Proposal of Brillouin optical correlation-domain reflectometry (BOCDR)

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Abstract: We propose a Brillouin optical correlation-domain reflectometry (BOCDR), which can measure the distribution of strain and/or temperature along an optical fiber from a single end, by detecting spontaneous Brillouin scattering with controlling the interference of continuous lightwaves. In a pulse-based conventional Brillouin optical time-domain reflectometry (BOTDR), it is difficult in principle to achieve a spatial resolution less than 1 m, and the measurement time is as long as 5-10 minutes. On the contrary, the continuous-wave-based BOCDR can exceed the limit of 1-m resolution, and realize much faster measurement and random access to measuring positions. Spatial resolution of 40 cm was experimentally demonstrated with sampling rate of 50 Hz.

OCIS codes: (060.2370) Fiber optics sensors; (280.4788) Optical sensing and sensors; (290.5830) Scattering, Brillouin.

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1. Introduction

Optical fiber sensors based on Brillouin scattering have been intensively studied as a promising technology for monitoring conditions in various materials and structures, due to the possibility of distributed measurement of strain and/or temperature along an optical fiber [1-13]. To obtain the location information of strain/temperature along the fiber, conventionally, pulse-based time-domain systems [5-10] have been used, which have the advantage of long measurement range over several tens of kilometers. Their long measurement time (~ several minutes) and inherent limitation in spatial resolution (~ 1 m) [10], however, are not satisfactory for practical applications.

In this paper, we propose a Brillouin optical correlation-domain reflectometry (BOCDR), which can measure the strain distribution along the optical fiber from a single end, by detecting spontaneous Brillouin scattering with controlling the interference of continuous lightwaves. Spatial resolution of 40 cm was experimentally demonstrated with sampling rate of 50 Hz.

2. Principle

Brillouin scattering-based fiber sensors are classified into two types: "reflectometries", in which a light beam is injected into one end of the fiber under test (FUT), and "analysis systems", in which two light beams are injected into both ends of the FUT. Several kinds of analysis systems have been studied, including the Brillouin optical time-domain analysis (BOTDA) [5-7] and the Brillouin optical correlation-domain analysis (BOCDA) [11-13]. These systems can obtain relatively large signals due to utilizing the stimulated Brillouin scattering (SBS). However, these methods need two-end access, which is often not feasible in long-range application, and cannot work completely when the FUT has even one breakage point. Considering the wide range of application, one-end access reflectometries are more favorable, even though their signal is not as large since they utilize the phenomenon of spontaneous Brillouin scattering. Brillouin optical time-domain reflectometries (BOTDR) has been proposed and studied [8, 9], as one-end access systems. However, these can't realize both of fast measurement speed and high spatial resolution.

When a light beam is injected into an optical fiber, backscattered light (Stokes light) is generated through the interaction with acoustic phonons, and it propagates in the direction opposite to the incident light. This phenomenon is called spontaneous Brillouin scattering. The Brillouin scattered light spectrum, also known as the Brillouin gain spectrum (BGS), takes the shape of Lorentzian function [14]. The frequency at which the peak power is obtained in the BGS is shifted for about 11 GHz from the incident light frequency when the incident light wavelength is 1.55 μm. This amount of frequency shift is called the Brillouin frequency shift (BFS) f_B. If tensile strain or temperature change occurs in the optical fiber, the BFS varies in proportion to the applied strain (1MHz/0.002%) or temperature change (1MHz/1K). Therefore, by measuring the distribution of the BFS along the FUT, the applied strain amplitude or temperature change can be derived.

3. Proposal

The conceptual schematic of the proposed BOCDR system is shown in Fig. 1. A light beam from a laser is divided into pump and reference light beams. The pump light is injected into the FUT, and the Stokes light is directed into a heterodyne receiver composed of two balanced photodiodes (PDs). The reference light is used as an optical local oscillator. The electrical

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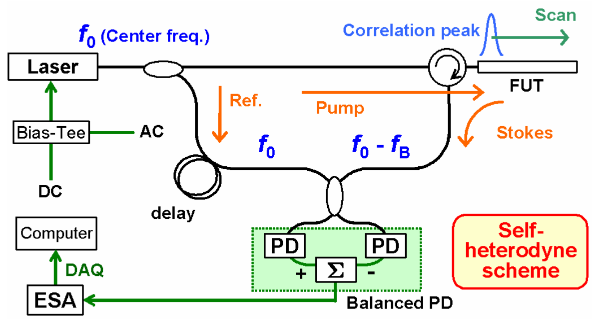

Fig. 1. Conceptual schematic of BOCDR system.

beat signal of the two light beams is monitored by an electrical spectrum analyzer (ESA). Since there is a frequency difference of about 11 GHz between the Stokes light and the reference light, this configuration is called self-heterodyne scheme.

