Long-range simplex-coded BOTDA sensor over 120 km distance employing optical preamplification

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In this Letter, we combine the use of optical preamplification at the receiver and optical pulse coding techniques with an optimized modulation format to effectively extend the sensing range of Brillouin optical time-domain analysis (BOTDA) sensors. Combining a return-to-zero modulation format with 25% duty cycle and linear gain preamplification allows for temperature and strain measurements over 120 km of standard single-mode fiber with 3 m spatial resolution and an rms strain–temperature accuracy of 3.1 °C/60 $\mu\varepsilon$ respectively.

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Distributed optical fiber sensors based on Brillouin scattering have been attracting a great interest in the past years, thanks to their unique distributed strain and temperature measurement capabilities. Among the different existing techniques, distributed sensing exploiting Brillouin optical time-domain analysis (BOTDA) provides one of the most attractive schemes, allowing for high-performance sensing over long fiber ranges [1,2].

In such a scheme, two counterpropagating optical waves interact with an acoustic wave in an optical fiber, leading to power transfer between the two optical signals. The most commonly used method (the so-called Brillouin-gain configuration [2]) employs a cw probe signal that is down-shifted in frequency with respect to an optical pulsed pump. Thus, when tuning the frequency shift between these two optical beams within the fiber Brillouin gain spectrum (BGS) range, the cw probe wave results are locally amplified by stimulated Brillouin scattering (SBS). Since the maximum amplification occurs at the fiber Brillouin frequency shift (BFS) value, which is linearly dependent on local strain and temperature, such two physical quantities can be measured along the sensing fiber as a function of the distance. The spatial information is obtained by a time-domain analysis, allowing for a spatial resolution that is proportional to the pump pulse width. The main limitations in long-range BOTDA sensors arise from the maximum allowed input pump power before onset of fiber nonlinear effects inducing measured BGS distortions, which finally lead to temperature and strain measurement errors [1,2]. Recently, the use of optical pulse coding techniques has been proposed for BOTDA sensors with meter-scale spatial resolution [2], allowing for an improved signal-to-noise ratio (SNR) and an extended sensing range, without incurring nonlinear effects.

In this Letter, we propose the use of optical preamplification at the receiver combined with an optimized simplex pulse coding configuration employing return-to-zero (RZ) modulation format to further enhance the dynamic range of BOTDA sensors with meter-scale spatial resolution. We demonstrate, for the first time to our knowledge, a BOTDA sensor with an enhanced dynamic range of ~27 dB, achieving 120 km sensing distance, with 3 m spatial resolution and a temperature/strain resolution of 3.1 °C/60 $\mu\varepsilon$ at the far fiber-end.

In BOTDA sensors, the BFS parameter is obtained by fitting the measured BGS, which is determined by sweeping the frequency difference of the two interacting optical waves and detecting the SBS-induced intensity variations of the cw probe signal ΔI_{CW} at fiber input ($z = 0$). For a single frequency difference $\Delta\nu$, we thus have [2]

$$\Delta I_{\mathrm{CW}}(t, \Delta\nu) = I_{\mathrm{CWL}} \exp(-\alpha L) \times \left\{ \exp\left[\int_{v_g t/2}^{v_g t/2+\Delta z} g_B(\xi, \Delta\nu) \times Ip(\xi, \Delta\nu) \mathrm{d}\xi \right] - 1 \right\}, \tag{1}$$

where I_{CWL} is the input probe intensity at the far end of the fiber ($z = L$), α is the fiber loss, L is the fiber length, v_g is the group velocity, Δ_z is the pulse interaction length determining the spatial resolution, and $g_B(\xi, \Delta\nu)$ and $I_P(\xi, \Delta\nu)$ are the BGS and the pump intensity, respectively, at position $z = \xi$.

