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Brillouin-based fiber sensing system employing a modified Brillouin ring laser

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Abstract

In this work we report on a tunable dual pump-probe optical source aimed at Brillouin optical time- and frequency-domain analysis sensing. The developed dual source exploits Brillouin ring laser technology and is capable of a large tuning range of ~200 MHz without using phase-locked loop or optical sideband generation techniques. With a linewidth narrower than 2.5 MHz and an output power ~0.5 mW, the proposed source has shown to be an efficient solution for Brillouin optical time-domain analysis (BOTDA) systems, allowing to achieve distributed sensing over 10 km single mode fiber in BOTDA experiments with strain and temperature resolutions of ~10 με and ~ 0.5 °C respectively.

1. Introduction

Distributed optical fiber sensors (DOFS) offer the possibility of monitoring several physical quantities along the optical length of the fiber in a distributed way through the analysis of the environment-dependent scattering suffered by the radiation travelling into the waveguide. DOFS based on Brillouin technology enable distributed measurements of both strain and temperature fields constitute the most studied and used DOFS systems in civil engineering and geological applications [3].

Brillouin Optical Time Domain Analysis (BOTDA) and Brillouin Optical Frequency-Domain Analysis (BOFDA) schemes exploit the temperature- and strain- dependence of the Brillouin frequency shift (BFS) of the back scattered radiation to reconstruct the spatial variation of the physical quantities under analysis over sensing length exceeding tens of km. Actually the phonon population of a portion of fiber is affected by local temperature and by the presence of mechanical deformation in accordance with the characteristic of fiber silica glass. Such spatial dependence of the phonon population leads to a variation in the spectrum of the Brillouin-scattered radiation, which can hence be used to reconstruct the temperature and strain distribution. In BOTDA schemes, the spatial variation of the BFS parameter is reconstructed by analysing the temporal intensity change of a continuous-wave (CW) probe signal which is counter-propagating with respect to a pulsed radiation (optical pump light). If the probe frequency lies within the Brillouin gain spectrum of the pump, some power is transferred from the pump to the probe. The efficiency of such transfer is given by the frequency difference between the probe signal and the Brillouin frequency shift which is dependent on the portion of material where the scattering takes place. The wavelength of probe signal is tuned so that the pump-probe frequency shift spans the whole Brillouin gain spectrum (BGS) of the pump. The BGS can be therefore reconstructed analysing the temporal variation of the probe signal intensity in correspondence of each of the selected frequencies.

In BOTDA schemes, the techniques which are commonly employed for tuning the probe signal frequency are based on Phase-Locked Loop (PLL) [4] or optical side-band (OSB) generation method [5]. In PLL technique, probe and pump signals are generated by different sources, slave and master laser, respectively. The slave laser is wavelength locked to the master slave through a feedback system which allows tuning the frequency of the probe signal. In OSB method, the probe signal is modulated through an Electro-Optical modulator (EOM) which is driven at a frequency which corresponds to the desired wavelength shift. Both techniques require the introduction of costly devices in addition to those employed in interrogator and sensor blocks. In particular, the PLL-based systems use narrow linewidth sources as slave lasers, and photodiodes and RF generators in the frequency-locking feedback system. On the other hand, OSB technique requires wide bandwidth EOM and an electrical signal generator exceeding 10 GHz. Furthermore, the complexity of the systems implementing the mentioned techniques leads to issues in terms of stability, accuracy in the wavelength shift and long term performance. Such aspects constitute indeed an obstacle to a larger scale development of BOTDA systems.

In this work we have studied a strain and temperature BOTDA sensing system which employs a recently developed pump-probe source based on Brillouin ring laser (BRL) technology. Such technique has been shown to provide good performance in terms of tunability, and features high efficiency and an inherent wavelength locking to the optical pump, despite the simplicity of the scheme which allowed for distributed sensing over 10 km single-mode fiber.

