Separation of temperature and strain measurement in photon-counting BOTDR

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ABSTRACT

This paper introduces a photon-counting Brillouin Optical Time-Domain Reflectometry (ν-BOTDR) system designed to separate the effects of temperature and strain along an optical fiber. Based on measurements taken at different working points of a fiber Bragg grating (FBG), the system's sensitivity to strain and temperature variations can be tuned accordingly. The main advantage of BOTDR is that it allows temperature or strain information to be recovered from the Brillouin frequency shift. However, when a Single Photon Avalanche Detector (SPAD) is used to improve the signal-to-noise ratio and range of these sensors, information on the frequency of the scattered signal is lost. In this paper, we present a new technique that enables frequency shifts to be measured unaffected by optical losses or intensity variations caused by Brillouin gain, while benefiting from the high sensitivity of SPADs.

This paper outlines the methodology and presents experimental results that distinguish strain and temperature variations over distances exceeding 50 km, with a spatial resolution of 2 m using standard single-mode fiber.

Keywords: Single-Photon Detector, SPAD, Distributed Temperature Sensor, BOTDR, Brillouin scattering.

1. INTRODUCTION

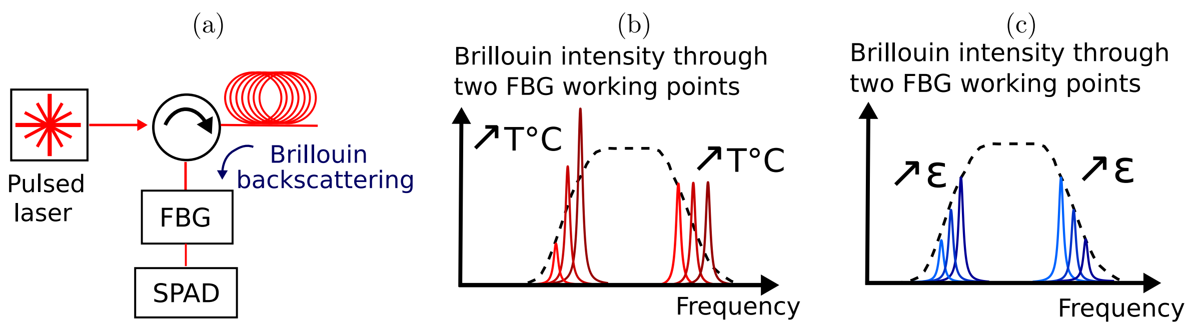

Figure 1: (a) Principle of the photon-counting BOTDR. FBG: fiber Bragg grating, SPAD: single-photon avalanche detector. (b) Illustration of the influence of temperature variation on the Brillouin intensity through the FBG, on two different operating points. The FBG response is represented in a dotted black line. Brillouin sensitivity coefficients according to temperature variation: 1.12 MHz/°C ** and 0.38 %/°C ** (c) Illustration of the influence of strain effects on the Brillouin intensity through the FBG, on two different operating points. Brillouin sensitivity coefficients according to strain effects: 0.046 MHz/$\mu\varepsilon^*$ and $-8 \cdot 10^{-4}$ %/$\mu\varepsilon^*$. Typical values are indicated with a single asterisk *,[1] while measured values are marked with a double asterisk **

The development of photon counters in the field of distributed sensors has witnessed substantial growth in recent years, driven by their unparalleled sensitivity and ability to detect extremely low optical power levels (-120 dBm).

Indeed, photon counters were initially used for OTDRs, both for long-range measurements,[2] but also to improve the spatial resolution of these instruments, achieving resolutions of a few centimeters.[3] Subsequently, photon counters were used to develop distributed temperature sensors, first using Raman scattering,[4–6] and then using Brillouin scattering.[7] Recent work has shown temperature measurements at a range of 100 km[7] thanks to the use of photon counters and Brillouin backscattering. Unlike Raman scattering, temperature generates not only a variation of the intensity of the detected Brillouin signal (ΔI_B) but also its frequency ($\Delta \nu_B$). Moreover, the Brillouin frequency shift ($\Delta \nu_B$) depends on the strains applied to the optical fiber[1] as shown in Fig. 1.