Equation (1) points out that the absolute amplitude of the measured signal ΔI_{CW} strongly depends on the spatial resolution, pump power, and total fiber length. To increase the SNR at the receiver while keeping a given spatial resolution, the pump power could be increased; however, its maximum level is limited by the onset of modulation instability and pump depletion, which actually distort the measured BGS [1–3]. Pump depletion increases with the distance and involved optical powers, limiting the range and performance of current BOTDA sensors [1]. To alleviate the trade-off between spatial resolution and sensing range, the use of optical pulse coding techniques has been successfully proposed for long-range BOTDA sensors [2]. Note that the pulse modulation format must be properly optimised when using pulse coding in order to avoid distortions in the BGS due to acoustic-wave preexcitation [4]. Considering that the dynamic range of BOTDA traces is ultimately determined by the receiver sensitivity, other techniques need to be

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employed to further extend the sensing distance. For instance, the use of distributed Raman amplification has been proposed for sensors based on the coherent detection of the Brillouin components [5] and recently in BOTDA sensors [3]. However, this approach could raise issues as the high optical power levels within the sensing fiber would have an impact on both system reliability and cost.

In this Letter, we effectively combine the use of preamplification and optical pulse coding techniques with an optimized modulation format [4], strongly increasing the measurement dynamic range. It is important to note that the use of optical preamplification in coded-BOTDA sensors is not straightforward, and it has been avoided so far because of the potential to induce distortions in the coded traces due to the slow transients and likely gain saturation. However, in the long-range case, the low received probe power (after 120 km propagation) results in linear gain operation of the optical preamplifier [e.g., erbium-doped fiber amplifier (EDFA)], leading to unprecedented sensing distance enhancement.

Long-range measurements have been carried out using the experimental setup shown in Fig. 1. The cw light from a distributed-feedback (DFB) laser operating at 1550 (13 dBm power) is split into two branches through an optical coupler. In the pump branch, an EDFA followed by a polarization controller (PC) and a Mach–Zehnder modulator (MZM) are used to generate high-power coded pulses with high extinction ratio (input pump peak power $P_{\mathrm{IN}} = 15.5$ dBm). The MZM is controlled by a waveform generator, providing 511 bit simplex-coded pulses with RZ modulation format with a 30 ns pulse width and a bit slot of 120 ns (25% duty cycle), allowing for 3 m spatial resolution and uniform Brillouin gain. A polarization scrambler (PS) has been used to depolarize the coded pump pulses, effectively reducing the polarization dependence of the Brillouin gain. In the probe branch, two sidebands around the laser wavelength are generated using an MZM controlled by a microwave generator. High carrier suppression was achieved by proper MZM bias adjustment and pump depletion was avoided through a variable optical attenuator (VOA) at fiber input (cw probe $P_{\mathrm{IN}} = -23$ dBm). A PS has also been used to depolarize the probe beam in order to further suppress polarization-dependent Brillouin-gain effects. The sensing fiber is composed of two 60 km spools of standard single-mode fiber for a total length of 120 km. Note that both sidebands of the probe beam are launched into the sensing fiber, reducing pump depletion and nonlocal effects [6]. At the receiver side, an optical circulator is used to extract both probe sidebands, which are then amplified by an EDFA operating in linear gain regime. Note that a linear SOA could be also used in this case. The amplified spontaneous emission (ASE) noise coming from the EDFA is then filtered out using a narrowband (6 GHz bandwidth) fiber Bragg grating (FBG) centered at the Stokes wavelength. The use of the FBG is also important to filter out the unwanted anti-Stokes and residual carrier components in the probe and the Rayleigh backscattered light from the coded pulses. A 125 MHz photoreceiver is then used connected to an oscilloscope to perform computer-controlled measurement sessions.

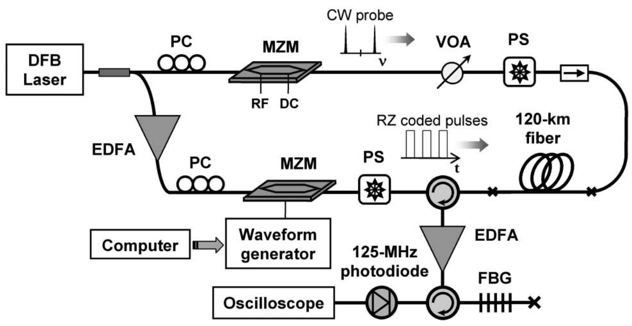

Fig. 1. Experimental setup for the coded-BOTDA sensor. DFB, distributed-feedback laser; PC, polarization controller; MZM, Mach–Zehnder modulator; EDFA, erbium-doped fiber amplifier; VOA, variable optical attenuator; PS, polarization scrambler; FBG, fiber Bragg grating.

