Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range

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In this Letter, we propose the use of optical pulse coding techniques for long-range distributed sensors based on Brillouin optical time-domain analysis (BOTDA). Compared to conventional BOTDA sensors, optical coding provides a significant sensing-range enhancement, allowing for temperature and strain measurements with 1 m spatial resolution over 50 km of standard single-mode fiber, with an accuracy of 2.2°C/44 $\mu\varepsilon$, respectively. © 2010 Optical Society of America

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In recent years, distributed optical fiber sensors based on stimulated Brillouin scattering (SBS) have attracted a great interest owing to their unique ability to carry out high-performance strain and temperature measurements over long distances [1,2]. In the time-domain approach, the so-called Brillouin optical time-domain analysis (BOTDA) [1–3], a pulsed pump beam and a counterpropagating continuous-wave (CW) probe beam, at different frequencies, interact through the intercession of an acoustic wave. Power transfer between both optical beams takes place at any position along the fiber when the frequency offset between them is within the local Brillouin gain spectrum (BGS). The frequency showing maximum gain is called Brillouin frequency shift (BFS) and depends linearly on strain and temperature, allowing us to perform distributed sensing [1]. The best performance reported so far for long-range BOTDA sensors results in 2 m/5 m spatial resolution over 40 km/51 km single-mode fiber [2,3], where pump depletion and modulation instability are the main factors limiting the sensing range [1,4].

In this Letter, we propose, for what we believe to be the first time, the use of optical pulse coding in a BOTDA sensor. We demonstrate that this technique effectively enhances the signal dynamic range, resulting in an extension of the sensing distance in BOTDA-based systems and providing the best performance reported so far, to our knowledge, temperature and strain sensing with 1 m spatial resolution over 50 km of standard single-mode fiber with an accuracy of 2.2°C/44 $\mu\varepsilon$ at the far end of the fiber.

In BOTDA sensors, the BGS is reconstructed along the fiber by sweeping the frequency offset ($\Delta\nu$) between the two counterpropagating optical signals around the BFS. Thus, intensity variations of the probe signal ΔI_{CW} are measured at the near end of the fiber ($z=0$) as a function of time t and $\Delta\nu$ and can be expressed as [1]

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

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, Δz is the spatial resolution related to the pump pulse duration, and $g_B(\xi,\Delta\nu)$ and $I_P(\xi,\Delta\nu)$ are the BGS and the pump intensity at position $z=\xi$.

From Eq. (1) we clearly notice that the CW-intensity contrast (ΔI_{CW}) mainly depends on the spatial resolution and the pump intensity. Thus, when short spatial resolution is required, the energy transferred to the probe is actually small, reducing ΔI_{CW}. This feature leads to measurements with low signal-to-noise ratio (SNR), limiting then the maximum sensing range. Moreover, the maximum pump and probe powers are limited by pump depletion [1] and modulation instability [4], which induce distortions in the acquired BGS. Pump depletion may actually produce significant deviation of the measured BFS with respect to the real local value [1], inducing errors in temperature/strain measurements. This nonlocal effect increases with the distance and optical power, resulting in the main limitation for long-range BOTDA sensors [1,4].

On the other hand, it has been recently demonstrated that optical pulse coding, as for instance Simplex coding, provides an enhanced SNR in distributed sensors based on spontaneous Brillouin scattering [5], resulting in an increased sensing range. The short SBS interaction length taking place in BOTDA sensors actually leads to a very small Brillouin gain, allowing us to linearize Eq. (1) as

$$\Delta I_{CW}(t,\Delta\nu) \propto \int_{v_g t/2}^{v_g t/2+\Delta z} g_B(\xi,\Delta\nu) Ip(\xi,\Delta\nu)\,\mathrm{d}\xi, \qquad (2)$$

so that if the pump signal $I_P(\xi,\Delta\nu)$ is implemented by Simplex-coded pulses, the upper limit of integration in Eq. (2) would need to consider the whole interaction length depending on the code length (L_c), changing Δz by $L_c\Delta z$. Note that ΔI_{CW} preserves the linear dependency on the pump even when using long code words, allowing us to use the conventional linear decoding process without any modification. Thus, by implementing Simplex coding in BOTDA sensors, the trade-off between spatial resolution and sensing range can be reduced owing to the SNR improvement [equal to $(L_c+1)/2L_c^{1/2}$], providing a significant sensing range enhancement while ensuring high spatial resolution.