In order to resolve the position in the FUT, the optical frequency of the light beam from the laser is directly modulated in a sinusoidal wave by modulating the injection current to the laser. From the viewpoint of time averaging, the correlation (or coherence) function is synthesized into a series of periodical peaks [15, 16], whose period is inversely proportional to the frequency of the sinusoidal modulation f_m. We control f_m to leave only one correlation peak within the range of the FUT, so that only the Brillouin scattering generated at the position correspondent to the peak has high correlation with the reference light, and then gives high heterodyne output. The peak frequency observed in the ESA gives the BFS caused at the position. By sweeping f_m, the correlation peak is scanned along the FUT to obtain the distribution of BGS or BFS. The spatial resolution Δz and the measurement range d_m (distance between the neighboring correlation peaks) of BOCDR are given by the same equations as those for BOCDA [11]:

$$\Delta z = \frac{V_g \Delta \nu_B}{2\pi f_m \Delta f} \quad (1)$$

$$d_m = \frac{V_g}{2\, f_m} \quad (2)$$

where V_g is the group velocity of light, $\Delta \nu_B$ is the Brillouin gain bandwidth (~ 30 MHz) in optical fibers, and Δf is the modulation amplitude of the light source.

4. Experiment

The actual experimental setup of BOCDR is depicted in Fig. 2. Before heterodyne detection, the reference light at frequency f_0 passed through a 2-km delay fiber, which is used to select

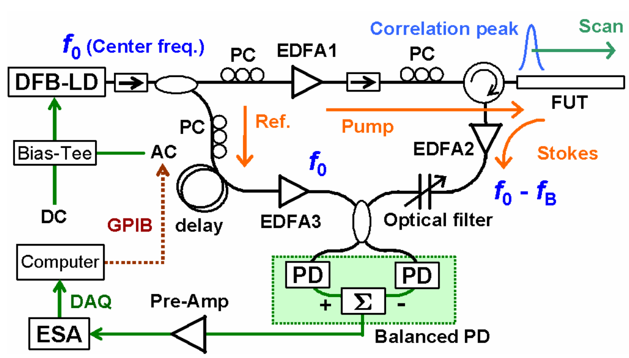

Fig. 2. Experimental setup of BOCDR system.

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the order of periodical correlation peaks, and an Er-doped fiber amplifier (EDFA) for enhancing the beat signal. The pump light at frequency f_0 was injected into the FUT after being amplified by a high-power EDFA. The weak Stokes light at frequency f_0-f_B backscattered from the FUT was amplified again by an EDFA. An optical filter was inserted after the EDFA in order to suppress the Rayleigh scattering and the Fresnel reflection from the FUT at frequency f_0. Before processing by an ESA, the heterodyned signal was amplified by an electrical pre-amplifier.

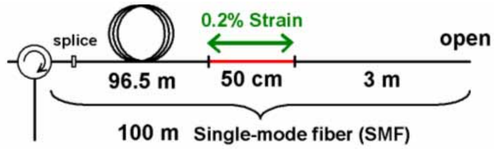

Fig. 3. Structure of the FUT.

The modulation frequency f_m was set to 457.4 – 458.4 kHz, which corresponds to the measurement range of 228 m according to Eq. (2). The amplitude of the frequency modulation Δf was 5.4 GHz, and the spatial resolution Δz was calculated to be about 40 cm from Eq. (1). Figure 3 shows the structure of the FUT comprising a 100-m conventional single-mode fiber (SMF), in which a 0.2-% strain is applied to a 50-cm section fixed on a translation stage using epoxy glue. One end of the FUT was spliced to a circulator, and the other end was kept open. The overall sampling rate of the BGS measurement for a single position was 50 Hz, which is much higher than that of the time-domain techniques (typical measurement time several minutes). Figure 4 shows the measurement result of the distribution of the BGS along the FUT. The BGS at the strain-applied section is clearly recognized. Figure 5 shows the distribution of the BFS. Spatial resolution better than 50 cm is achieved. The change of the BFS was about 100 MHz, which is in good agreement with the applied strain of 0.2 %.

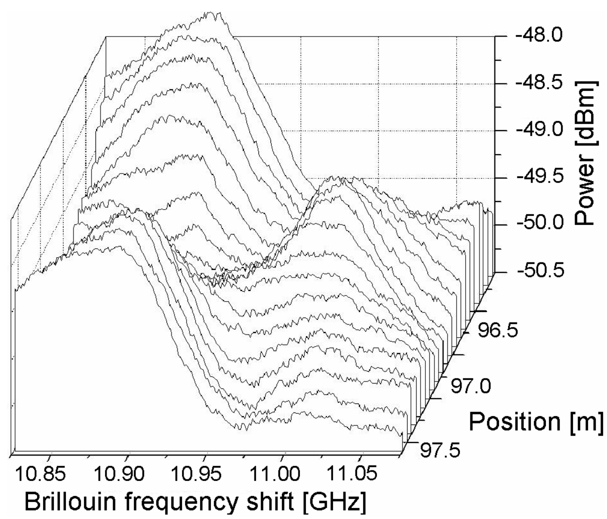

Fig. 4. Distribution of the BGS along the FUT.

