer (PZT), and the last 80 m was wound in circles of equal radius and put in a water bath. Brillouin gain spectrum (BGS) along the fiber was obtained with a frequency sweep range of 200 MHz and a sweeping step of 2 MHz.

The width of the Brillouin pump pulse was 50 ns, corre-

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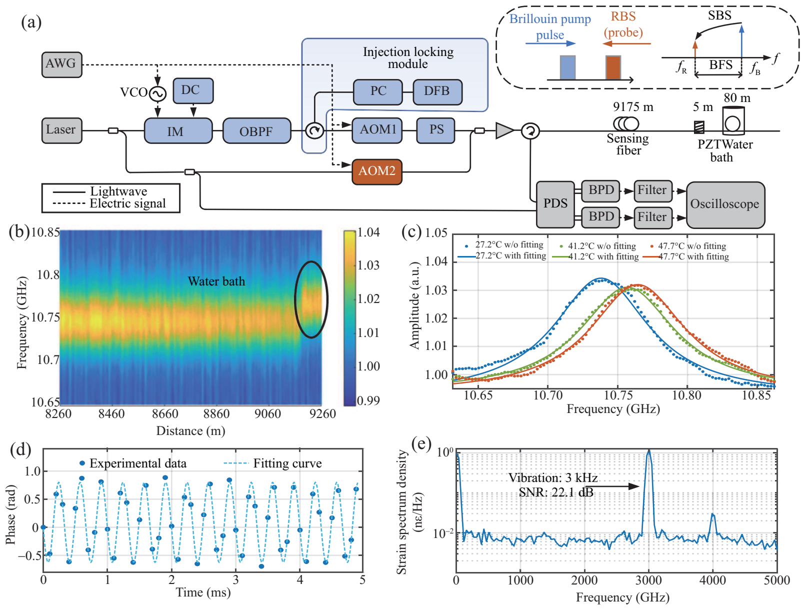

Figure 1 (Color online) Experimental setup and results. (a) Experimental setup. AWG: arbitrary waveform generator, IM: intensity modulator, OBPF: optical bandpass filter, PC: polarization controller, DFB: distributed feedback laser, AOM: acousto-optic modulator, PS: polarization scrambler, PDS: polarization diversity scheme, BPD: balanced photo-detector. (b) BGS along the last 500 m of sensing fiber. (c) BGS at the position of 9182 m when the water temperatures are set to be 27.2°C, 41.2°C, and 47.7°C. (d) Time domain curve of differential phase. (e) Strain spectrum density of differential phase.

sponding to 5 m spatial resolution (SR) in BOTDA, while the width of the Rayleigh probe pulse was 100 ns, corresponding to 10 m SR in the φ-OTDR system.

Results and discussion. The beating signals can be transformed into analytical signals using Hilbert transform, providing real and imaginary parts that are demodulated as the amplitudes and phases of the RBS lightwave [4].

Figure 1(b) depicts the BGS after being normalized, which is the result along the last 500 m fiber when the water temperature is set to be 47.7°C. During the BGS measurement, the influence of vibration is successfully eliminated by 260 averages used during processing.

Figure 1(c) depicts the BGSs measured at the position of 9182 m when the water temperature is varied. The discrete dots represent experimentally measured data, whereas the solid lines represent results after Lorentzian fitting. After linear fitting, the temperature sensing coefficient obtained is 1.08 MHz/°C. The BFS standard deviation of the scheme has an average of 1.38 MHz along the fiber.

The PZT is used to apply vibration and is supplied by a 3-kHz sinusoidal signal to measure vibration. Figure 1(d) shows the result of the measured differential phase, which properly restores the sinusoidal shape of the vibration signal. Figure 1(e) presents the strain spectral density of the measured differential phase at the position of applied vibration, and the signal-to-noise ratio (SNR) is 22.1 dB. The maximal detectable vibration frequency is limited by the fiber length and Nyquist sampling theorem, and frequencies up to 5 kHz can be measured with a fiber length of approximately 10 km.

Unlike conventional, the hybrid system introduces a Brillouin pump pulse to amplify the RBS lightwave to perform the static measurement. Therefore, the Brillouin gain will have a negative impact on the SNR of φ-OTDR. The main one is supposed to be the spontaneous Brillouin scattering (sp-BS) lightwave of the Brillouin pump pulse, whose frequency is close to the RBS lightwave of the probe pulse and can be received by the BPD. The sp-BS noise can be reduced using a fiber with a smaller Brillouin gain coefficient. Moreover, due to the interference, the RBS lightwave has extremely low amplitudes at some positions, called fading positions. Signals at these positions may be lower than sp-BS noise. Therefore, in a hybrid system, BGSs at the fading positions will be difficult to fit due to their poor SNRs, which increases BFS measurement error and decreases measurement accuracy after the Lorentzian fitting. This restriction can be solved by using the average process and passing the signals to a digital bandpass filter to enhance the SNR in fading positions.

Conclusion. A simplified single-end Rayleigh/Brillouin hybrid distributed sensing system is proposed and experimentally demonstrated, which can simultaneously measure static parameters and dynamic parameters by integrating BOTDA for static parameters and φ-OTDR for dynamic parameters. Although there is an interaction between Rayleigh and Brillouin processes, a high-performance hybrid system is realized by carefully designing parameters considering the two kinds of influence.

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