BOTDA sensor utilizing digital optical frequency comb based phase spectrum measurement

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***Abstract*—An ultra-fast sweep-free distributed BOTDA sensor is proposed and experimentally demonstrated employing coherent de-modulation of digital optical frequency comb (DOFC) probe signal. The phase shift of each frequency tone induced during the Stimulated Brillouin Scattering (SBS), corresponding to the Brillouin Phase Spectrum (BPS), is simultaneously measured in a single shot without frequency sweeping and averaging. We demonstrate an ultra-fast BOTDA sensor in10km long fiber with the measurement time of 10 μs, which is depending on the time-of-flight of the fiber. The minimum detectable fiber length is 51.2m with a 1.95 MHz frequency resolution among 1 GHz sensing coverage. The BFS uncertainty of our ultra-fast BOTDA using BPS is calculated to be~1.5 MHz near the end of fiber under test (FUT), which is significantly improved by ~50% compared with that using BGS.**

Keywords—Fiber optics sensors; Scattering, stimulated Brillouin; Nonlinear optics

I. Introduction

Distributed Brillouin optical time domain analyzer (BOTDA) has been investigated in depth in recent decades owing to their capability to measure strain and temperature distribution with high precision [1]. However, conventional BOTDA systems is still suffered from slow response speed, which has not been solved well till now. Typically, in conventional BOTDA, more than 100 times of frequency sweep is required between probe and pump signal to interrogate Brillouin amplification characteristics at different positions along the fiber [2-4]. The sweeping process is inevitable to locate the Brillouin frequency shift (BFS) and is rather time-consuming. Several novel schemes have been proposed to improve the measurement speed of BOTDA by avoiding frequency scanning [5-8]. Recently, we demonstrate a scanning-free BOTDA based on digital optical frequency comb (DOFC) featured the capability of single time reconstruction of BGS without any frequency scanning [9].

In this paper, we report an BOTDA sensor based on coherent de-modulation of the phase shift of DOFC probe signal without any frequency scanning and averaging. The basic principle resides in that phase shift of DOFC probe induced during the Stimulated Brillouin Scattering (SBS), after interacting with the counter-propagated pump signal in the fiber under test (FUT) is fully mapped in the electrical domain with coherent detection method. Therefore, no averaging or frequency sweeping is used. As a result, the sensing speed is only limited by the monitoring range. The required sensing time is reduced further without average in addition to avoiding frequency sweep [2].

II. Experiment Setup

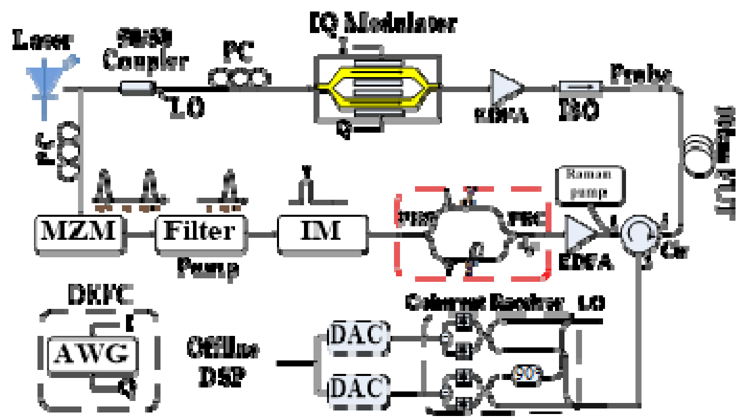

Fig. 1. Experiment setup of scanning-free BOTDA based on polarization-diversity pump. PC: polarization controller; EDFA: erbium-doped fiber amplifier; ISO: isolator; MZM: Mach-Zehnder modulator; IM: intensity modulator; PBS: polarizing beam splitter; PBC: polarizing beam combiner; Cir: circulator; LO: local oscillator; DAQ: data acquisition card; OSC: oscilloscope.