The experimental setup shown in Fig. 1 has been used to evaluate the performance of the proposed Simplex-coded BOTDA sensor. A distributed-feedback (DFB) laser operating at 1535 nm with an optical power of ~10 dBm has been used. An optical coupler is used to split the CW-light into pump (70%) and probe (30%) branches. In our setup, differently to common BOTDA systems, the Mach–Zehnder modulator (MZM) used for pulse shaping (6 dB insertion loss) is placed after an erbium-doped fiber amplifier (EDFA), thus avoiding distortion of the coded-pulse sequences due to gain depletion in the EDFA and allowing for 15 dBm pump power at the fiber input. Considering the limitations to the peak pump power [1,4], this modification does not represent a significant penalty for the sensor, and it is essential to keep the original properties of the code. A waveform generator is used to control the MZM and generate either single pulses or 511-bit Simplex-coded pulses, with individual pulse duration of 10 ns, allowing for 1 m spatial resolution. In the probe branch, the laser light is intensity modulated using a MZM driven by a microwave [radio frequency (RF)] generator and a direct current (DC) voltage, producing two modulation sidebands around the laser frequency with a highly suppressed carrier [2]. Thus, by sweeping the frequency of the RF signal, the optical frequency of the probe can be conveniently scanned to sample the BGS along the fiber. To properly adjust the probe power launched into the fiber (set to −13 dBm per sideband), an EDFA and a variable optical attenuator (VOA) have been used. A polarization scrambler is used to depolarize the probe signal and reduce polarization-induced fading in the measurements. Probe and pump signals are launched in counter-propagating directions into a 50 km fiber. Note that the propagation of both sidebands of the probe signal reduces pump depletion and nonlocal effects [6], alleviating the possible additional depletion introduced by Simplex coding in long-range measurements. At the receiver side, only the lower frequency sideband (the Stokes component) is selected using a narrow-band fiber Bragg grating (FBG) (<0.1 nm) and detected by a 125 MHz photodiode, connected to a computer-controlled oscilloscope.

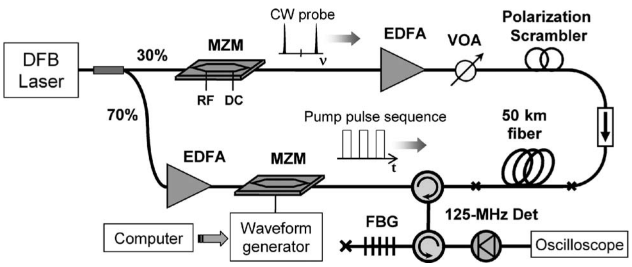

Fig. 1. Experimental setup for the coded-BOTDA sensor. DFB, distributed-feedback laser; MZM, Mach–Zehnder modulator; EDFA, erbium-doped fiber amplifier; VOA, variable optical attenuator; FBG, fiber Bragg grating.

