Realization of High-Speed Distributed Sensing Based on Brillouin Optical Correlation Domain Analysis

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Abstract: A novel method is proposed to demodulate the output of Brillouin optical correlation domain analysis by using an analog signal processing unit free from the update rate limitation of the conventional method. The distributed Brillouin interaction per pump-probe frequency offset is continuously recorded during linearly sweeping the sensing positions. In experiment, we realize ~20-Hz distributed sensing over the entire 50-m fiber with 5-cm spatial resolution.

OCIS codes: (060.2370) Fiber optics sensors; (290.5900) Scattering, stimulated Brillouin.

Brillouin-based distributed sensors have the advantage to provide fully-distributed strain or temperature information [1-2], and even both simultaneously [3]. Compared with the pulse-based time-domain Brillouin sensor [1], a correlation-based Brillouin sensing system, called as Brillouin optical correlation domain analysis (BOCDA) [2], has unique features of high spatial resolution (~cm or even sub-cm) and short measurement time. The measurement speed has been demonstrated as high as ~57 Hz [4] by using a microwave synthesizer or ~1 kHz [5] by using direct current modulations, which are both used to sweep the pump-probe frequency offset for acquiring the local Brillouin gain spectrum (BGS) of stimulated Brillouin scattering (SBS) and thus evaluating the local Brillouin frequency shift (BFS, ν_B). Up to date, the above high measurement speeds are realized for one-position measurement although the sensing position is random accessible. It takes rather long time to repeat the local BGS measurement at all sensing positions by resetting or re-uploading the parameters of the frequency modulation to the laser source, such as the modulation frequency (f_m) [4] or modulation waveforms [5].

This problem can be solved by auto-sweeping the modulation frequency f_m and recording the corresponding distributed Brillouin interaction along the entire fiber per pump-probe frequency offset. However, in the current BOCDA systems, the optical output of the amplified probe at each sensing location is demodulated by a commercial lock-in amplifier (LIA) [2-5] where a finite time (several tens or hundreds of μs) is necessary for electronic signal processing and signal update. In this work, an analog signal processing (ASP) unit, instead of the LIA, is adopted to demodulate the optical output of the BOCDA system, which results in no limitation of signal update rate. This implementation improves the entire distributed sensing speed (~20 Hz) of the BOCDA system with 50-m measurement range and 5-cm spatial resolution.

The experimental setup is depicted in Fig. 1. A 1549-nm distributed-feedback laser diode (DFB-LD) was used as a light source with the output divided by a 3-dB coupler for the SBS pump and probe waves. A ~1.8-km delay fiber was introduced into the probe wave (~2.1 mW) to localize a higher-order correlation peak in a 50-m polarization maintaining fiber (PMF). The pump wave with the optical frequency up-shifted from the probe by around ν_B (~10.9 GHz) of the PMF was prepared by a single-sideband modulator (SSBM) that was driven by a microwave synthesizer.

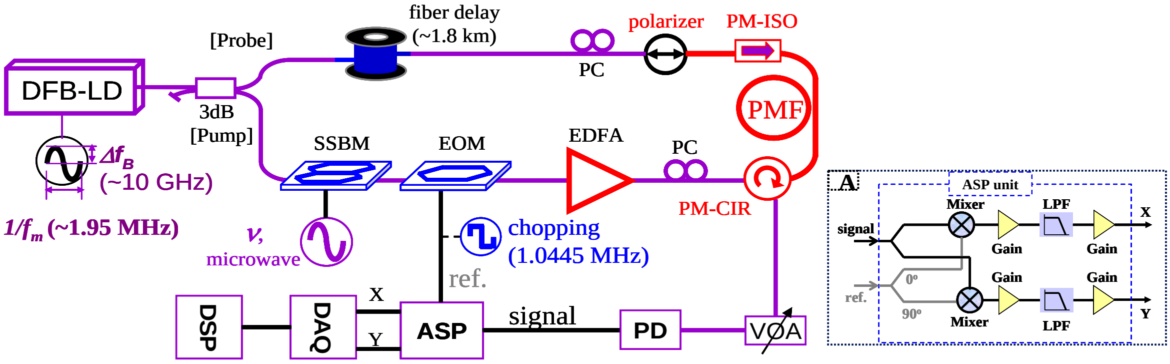
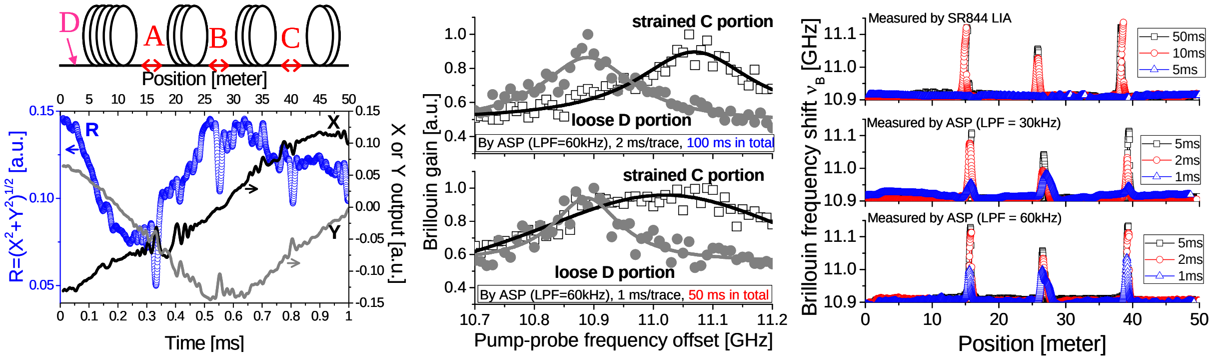


Fig. 1. Experimental setup of high-speed BOCDA system. Inset 'A' shows the structure of our configured analog signal processing (ASP) unit. DFB-LD, distributed-feedback laser diode; SSBM, single-sideband modulator; EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; PC, polarization controller; PMF, polarization maintaining fiber; PM-ISO, PM isolator; PM-CIR, PM circulator; PD, photo-detector; VOA, variable optical attenuator; DAQ, data acquisition card; DSP, digital signal processing; LPF, electronic low-pass filter.

