Coherent-detection-assisted BOTDA system without averaging using single-sideband modulated local oscillator signal

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ABSTRACT

A novel setup for coherent-detection-assisted Brillouin optical time domain analysis (BOTDA) is proposed and demonstrated. Performance enhancement is enabled by a power-controllable local oscillator (LO) generated using single-side-band (SSB) modulation. Through employing a commercial coherent receiver and polarization diversity scheme, the Brillouin gain traces carried on a stable intermediate frequency (IF) are obtained in real time without any averaging and processed by digital signal processing (DSP) without the need of ultra-narrow optical band pass filter. A spatial resolution of 4 m and frequency uncertainty of 1.473 MHz are achieved over 40 km sensing range using a single scan.

Keywords: Distributed fiber sensor, stimulated Brillouin scattering, BOTDA, coherent detection, digital signal processing.

1. INTRODUCTION

As one of the most popular distributed optical fiber sensors, Brillouin optical time domain analysis (BOTDA) has attracted enormous research efforts due to its ability of distributed temperature and strain monitoring.[1,2] The performance parameters of a BOTDA system, including spatial resolution, sensing range, and frequency uncertainty, are limited by the signal-to noise ratio (SNR) of the sensor response.[3] In order to enhance the SNR performance of the system, the power of both pump and probe lightwaves need to be increased. However, the peak power of the pump pulse is restricted by fiber nonlinearities, such as modulation instability[4], meanwhile, the power of the probe lightwave is also limited to avoid the non-local effects[5]. To overcome the limitations mentioned above, various techniques have been proposed[6-10]. Among them, coherent detection is an attractive solution for enhancing the SNR performance[8-10] and to enable detection of Brillouin phase information[9]. In the proposed coherent detection schemes, a local oscillator (LO) lightwave is often generated together with the probe, and injected into the fiber under test (FUT). However, for applications with ultra-long sensing range, the power of LO could be insufficient after transmission in the FUT, and will limit the performance of coherent detection. An alternative scheme has been proposed using a separated laser as the LO together with a commercial coherent receiver to allow shot noise dominated performance for better SNR performance of the detected signal. At the same time, the scheme allows filtering of the probe signal to be carried out in electrical domain using DSP. The advantage of this is that the ultra-narrow optical band pass filters at the detector is no longer needed, since controlling the precise alignment of the filter with the probe signal is often a very challenging task in practical BOTDA systems.[10] However, the system suffered from the distortion originating from the drift of relative frequency between the both lasers, which led to the instability of the intermediate frequency (IF) and distortions after electrical and digital filtering.

In this paper, a new configuration of coherent-detection-assisted BOTDA is proposed and demonstrated using single-side-band (SSB) modulation technique to guarantee a stable intermediate frequency carrying the Brillouin signal. Using digital signal processing algorithms, the Brillouin gain traces are recovered from the real-time collected signals without any averaging. The system realizes distributed sensing over 40 km fiber with a spatial resolution of 4 m and frequency uncertainty of 1.473 MHz, with no averaging operation carried out in the process.

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2. EXPERIMENT

2.1 Experiment setup

Figure 1 illustrates the experiment setup of the proposed coherent BOTDA system. The output of a 1550 nm laser is splitted into three branches by a 20/80 and 50/50 coupler. The same as a conventional BOTDA system, the upper and the lower branches in the experiment setup are utilized to generate the pump pulse and dual-sideband probe of the system. In the upper branch, 40 ns pump pulses with extinction ratio of 40 dB are generated by a Mach-Zehnder modulator (MZM1) and a pulse pattern generator (PPG). The erbium-doped fiber amplifier (EDFA) in the branch is used to boost the peak power of the pulses to ~21 dBm, and the following band pass filter with bandwidth of 1 nm is employed to reduce the amplified spontaneous emission (ASE) noise of the EDFA. A polarization switch (PSW), driven by a function generator synchronized with the pump pulses, is used to generate two sequential Brillouin responses orthogonal to each other, to minimize the polarization dependent fluctuation of Brillouin signal. Afterwards, the pump pulses are guided in the fiber under test (FUT). The lower branch produces a dual-sideband probe lightwave with carrier suppressed by over 30 dB. A tunable radio frequency (RF) synthesizer provides the scanning frequencies for the BOTDA. A variable optical attenuator (VOA) is inserted to control the power of each side band to be ~-8 dBm, and an isolator to block the counter-propagating pump lightwave. An IQ modulator and a frequency-fixed RF synthesizer in the middle branch are used to generate a lightwave as local oscillator (LO) using single-side-band (SSB) modulation technique for coherent detection. The carrier is carefully suppressed by over 30 dB and the upper side band is suppressed by up to 40 dB. To be noted, the two RF synthesizers are synchronized with each other to ensure a stable value of the IF. The subsequent EDFA is used to amplify and control the power of LO to ~10 dBm, and a second BPF is used to reduce the ASE noise. The relationship of the three lightwaves in the system are depicted in Figure 2. The probe lightwave and the LO are then injected into a commercial integrated coherent receiver(ICR). The in-phase and quadrature-phase signals of the two orthogonal polarizations are collected by the four channels of a real-time oscilloscope (OSC). A DC-1.3GHz low pass filter at each channel is employed to block the unwanted high frequency components within the beating signals of the probe and the LO lightwaves, i.e., only electrical signals at frequency of $f_{IF} = f_s - f_{LO}$ are collected, as shown in figure 2.