To verify the real benefit resulting from coding techniques in BOTDA sensors, experiments were carried out using both 511-bit Simplex coding and single pulses by imposing similar measurement times. Thus, every code word has been averaged four times, which is equivalent to 2048 averages in the single-pulse case, and corresponds to a measurement time of ~1 s per frequency step. Figure 2 shows normalized BOTDA time traces measured at the maximum Brillouin gain (~10.986 GHz) when using both coded and conventional BOTDA schemes. The experimental coding gain (~10.3 dB) actually agrees with the expected theoretical value (10.5 dB). Thus, the far fiber end appears clearly visible when using coding, obtaining ~5 dB of SNR at 50 km distance, while a similar SNR is obtained only at 10 km distance in the conventional sensor. The 40 km distance enhancement is actually observed and is in full agreement with the prediction, considering the improved SNR and the fiber loss. Actually, in the conventional BOTDA sensor, BGS measurement is possible up to ~30 km distance only. However, when using Simplex coding, the BGS can be completely measured, with no distortion, along the 50 km of fiber, as shown in Fig. 3, allowing us to precisely evaluate the BFS along the fiber, as shown in Fig. 3 inset. The frequency accuracy on the BFS evaluation is ~2.2 MHz at 50 km distance in the case of coding, corresponding to a temperature and strain resolution of ~2.2°C and ~44 $\mu\varepsilon$, respectively. Figures 4(a) and 4(b) show the normalized BGS measured at 45 km distance for both Simplex-coded and single-pulsed cases, respectively. This comparison clearly points out the advantage of using pulse coding for long-range BOTDA sensors when high spatial resolution is required, since a com-

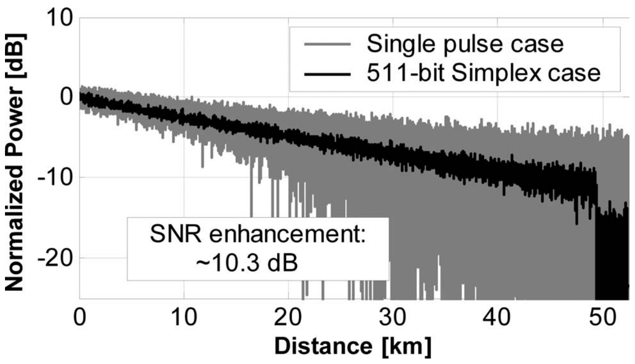

Fig. 2. BOTDA traces at 10.986 GHz for both Simplex coding (black line) and single-pulse (gray line) cases.

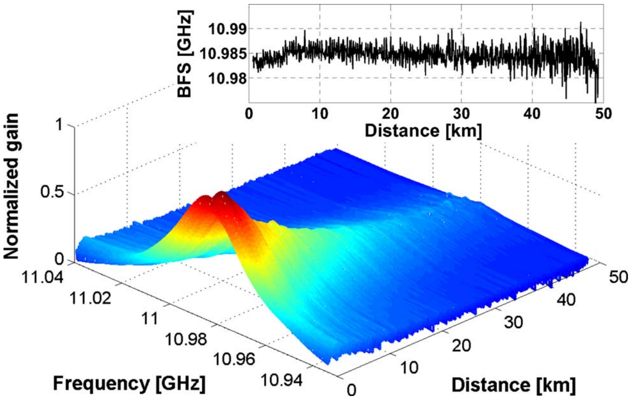

Fig. 3. (Color online) Brillouin gain spectrum and Brillouin frequency shift (inset) as a function of distance when using Simplex coding.

pletely noise-dominated spectrum, as the one obtained by the conventional sensor [Fig. 4(b)], can be effectively measured when using Simplex coding. Since pump depletion and nonlocal effects represent the main limitation of long-range BOTDA sensors, they have been carefully investigated in our measurements. If pump depletion occurs, the BGS should exhibit a hole "burned" around the BFS [6], which is not present in any of our measured spectra (see Figs. 3 and 4). To experimentally estimate the level of pump depletion, the relative change of pump power after propagation along the fiber has been measured with and without SBS interaction, resulting in a residual pump variation of less than 0.7%, indicating then negligible pump depletion. This feature is also confirmed by the linear behavior (in decibel scale) of the traces in Fig. 2. Moreover, when large pump depletion takes place, a sensible deviation of the BFS profile along the fiber should be present [1]; this effect has not been observed in our measurements, as shown in Fig. 3 inset.