The experimental setup used to demonstrate the proposed sweep-free BOTDA is sketched in Fig. 1. The output of laser source is divided into equal parts by 50/50 coupler to serve as pump and probe signal respectively. The operating wavelength is set at 1550 nm with the linewidth of approximately 100 kHz.

Different from conventional implementation of BOTDA, the optical frequency of pump up-converted to ~11Ghz to excite Brillouin effects. At first, a Mach-Zehnder modulator

(MZM) biased at minimum power level is used to generate double-sideband signal with the RF port driven by a synthesizer running at the frequency around the BFS. As the modulator is polarization sensitive, a polarization controller (PC) is inserted to adjust the input polarization of signal while maintain high modulation efficiency. Then the high frequency sideband, corresponding to short wavelength, is selected by a narrow optical bandwidth filer. In the experiment, a Fiber Bragg grating (FBG) with 3dB bandwidth of 10Ghz is used as the optical signal filter. The power of residual sideband is 2 orders lower than the required one. Then the up-converted pump signal is modulated by intensity modulator (IM). Driven by an electrical pulse generator, optical pulse train with the duration length of 100ns and period of 12us is formed. The IM allows shaping high extinction ratio optical pulses (~40 dB). Then polarization multiplexed pump signal is generated using the following setup to suppress the polarization induced noise. The generated optical pulse is adjusted by PC to guarantee an equal splitting after polarizing beam splitter (PBS) with orthogonal polarization state. X/Y polarization is delayed by 100ns before recombined in the subsequent polarizing beam combiner (PBC). At last, generated polarization multiplexed pump pair is directed into the FUT via a circulator. The average power of pump is set at 0 dBm using an erbium-doped fiber amplifier (EDFA).

In the opposite direction, the optical signal is divided further with another 3dB coupler for probe and local oscillator (LO), respectively. With this arrangement, laser frequency difference between LO and prove could be largely avoided which is beneficial for the post signal processing. DOFC probe signal is generated using an IQ modulator while the in-phase and quadrature RF port is driven by the in-phase and quadrature of the DEFC. Similarly, the output optical signal comprises a baseband optical frequency comb with a frequency range of 1 GHz and 1.95 MHz spacing. Before directing into the FUT and counter-propagates with the pump signal, optimum power of the probe is achieved using EDFA.

coherent receiver is used at the detection end fully map the DOFC to the electrical domain and to recover the phase shift directly. After Brillouin interaction, the DOFC probe signal is detected by optical coherent receiver. Taking advantage of the high sensitivity of coherent detection, EDFA commonly used before direct detection is eliminated. The obtained electrical signals are collected by data acquisition card (DAQ) with 2 GHz sampling rate and further processed in the computer to reconstruct the distribution of BFS along the fiber.

III. PREPARE YOUR PAPER BEFORE STYLING

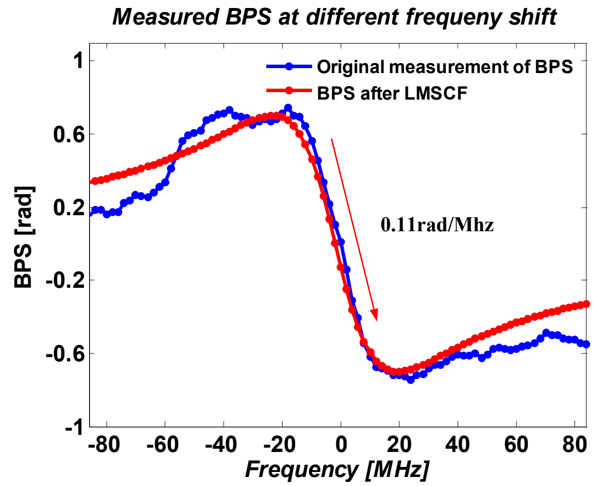

Fig. 2. Brillouin phase spectrum measured by coherent detection of DOFC probe signals at the beginning of FUT.