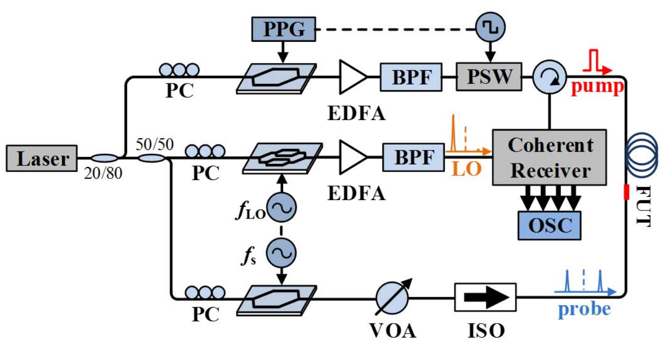

Figure 1. Experiment setup for the coherent-detection-assisted BOTDA system with single-side-band (SSB) modulated local oscillator (LO) light. PC, polarization controller; PPG, pulse pattern generator; EDFA, erbium-doped fiber amplifier; BPF, band pass filter; PSW, polarization switch; OSC, oscilloscope; FUT, fiber under test; VOA, variable optical attenuator; ISO, isolator.

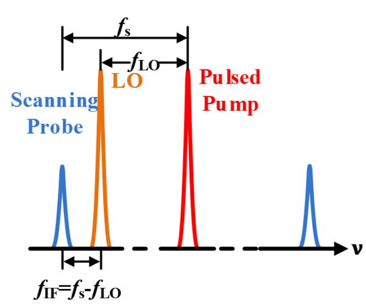

Figure 2. The frequency relationship among the pulsed pump, the dual-side-band probe, and the single-side-band LO.

2.2 Operation and Offline Digital Signal Processing

In our experiment, the fixed RF synthesizer f_{LO} is set as 10 GHz. To reconstruct the distributed Brillouin gain spectrum (BGS), the tunable RF synthesizer f_s is scanned from 10.78 to 10.88 GHz with a scanning step of 1 MHz. Owning to the use of the phase- & polarization-diversity commercial coherent receiver, the beat signal at each frequency by the lower side band of the probe and the LO is obtained by 4 outputs, which can be expressed as: [10]

$$I_x = R\sqrt{\frac{\alpha P_s(t) P_{LO}}{2}}\cos\left[2\pi f_{IF} t + \varphi_{LO} - \varphi_s(t) + \varphi_N\right] \quad (1)$$

$$Q_x = R\sqrt{\frac{\alpha P_s(t) P_{LO}}{2}}\sin\left[2\pi f_{IF} t + \varphi_{LO} - \varphi_s(t) + \varphi_N\right] \quad (2)$$

$$I_y = R\sqrt{\frac{(1-\alpha) P_s(t) P_{LO}}{2}}\cos\left[2\pi f_{IF} t + \varphi_{LO} - \varphi_s(t) + \varphi_N\right] \quad (3)$$

$$Q_y = R\sqrt{\frac{(1-\alpha) P_s(t) P_{LO}}{2}}\sin\left[2\pi f_{IF} t + \varphi_{LO} - \varphi_s(t) + \varphi_N\right] \quad (4)$$

Where P_s, P_{LO} are the power of the lower sideband of the probe and the LO, R is the responsivity of the detector, α is the split ratio of the two polarization components in the receiver, φ_s, φ_{LO}, and φ_N are the lower sideband probe phase, the LO phase, and the phase noise between the two lightwaves, respectively. These four signal traces are acquired by the real-time oscilloscope, and transmitted to the computer for processing. During the DSP process, fast Fourier transform (FFT) is used to transform the signal traces into frequency domain. And a subsequent digital band pass filter with 80 MHz bandwidth, whose center frequency is exactly the same as the IF carrier, is designed and used to extract the desired signal frequency and to remove most of the noise in frequency domain. After transforming back to time domain, the four traces are combined to recover the Brillouin gain trace based on the following relationship: [10]

$$P_s(t) \propto I_x^2 + Q_x^2 + I_y^2 + Q_y^2 \quad (5)$$

At each scanning frequency, due to the use of the polarization switch (PSW), two recovered adjacent periods of Brillouin gain traces triggered by two pump pulses of orthogonal polarizations are utilized to minimize the polarization dependent fluctuation of Brillouin signal.