Finally, to fully demonstrate a spatial resolution of 1 m over 50 km, we have changed the temperature (up to 50°C) of 1 m of fiber near 50 km distance, while keeping the rest of the fiber at room temperature (25°C). The BGS measured at the far end of the fiber is reported in Fig. 5(a), while Fig. 5(b) shows the BFS parameter in that region. We can clearly observe a variation of ~25 MHz in the BFS, corresponding to a ~25°C temperature change. The measured FWHM of the BFS change is ~1.0 m, demonstrating the potential of using optical pulse coding to achieve high spatial resolution in long-range BOTDA sensors.

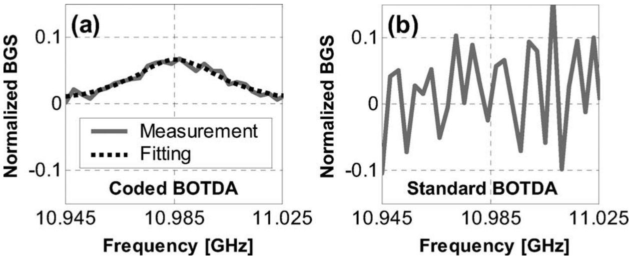

Fig. 4. Brillouin gain spectrum at 45 km distance when using both (a) Simplex-coded and (b) single-pulse BOTDA sensors.

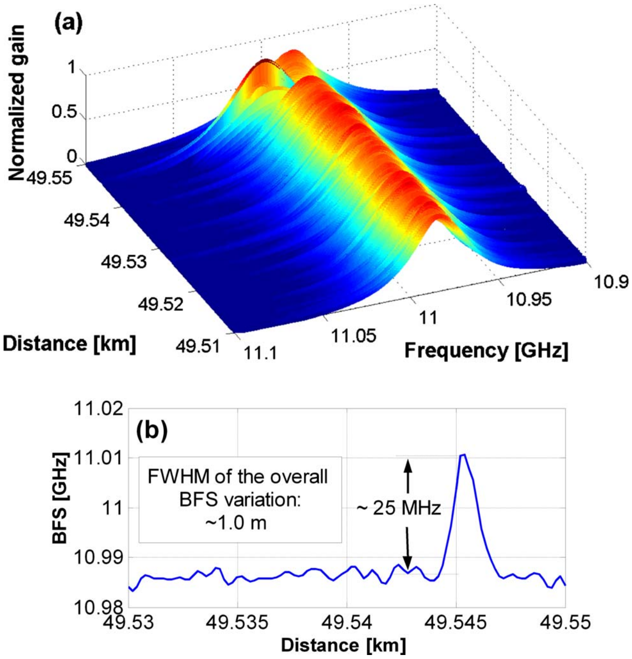

Fig. 5. (Color online) Experimental demonstration of 1 m spatial resolution over 50 km distance. (a) BGS and (b) BFS as a function of distance for the final meters (the initial part is omitted for clarity).

In conclusion, we have experimentally demonstrated that optical pulse coding can successfully extend the range of BOTDA-based sensors while maintaining high spatial resolution, allowing us to reach strain and temperature sensing over 50 km of single-mode fiber using 1 m spatial resolution and with an accuracy of 44 $\mu\varepsilon$ and 2.2°C, respectively.

References

1. A. Minardo, R. Bernini, L. Zeni, L. Thévenaz, and F. Briffod, Meas. Sci. Technol. **16**, 900 (2005).
2. S. Diaz, S. F. Mafang, M. Lopez-Amo, and L. Thévenaz, IEEE Sens. J. **8**, 1268 (2008).
3. X. Bao, J. Dhliwayo, N. Heron, D. G. Webb, and D. A. Jackson, J. Lightwave Technol. **13**, 1340 (1995).
4. D. Alasia, M. González Herráez, L. Abrardi, S. Martin-López, and L. Thévenaz, Proc. SPIE **5855**, 587 (2005).
5. M. A. Soto, G. Bolognini, and F. Di Pasquale, IEEE Photon. Technol. Lett. **21**, 450 (2009).
6. A. Minardo, R. Bernini, and L. Zeni, IEEE Sens. J. **9**, 633 (2009).