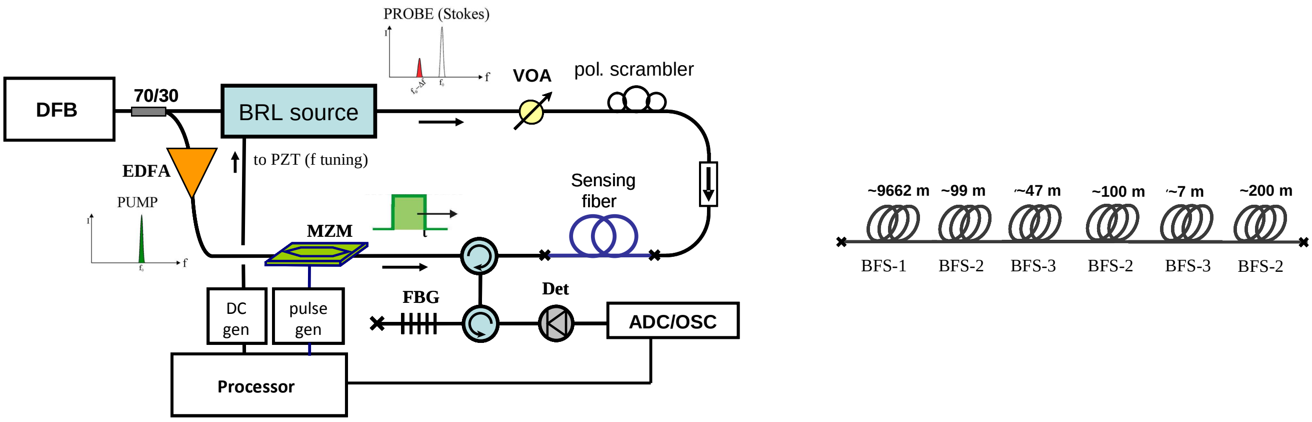

Fig. 2. (left) Brillouin optical time-domain analysis (BOTDA) sensor employing BRL light source. (right) Sensing fiber configuration including fiber spools with different BFS characteristics

2. BOTDA sensor experiment with BRL

The BOTDA system shown in Fig.2 (left) employs our recently developed tunable probe signal source based on Brillouin ring laser (BRL) technology [6]. The seed radiation, at λ =1551 nm with linewidth ~1.25 MHz, is generated by a distributed feedback (DFB) laser and is injected through a optical circulator in the fiber ring loop [7].

In BRL scheme, the probe signal is generated through Stimulated Brillouin Scattering (SBS) of the pump signal implemented through a recirculation loop employing a modified Brillouin fiber ring laser (BRL) [6]. A PZT actuator is used to impart a tensile strain on the fiber ring and shift the BFS so that the frequency of the generated probe signal is accurately tuned [6]. The Brillouin signal is then extracted through an optical coupler and used as probe signal in the BOTDA sensing systems. As shown in [6], for a 25 mW seed power, the attained probe power (0.5 mW), the bandwidth (FWHM) values (2.5 MHz) and tuning range (~200 MHz) are comparable with those of the signals commonly employed in BOTDA schemes.

3. Results

We have evaluated the performance of the developed BRL laser in a typical BOTDA pump-scheme sensor rshown in Fig. 2 (left). One portion of the seed signal (approximately 30%), is used to generate the CW probe signal through the employment of the BRL laser. The remaining power of the seed signal is used as the BOTDA pump signal which transfers part of its power to the probe signal along the fiber length accordingly to the frequency difference between the two signals.

A Mach Zehnder modulator (MZM) driven by a pulse generator modulates the intensity of the pump signal so that 40 ns pulses are generated. Both the pulse generator and the DC-voltage generator used for the PZT actuators are digitally controlled. The CW probe signal and the pulsed pump signals are inserted, in opposite direction, into the sensing fiber. The sensing fiber configuration is shown in Fig. 2 (right).

As described in the previous section, the frequency of the probe signal, is adjusted imparting an amount of tensile strain on the fiber ring coil in the BRL Source. The probe signal is

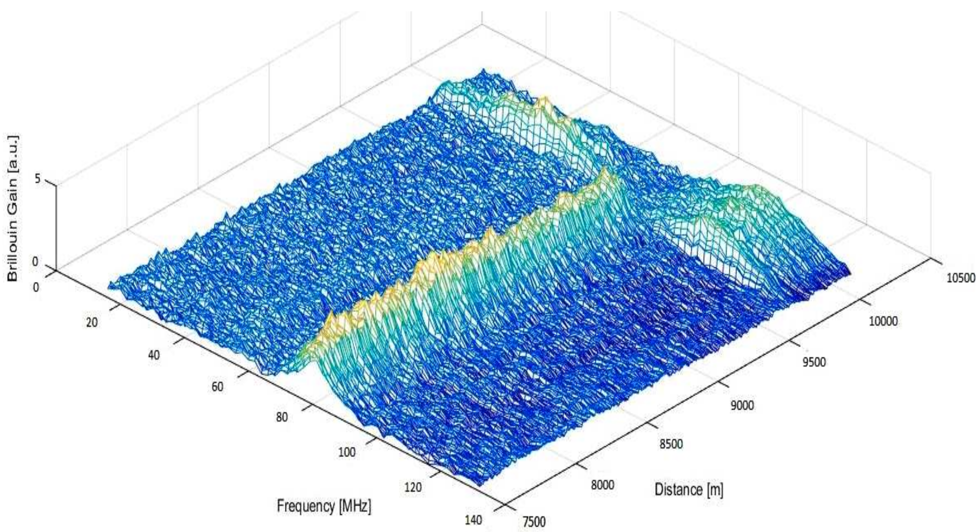

Fig. 3. Measured Brillouin gain spectrum (BGS) versus fiber length near fiber end.