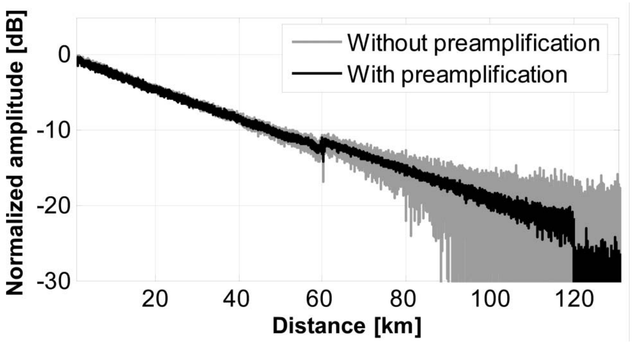

Fig. 2. BOTDA traces at 10.863 GHz for both simplex coding with (black line) and without (gray line) optical preamplification.

The benefit of employing optical preamplification combined with the simplex coding technique based on RZ modulation format was first analyzed by measuring BOTDA traces at a frequency corresponding to the BFS of the second fiber (~10.863 GHz). Figure 2 shows two decoded traces comparing the use of simplex coding only and its combination with optical preamplification. Considering that, when using 511 bit simplex coding with RZ pulses, the intensity contrast of the cw probe signal is ~256 times larger than the one obtained in a conventional BOTDA sensor [2,4] (assuming linear Brillouin gain), optical preamplification is effectively enhanced by the use of coding, leading to strongly reduced ASE noise with respect to the single-pulse case. Note that the preamplification of coded-BOTDA traces requires a careful optimization of both gain and output saturation

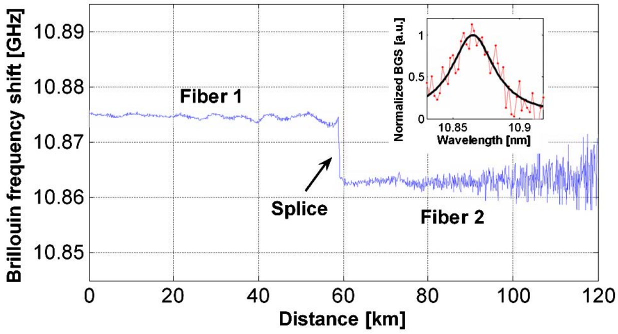

Fig. 3. (Color online) Measured Brillouin frequency shift versus distance. Inset, Brillouin gain spectrum near 120 km distance.