3. RESULTS

In our experiment, the FUT is a 40.65 km single-mode fiber (SMF) with the last 200 m section placed in an oven. The last section is heated to 40 °C, while the rest of the FUT is kept under room temperature (25 °C). Figure 3 (a) illustrates the BGS distribution versus distance along the whole FUT, and Figure 3 (b) shows corresponding BGS distribution around the last ~2 km, in which the heated section can be observed clearly. Note that no averaging is used in obtaining the BGS, and the sampling rate of the oscilloscope is 3.3 GS/s.

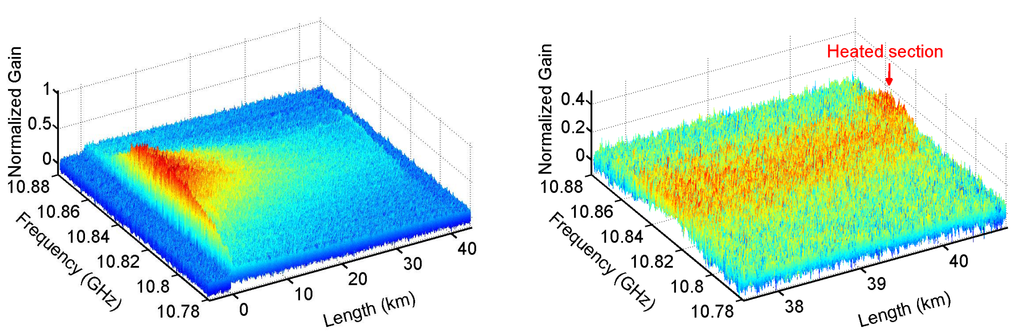

Figure 3. BGS distribution (a) along the whole FUT and (b) around the last ~2 km fiber

By using Lorentzian curve fitting method, the distribution of Brillouin frequency shift (BFS) along the FUT is obtained, which is shown in Figure 4 (a). Figure 4 (b) gives the zoom-in view of the BFS distribution of the last 350 m, and the BFS uncertainty near the fiber end is calculated to be 1.437 MHz. In Figure 4 (c), the BFS transition from the section under room temperature to the heated one is illustrated, which indicates the temperature difference of 15 °C, given the BFS temperature coefficient of ~1 MHz/°C. Figure 4 (c) also implies a spatial resolution of ~4 m, corresponding to 40 ns pump pulse.

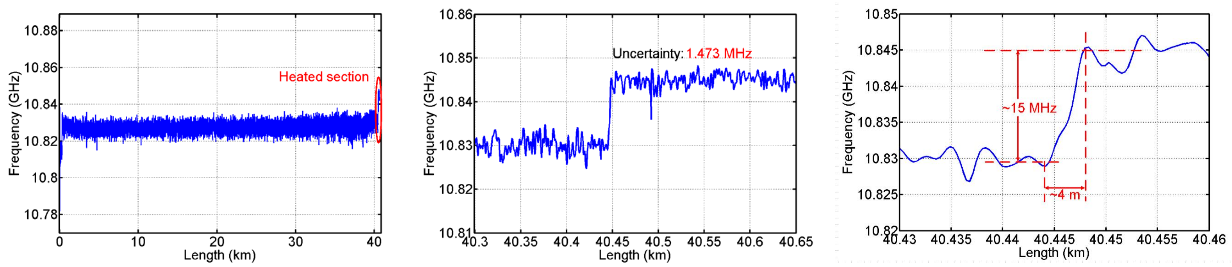

Figure 4. Measured distributed BFS (a) along the whole FUT, (b) zoom-in view of the last ~350 m fiber, and (c) zoom-in view of the transition section.

4. CONCLUSION

We proposed and demonstrated a novel setup for coherent-detection-assisted BOTDA system for performance enhancement of distributed fiber-optic sensing. In the experiment, the LO light for coherent detection is separately generated by modulating the third branch output of the same laser source of a BOTDA system, so that the power of LO and the SNR of the Brillouin signals can be easily controlled and enhanced. Because of the use of SSB modulation, Brillouin signals are carried on a stable IF after the detection by the commercial coherent receiver. Two Brillouin response traces triggered by two orthogonal polarization pump pulses in a serial manner are collected in real time without any averaging for each scanning frequency, and the Brillouin gain traces are processed and demodulated by offline DSP. A spatial resolution of 4 m and BFS uncertainty of 1.473 MHz have been achieved over 40 km sensing range without the need of any averaging. The configuration is promising for real time monitoring of dynamic events using Brillouin distributed sensing systems.

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