After chopped by an electro-optic modulator (EOM) at 1.0445 MHz, the pump wave was amplified to ~200 mW by an erbium-doped fiber amplifier (EDFA). Both pump and probe waves were maintained propagating along the PMF's slow axis via a PM circulator and a polarizer, respectively. The sinusoidal frequency modulation to the light source was carried out by a waveform generator providing the modulation frequency f_m = ~1.95 MHz and the modulation amplitude Δf_B = ~10 GHz, which correspond to the measurement range z_m = ~50 m and the spatial resolution Δz_B = ~5 cm [2]. The chopped output of the amplified probe wave was transferred to electronic analog signal via a photo-detector (PD). The analog signal is under processing by our configured ASP unit (see the inset 'A' in Fig. 1) that includes two parallel channels to demodulate the chopped signal with 90^o shifted. Two analog outputs (X and Y) of the ASP were simultaneously recorded by a 2-MS/s 18-bit-resolution data acquisition card (DAQ) and digitally processed to give the amplitude $R=(X^2+Y^2)^{1/2}$ of the synthesized Brillouin interaction along the entire fiber.



(a) (b) (c)

Fig. 2. (a) Measured traces (X and Y) of the ASP unit with 60-kHz LPF for 1-ms sweeping period of f_m (T_{fm}=1 ms) and a microwave frequency ν = 10.901 GHz. The amplitude $R = (X^2+Y^2)^{1/2}$ is numerically calculated. The top shows the 50-m PMF sample comprising three 5-cm strained portions (A, B, and C). (b) Comparison of BGS measured by the ASP with 60-kHz LPF for T_{fm} = 2 ms and 1 ms, respectively. Points, experimental data; Curves, Lorentz fitting. (c) Distributions of Brillouin frequency shift along the PMF sample for different T_{fm}, which are characterized by the LIA (top) and the ASP with 30-kHz (middle) and 60-kHz (bottom) LPF, respectively.

When the microwave frequency is set as ν = 10.901 GHz and the modulation frequency f_m is auto-linearly swept from 1.92 MHz to 1.98 MHz with a sweeping period of T_{fm} = 1 ms, X and Y traces of the ASP unit with 60-kHz electronic low-pass filter (LPF) are recorded. The amplitude R is evaluated in real-time way, which denotes the synthesized Brillouin interaction along the entire fiber. The results are plotted in Fig. 2(a) where the top shows the fiber sample with three strained portions (A, B, and C). Scanning the microwave frequency ν from 10.7 GHz to 11.2 GHz with 50 steps, we repeat the measurement in Fig. 2(a) and accumulate the BGS distribution along the entire fiber with 2.5-cm step. Two BGS examples of strained C and loose D portions measured by the ASP unit with 60-kHz LPF are plotted in Fig. 2(b), respectively. It is seen that the BGS for T_{fm} = 1 ms has slightly-worsened SNR with respect to that for T_{fm} = 2ms, but both cases reasonably indicate the applied strain. Fig. 2(c) depicts the comparison of the distributions of the BFS (ν_B) along the entire fiber, which are estimated by Lorentz fitting to the BGS distributions measured by different ways, such as the LIA with the fastest update rate (~100 kHz) and the ASP with 30-kHz or 60-kHz LPF, respectively. For the LIA, when T_{fm} goes below 10 ms, the strained portions can not be interrogated. For our ASP unit, when the LPF is set at 30 kHz, the strained portions can be correctly diagnosed till T_{fm} = 2 ms; when the LPF is set at 60 kHz, even a fast sweeping T_{fm} = 1 ms is possible to figure out the strained portions. The last case corresponds to ~20-Hz distributed sensing speed of the BOCDA system.

In conclusion, we have experimentally demonstrated ~20-Hz distributed sensing over the entire 50-m fiber with 5-cm spatial resolution by employing our configured ASP unit to the BOCDA system. It is planed next to verify the capacity of high-speed distributed sensing in detecting dynamic strain along the entire fiber.

[1] X. Bao, M. DeMerchant, A. Brown and T. Bremner, "Tensile and compressive strain measurement in the lab and field with the distributed Brillouin scattering sensor," J. Lightwave Technol. **19**, 1698-1704 (2001).

[2] K. Hotate and T. Hasegawa, "Measurement of Brillouin gain spectrum distribution along an optical fiber using a correlation-based technique—proposal, experiment and simulation," IEICE Trans. Electron. **E83-C**, 405–412 (2000).

[3] W. Zou, Z. He, and K. Hotate, "Fiber-optic Brillouin distributed discrimination of strain and temperature with 11-cm spatial resolution using correlation-based continuous-wave technique," in Proc. of ECOC 2008, We3B3 (Sep. 2008).

[4] K. Hotate and S. S. L. Ong, "Dynamic strain measurement at 50Hz using a Brillouin optical correlation domain analysis based fiber optic sensor," in Proc. of CLEO/Pacific Rim 2003, 672 (Dec. 2003).

[5] K. Y. Song, and K. Hotate, "Distributed fiber strain sensor with 1-kHz sampling rate based on Brillouin optical correlation domain analysis," IEEE Photon. Technol. Lett. **19**, 1928-1930 (2007).