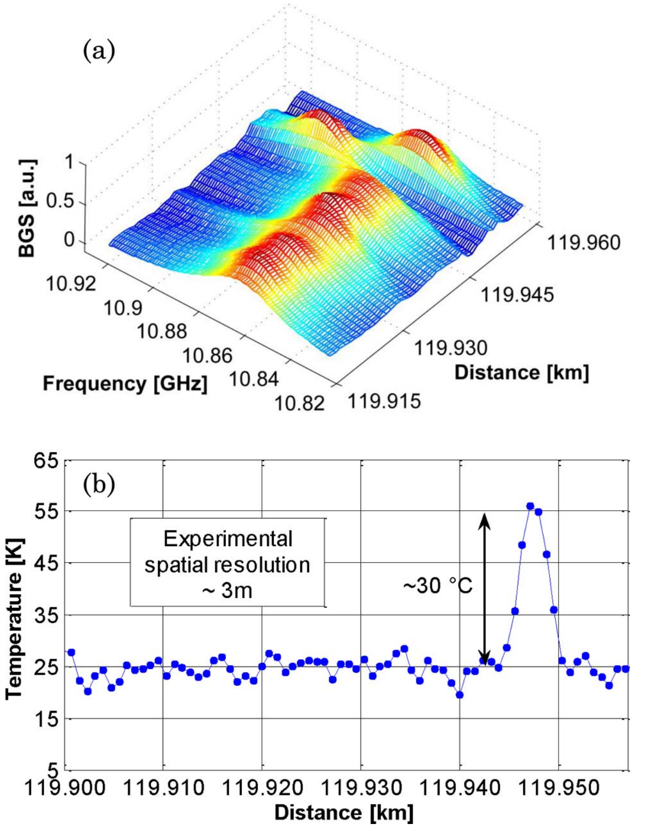

Fig. 4. (Color online) Experimental validation of 3 m spatial resolution over 120 km distance. (a) BGS and (b) BFS versus distance (near far fiber-end).

power of EDFA in order to provide an adequate SNR enhancement and simultaneously avoid amplifier gain saturation, which would lead to coded-trace distortions. Actually, the possible occurrence of such an effect represents an important limitation for the preamplification of coded-BOTDA traces, since it might introduce significant errors in the linear decoding process. However, this represents a less critical issue in very long sensing ranges, owing to lower cw-probe output power, which allows the EDFA to operate in linear regime, thus fully exploiting the benefits of both coding and EDFA preamplification. Thus, while a decoded BOTDA trace without EDFA exhibits a dynamic range of ~17 dB (electrical-noise limited), allowing for ~80 km sensing distance, a simplex-coded BOTDA trace preamplification allows for ~10 dB SNR enhancement, with an overall dynamic range increase up to ~27 dB (ASE-limited noise), and the achievement of a final sensing distance of 120 km. Moreover, the use of an optimized duty cycle of the RZ simplex-coded pulses effectively increases the pump-probe interaction along the fiber (providing ~10.5 dB SNR enhancement) and avoids BGS distortion due to acoustic wave preexcitation [4]. It is important to point out that the effect of pump depletion is negligible in our system, as confirmed by the linear attenuation of BOTDA traces in Fig. 2 and by the undistorted BGS near the far fiber-end (see Fig. 3 inset) [1,6]; this has also been verified by an estimation of pump depletion with ON-OFF probe signal, indicating approximately 1% residual pump depletion after propagation at the maximum gain. The measurement accuracy (indicated by the measurement rms σ) is obtained from the standard deviation of the BFS measurements reported in Fig. 3, indicating an accuracy of 3.1 MHz at the far fiber-end and leading to temperature/strain resolutions of 3.1 °C/60 $\mu\varepsilon$. Note that the sensing fiber used (120 km, single manufacturer) is composed of two fiber segments with slightly different BFS values (~10 MHz difference, within Brillouin gain linewidth), providing uninterrupted SBS interaction along 120 km and representing a realistic condition of sensor deployment with single manufacturer fiber.

Finally, the worst-case attainable spatial resolution has been measured by increasing (to 55 °C) the temperature of a 3 m fiber-spool in proximity of the far fiber-end, while keeping the rest of the fiber at room temperature (25 °C). Figure 4 shows both the decoded BGS at a region around ~120 km Fig. 4(a) and the temperature measurement obtained from the BFS parameter within such a far-end region Fig. 4(b). The use of RZ simplex-coded pulses with a 25% duty cycle is key in providing uniform Brillouin amplification for all simplex-coded BOTDA traces, avoiding acoustic-wave pre-excitation and BGS distortions introduced by the decoding process [4]. Note that the sensing range achieved with the proposed scheme constitutes, to our knowledge, the longest distance reported in a BOTDA sensor. Furthermore, the achieved spatial and temperature resolutions (3 m/3.1 °C) are similar to previously reported experiments, which, however, attained a much shorter distance (e.g., in [3], the spatial/temperature resolution values were 2 m/3 °C at 75 km distance, using additional Raman amplification).

In conclusion, we have experimentally demonstrated that combination of linear optical preamplification and optical pulse coding with an optimized modulation format can successfully enhance the range of BOTDA sensors, leading to a simple and cost-effective solution compared to existing ones. This feature has allowed us to perform temperature/strain sensing with 3.1 °C/60 $\mu\varepsilon$ accuracy and 3 m spatial resolution throughout a 120 km fiber length.

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