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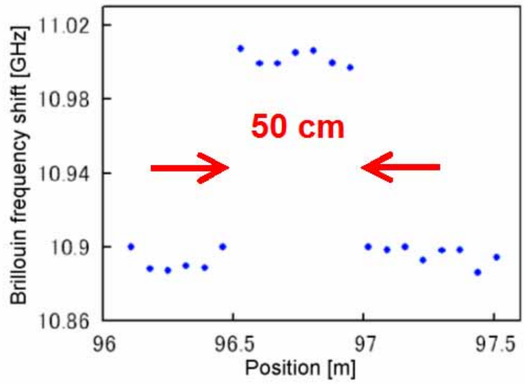

Fig. 5. Distribution of the BFS (peak of the BGS) along the FUT.

5. Discussion

As shown in Eqs. (1) and (2), there is a trade-off between the measurement range and the spatial resolution in BOCDR, and the ratio of the two values is purely dependent on the amplitude of the modulation frequency Δf. Therefore, Δf needs to be increased in order to obtain substantial improvement in the performance of BOCDR. However, Δf cannot be increased to the limit discussed below.

Figure 6(a) shows optical spectra of the reference light and the reflected light just before heterodyne detection when the frequency of the light source is sinusoidally modulated with the modulation amplitude Δf. The Rayleigh scattered light is too strong to be suppressed

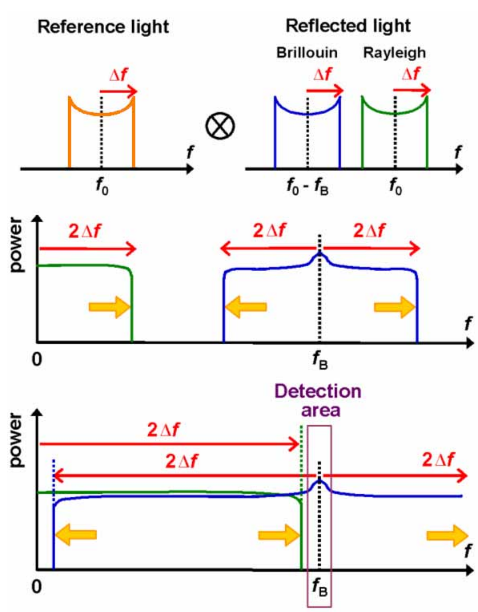

Fig. 6. Schematics of (a) optical spectra of the reference light and the reflected light when the frequency of the light source is modulated with the amplitude Δf, (b) electrical spectra with sufficiently small Δf, and (c) electrical spectra with large Δf.

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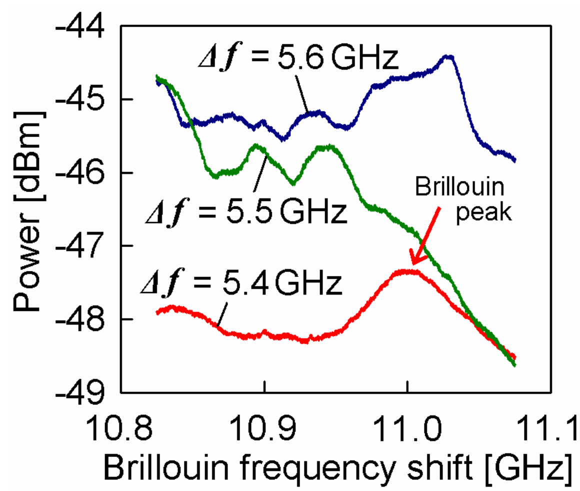

Fig. 7. Measured BGS when Δf is 5.4 GHz, 5.5 GHz, and 5.6 GHz.

completely by an optical filter, thus it remains in the reflected light. The electrical spectra after heterodyne detection with sufficiently small Δf is shown in Fig. 6(b). The spectrum of the Brillouin scattered light broadens in both directions for $2\Delta f$ with a center frequency f_B. On the other hand, the spectrum of the Rayleigh scattered light broadens from 0 Hz to $2\Delta f$, considering that negative frequency is folded back to positive one. Figure 6(c) shows electrical spectra when $2\Delta f$ is increased to the value slightly lower than f_B. Though the Rayleigh spectrum is approaching the detection area, so long as it is outside the area, the measurement is free from its influence. However, if $2\Delta f$ is further increased beyond f_B, the Rayleigh spectrum starts to overlap with the detection area, resulting in a considerable amount of noise. Thus, it is undesirable for Δf to be higher than half of f_B.

In the experiment, Δf was set to 5.4 GHz, which is slightly lower than half of the Brillouin frequency shift of 11 GHz in SMF. If Δf larger than 5.4 GHz was applied to the system, the S/N ratio decreased drastically, as shown in Fig. 7.

6. Conclusion

We have proposed a new type of sensing technology called BOCDR based on spontaneous Brillouin scattering with controlling the correlation of continuous lightwaves, and demonstrated one-end-access distributed strain measurement with 40-cm spatial resolution and 50-Hz sampling rate. We expect that the BOCDR system will become a promising technology for practical use as a fiber-optic nerve system in the smart materials and structures.

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