2. EXPERIMENTAL SETUP

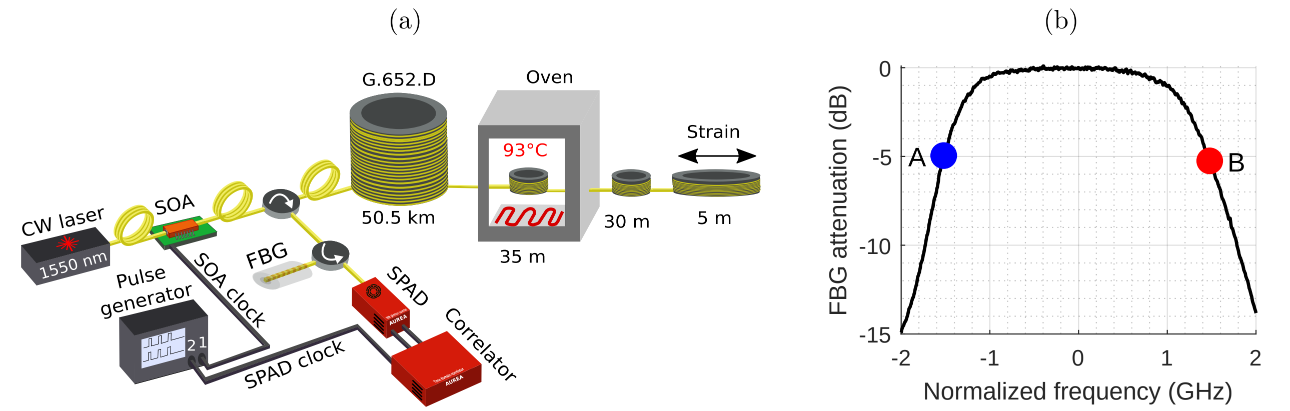

Figure 2: (a) ν-BOTDR experimental setup, with an experimental bench of temperature and strain measurements. (b) Fiber Bragg grating (FBG) response, with the operating points A and B.

The experimental setup is represented in Fig. 2 (a). A tunable narrowband laser in the infrared domain (1550 nm) is modulated in intensity with a semiconductor optical amplifier (SOA), to generate optical pulses with a duration of 20 ns and a peak power of 13.6 dBm. A circulator allows to send the optical pulses into the single-mode fiber under test (G.652.D) of 50.5 km with optical losses $\alpha = -0.187$ dB/km. In order to measure temperature variation, a coil of 35 m is placed in an oven heated to 93°C (+70°C compared to the ambient temperature). Then, the optical fiber is stretched, to generate a strain along 5 m of optical fiber. The backscattered light is recovered with the third arm of the circulator, and is composed of Rayleigh, Brillouin, and Raman scattering. The signal is filtered through a fiber Bragg grating (FBG) with a thermal-insensitive packaging, shown in Fig. 2 (b), to detect only the Brillouin anti-Stokes photons on the single-photon avalanche detector (SPAD).[8] The SPAD is activated with a delay corresponding to the time of flight of photons into the optical fiber, after the activation of optical pulses from the SOA. The pulse generator allows controlling this delay. The temporal correlator[9] is used to determine the time arrival of detections of photons on the SPAD. From the time of arrival, the spatial information can be deduced.

3. MEASUREMENT OF THE FREQUENCY SHIFT WITH A DIRECT DETECTION (ν-BOTDR)

This work is based on two different operating points, A and B, shown in Fig. 2 (b). Thanks to the tunable laser, the pump's frequency can be shifted to 10.8 GHz from the frequency of the FBG operating point, to measure the Brillouin anti-Stokes backscattering else on the positive slope (operating point A), or, on the negative slope (operating point B). By performing a differential measurement using the two operating points, it is possible to obtain the frequency information, as shown in Fig. 1.

$$\Delta f_B \approx \frac{\dfrac{I_A - I_{A,ref}}{S_A} - \dfrac{I_B - I_{B,ref}}{S_B}}{2} \tag{1}$$

With I_A and I_B, the Brillouin signal measured at operating points A and B respectively. $I_{A,ref}$ and $I_{B,ref}$ the reference of the intensity measured at operating points A and B. $S_A = 11,7$ dB/GHz and $S_B = 9,8$ dB/GHz are the slopes of the FBG.

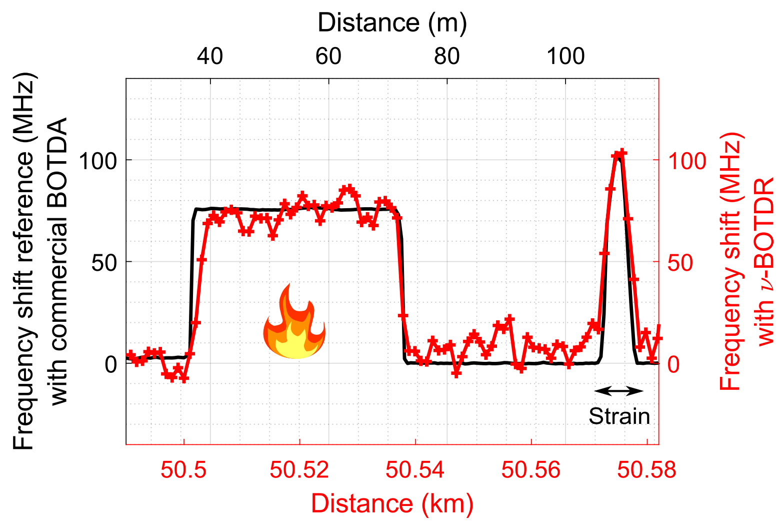

Figure 3: Comparison between the reference frequency profile get with a commercial BOTDA (Ditest, Omnisens) realized at 50 m in black, and a measurement of the frequency profile measured with the ν-BOTDR at 50 km, in red. Both measurements were obtained with a spatial resolution of 2 m.