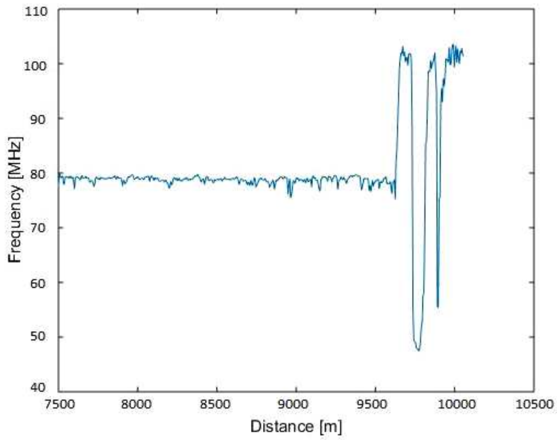

Fig. 4. Brillouin frequency shift (BFS) versus fiber distance.

collected at one end of the sensing fiber, through an optical circulator and coupled into a 100-MHz bandwidth photo-detector, sampled through an analog-to-digital converted and stored. In order to emulate the presence of temperature gradients and/or mechanical strain, the employed sensing fiber shown in Fig. 3(right) is constituted by several spools of single mode fibers having different BFS values.

Merging all the acquired probe traces for different frequency shift values and converting the time scale into fiber position in accordance with its time of flight, we obtained the BGS spectra for each fiber location. In Fig. 3 we have reported the obtained BGS spectra for the last kilometers of the sensing fiber, as a function of the distance. The blue- and red-shift of the BGS can be neatly observed in the last meters in correspondence of the presence of different spools of sensing fibers. The spatial interval at which BSF occur match with the length and position of the fiber spools.

Then, we inferred the BFS parameters through a Lorentzian fitting of the gain spectra for each spatial position. The results of such analysis are reported in Fig. 4 where the obtained BFS values are reported as a function of the distance from the end fiber. The behavior of the BFS clearly matches the one expected; in particular, in correspondence of the position of the fiber spool (BFS2) whose BFS is ~20-MHz up-shifted with respect to initial fiber, it is possible to observe an abrupt increase of the measured values. The same happens for the BFS3 fiber spools.

The frequency accuracy attained by BOTDA sensing with our proposed source, estimated by root-mean square variation form BFS graphs as the one shown in Fig. 4, results to be ~0.5 MHz, representing a resolution in temperature and strain equivalent to ~0.5 °C and ~10 $\mu\varepsilon$, respectively Even the BFS variation for the 7m short fiber spool (BFS3) is revealed by the graph. It is worth noting that such interval is close to the spatial resolution (4 m) achievable by the employed pump pulse duration.

Conclusions

We have carried out an experimental analysis aimed at the characterization of a BOTDA sensor employing the recently developed Brillouing ring laser (BRL) technology as pump-probe source. Such optical source, based on a modified Brillouin fiber ring laser, represents a cost-effective alternative to expensive and costly sources employed in conventional BOTDA systems and provides an easily tunable, pump-locked, narrow-wavelength probe signal. The analyzed BOTDA sensor is based on pump-probe scheme and has been tested on sensing fiber more than 10 km long. The experimental analysis has shown that the BRL based BOTDA sensor is capable of providing promising results in terms of temperature and strain resolution spatial accuracy. In particular, the measurements yielded strain resolution of ~ 10 $\mu\varepsilon$ and temperature resolution of ~ 0.5 °C and showed that spacial resolution limit imposed by the temporal width of the pulse is achieved.

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References

[1] T. Horiguchi, K. Shimizu, T. Kurashima, M. Tateda and Y. Koyamada, “Development of a distributed sensing technique using Brillouin scattering,” J. Lightwave Technol., vol. 13, no. 7, pp. 1296-1301, 1995.

[2] Soto M. A., Bolognini G., Di Pasquale F., and Thévenaz L., “Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range,” Opt. Lett., vol. 35, no. 2, pp. 259-261, 2010.

[3] Barrias, António, Joan R. Casas, and Sergi Villalba. "A review of distributed optical fiber sensors for civil engineering applications", Sensors, vol. 16, no. 5, pp.748.1-35, 2016

[4] Brown A.W., Smith J. P., Bao X., Demerchant M., and Bremner T., “Brillouin scattering based distributed sensors for structural applications”, J. Intell. Mater. Syst. Struct., vol. 10, pp. 340-349, 1999.

[5] Nikles M., Thévenaz L., and Robert P. A., “Simple distributed fiber sensor based on Brillouin gain spectrum analysis,” Opt. Lett., vol. 21, no. 10, pp. 758–760, 1996.

[6] Bastianini F., Marini D., and Bolognini G., “Modified Brillouin ring laser technology for Brillouin-based sensing”, proc. SPIE, vol. 9634, pp. 5E1-4, 2015.

[7]Ajiya M. et al., "Reduction of stimulated Brillouin scattering threshold through pump recycling," Laser Phys. Lett., vol. 6, no.7, pp. 535-538, 2009.