The obtained phase for each frequency (denoted as the relative frequency deviation to the BFS) illustrated as the blue curve in Fig. 2. While the red curve shows the fitting result with least mean square curving fitting (LMSCF). The center of the liner slope, which is about 40Mhz and calculated to be 0.11 rad/MHz, is recognized as the BFS distribution. By locating the linear center of BPS fitting process, the BFS as well as the temperature or strain information is readily extracted.

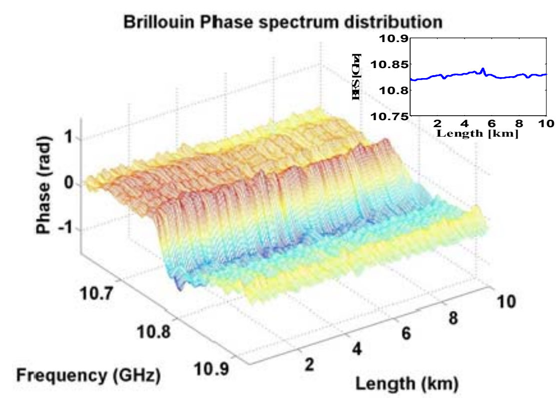

Fig. 3. Brillouin phase spectrum and the measured BFS distribution (inset) along the FUT.

In our experiment, probe signal is generated by modulation which composed of multiple DOFC frames. And each DOFC frame interact with pump in sequence through SBS in the fiber. In this way, FUT can be divided as M independent sections. Then the BPS distribution can be obtained by analyzing the Brillouin phase profile of each section, the total response time of our proposed sensor is solely limited by the FUT length which is 10km in the experiment, corresponding to 10 μs. The inset in Fig. 3 illustrates the BFS distribution and the fluctuation could be attribute to the non-uniform strain applied on the fiber.

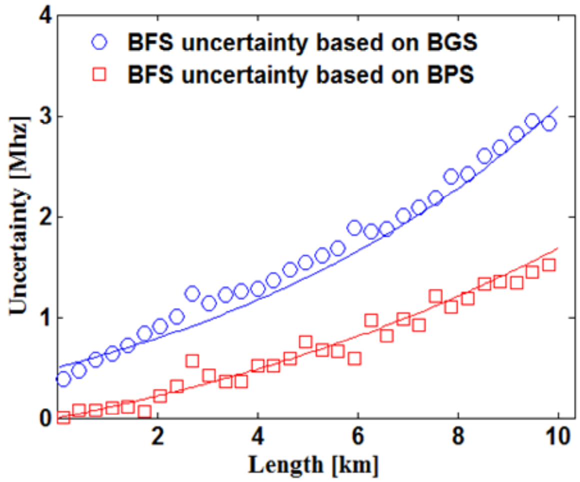

Fig. 4. Brillouin phase spectrum and the measured BFS distribution (inset) along the FUT.

With the degradation of signal contrast, the advantage of using BPS over BGS is highlighted in Fig.4. Although relatively poor SNR is observed as no average is used in the proposed method. LCF method is applied for the location of BFS while liner fitting method is used for BPS. As show in the figure, the measurement uncertainty based on BPS and BGS deteriorate with the decrease of SNR, the measurement accuracy based on BPS is estimated to be ~1.5MHz. The performance in terms of measurement accuracy nearly doubled compared with BGS at the end of fiber.

IV. CONCLUSION

In conclusion, an single measurement distributed BOTDA sensor is proposed and experimentally demonstrated employing coherent de-modulation of DOFC probe signal. The Brillouin Phase Spectrum (BPS), is simultaneously measured in a single shot without frequency sweeping and average. To avoid the averaging process and maintain the SNR, first order Raman amplification is introduced to realize such ultra-fast BOTDA with a response time of 10 µs, limited only by the fiber length. Temperature measurement is performed and the BFS uncertainty is improved by 50% compared with that using conventional BGS. The characteristics of ultra-fast response time and phase detection make our ultra-fast BOTDA potential for wild range of dynamic sensing scenarios with high accuracy, such as railway strain induced deformation sensing, infrastructure health condition monitoring, etc.

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