In Fig. 3 a comparison between a reference frequency profile (commercial BOTDA) and home made photon-counting BOTDR (ν-BOTDR) measurement is shown. The reference measurement is directly taken at the instrument's output to ensure the most accurate reference. A good agreement is observed between the two measurements, demonstrating that the differential method allows for measuring a frequency shift without the need to compensate for optical losses, through a Rayleigh scattering measurement.

4. STRAIN AND TEMPERATURE SEPARATION WITH A ν-BOTDR

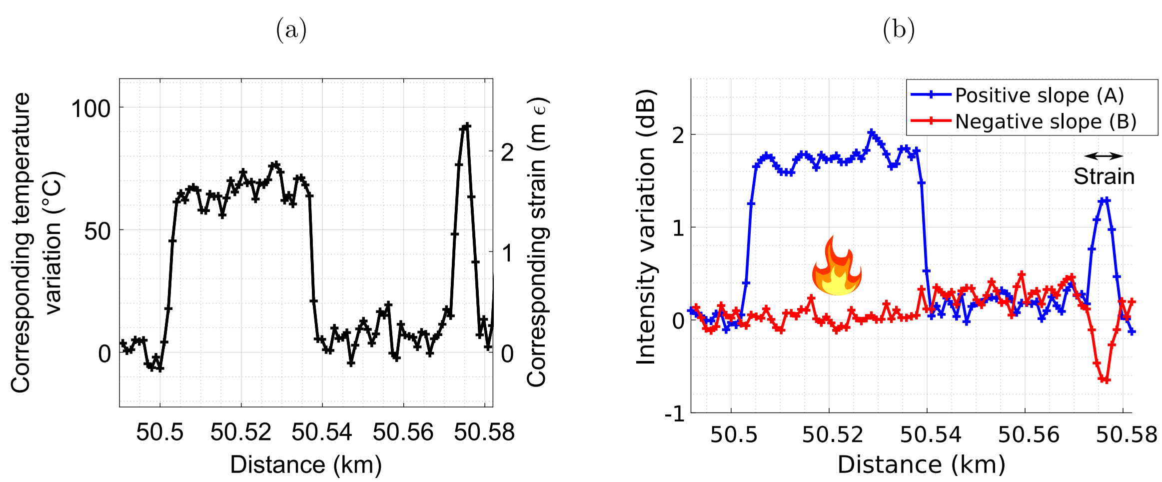

Figure 4: (a) Conversion of the frequency shift into an equivalent temperature variation and strain from measurement shown in Fig. 3. (b) Identification of strain and temperature effects, with a comparison between the intensity variation measured on operating point A (positive slope) with operating point B (negative slope). Measurement realized with the ν-BOTDR with a 2 m spatial resolution, and a 1 m sampling interval.

Brillouin frequency shift depends on temperature variation and strain effects, as shown in Fig. 1. From sensitivity coefficients $C_{\nu_B T}$ and $C_{\nu_B \varepsilon}$, the temperature variation and strain measurement can be deduced with the frequency profile. Results are shown in Fig. 4 (a). However, using only the frequency information, the distinction between a strain and a temperature effect, can't be realized.

A temperature increase raises both frequency and intensity, as shown in Fig. 1. Through the operating point "A", as the slope is positive, an increase in frequency increases the signal. These two effects accumulate. On the other hand, for a negative slope, a decrease in the measured signal translates into an increase in frequency. Thus, the increase in the signal generated by the increase in temperature is partly compensated by a decrease in the signal generated by the frequency shift on the negative slope. Experimentally, a temperature variation at operating point B generates almost no variation in intensity, as shown with the red curve in Fig. 4 (b).

For a strain measurement, both operating points are sensitive to the frequency. As a consequence, on point A, a strain results in an increase of the signal, whereas at point B, a strain results in a decrease in the measured signal. Thus, by analyzing the intensity variation, we can deduce whether it is a temperature change or a deformation.

5. CONCLUSION

In this paper, we present an experimental setup to measure a Brillouin frequency shift with direct detection based on a single-photon avalanche detector. We also show the possibility to separate a temperature variation from a strain effect at 50 km with a spatial resolution of 2 m. The main advantage of our method is that there is no need to measure Rayleigh scattering losses. However, the frequency stabilizing of the Bragg grating with respect to the pump laser frequency is the main challenge.

ACKNOWLEDGMENTS

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