BOTDA sensing system employing a tunable low-cost Brillouin fiber ring laser pump-probe source

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ABSTRACT

In this paper we show a Brillouin optical time-domain analysis (BOTDA) sensing system experiment employing a tunable narrow-linewidth dual pump-probe source based on modified Brillouin ring laser technology. The developed cost-effective source generates a tunable pump-locked probe light, with suitable wavelength shift, large tuning range (~200 MHz), narrow linewidth (<2.5 MHz) and adequate power (~0.5 mW). The developed source was hence employed in BOTDA system experiments providing distributed sensing over ~10 km single mode optical fiber, and attaining strain and temperature resolutions of ~10με and ~0.5 °C respectively, indicating the pump-probe source as an efficient and cost-effective solution for BOTDA avoiding high-frequency signal generators or complex locking techniques.

Keywords: Fiber ring laser, Brillouin sensing, Brillouin optical time-domain analysis

1. INTRODUCTION

Distributed optical fiber sensors (DOFS) recently raised significant interest thanks to their unique capability of allowing spatial resolved measurements over long distance in applications ranging from energy to security, defense and structural health monitoring. DOFS based on Brillouin technology are in particular of increasing interest for structural and geological applications since they enable distributed measurements of both temperature and mechanical strain. Most popular Brillouin fiber interrogation schemes, such as Brillouin Optical Time-Domain Analysis (BOTDA) and Brillouin Optical Frequency-Domain Analysis (BOFDA), exploit the temperature-strain dependence of the Brillouin frequency shift (BFS) parameter [1,2] over sensing lengths exceeding some tens of km of Single-Mode Fiber (SMF), and are based on detection of stimulated Brillouin Scattering (StBS) detection with a pump-and-probe scheme.

Most BOTDA systems, in particular, work by reconstructing the BFS distribution along the fiber by acquiring the time-domain intensity change of a continuous-wave (CW) probe light that counter-propagates in the sensing fibre with respect to a pulsed pump light at a number of different pump-probe frequency shifts (fixed pump, tunable probe). The maximum probe light amplification (at the expenses of the pump energy in such a Brillouin-gain scheme) occurs when pump-probe frequency shift ($\Delta\nu$) equals the local acoustic phonon resonance frequency (i.e. the BFS), and then the acquired data in frequency-shift and time domains are processed to reconstruct the whole Brillouin Gain Spectrum (BGS) along the fiber, whose peak leads to BFS variations which carry the well known strain-temperature dependence [1]. Typical methods for generating a frequency-shift sweep of the probe light with respect to the pump λ involve the use of an optical Phase-Locked Loop (PLL) [3] or optical side-band (OSB) generation method [4]. In OSB, the probe light is obtained by modulating a fraction of the pump light through an Electro-Optical Modulator (EOM) that is driven by a microwave signal at the desired wavelength shift frequency, this requiring a fast EOM and 10 GHz-range tunable signal generator that implies increased costs and complexity. In PLL schemes, on the other hand, the probe is obtained from a secondary (slave) laser source wavelength-locked to the primary (master) laser through a feedback system capable to impose and keep constant a inducing a known, tunable wavelength shift between them. PLL-based solutions require essentially narrow linewidth sources as master lasers for adequate frequency-locking stability, and exhibit issues in feedback optimization/alignment and long term performance. Both PLL and sideband techniques above are complex and costly, and hindered the deployment of BOTDA systems over a large scale.

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In this paper, we apply the recently developed light source[†] providing pump-locked probe light [5], to a Brillouin sensor system based on BOTDA. The pump-probe source, implemented through a recirculation loop employing a modified Brillouin fiber ring laser (BRL), shows good tunable capabilities suitable for Brillouin sensing. A BOTDA system experiment session demonstrated distributed sensing over up to 10 km single mode optical fiber, attaining strain and temperature resolutions of ~10$\mu\varepsilon$ and ~0.5 °C respectively, indicating the pump-probe source as an efficient and cost-effective solution avoiding high-frequency signal generators or the use of PLL techniques.

2. BRILLOUIN FIBER RING LASER

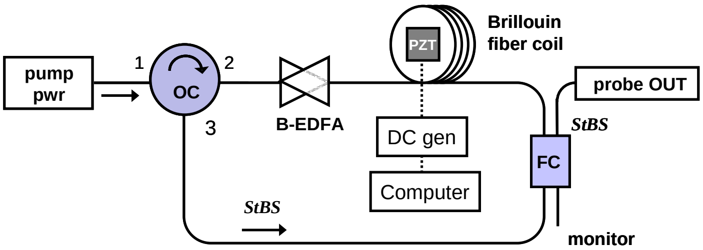


Fig. 1. Modified BRL source. B-EDFA: bi-directional Erbium-doped fiber amplifier, FC: fiber coupler, OC: optical circulator

The scheme of the developed modified BRL employed in BOTDA is shown in figure 1. The pump power employed in BOTDA (see next Section) is given by a distributed feedback laser (DFB) centered at λ = 1551 nm with ~1.25 MHz linewidth. A portion of pump power is employed in our BRL source, and is hence coupled to a single mode fiber (SMF) through port 1 on an optical circulator. No pump light recirculation is allowed in our scheme, unlike other coupler-based ring configurations [6]. A bi-directional Erbium Doped Fiber Amplifier (B-EDFA) [7] is then placed in order to boost the seed power and amplifying the generated StBS light, then effecting lowering the threshold level and enhancing the system efficiency. Note that no significant power oscillations were observed for gain values lower than ~15 dB. The Brillouin Scattering product Stokes line, together with the Rayleigh signal of the pump, propagating in the opposite direction of the seed, are reintroduced in the loop from OC port 2 through OC port 3. A portion of generated StBS backward-propagating radiation is tapped from the ring cavity by using an optical coupler (OC, 95/5 splitting ratio), and employed in BOTDA systems (probe OUT). The generated radiation must necessarily be tunable in BOTDA for accomplishing BGS reconstruction. Actually, to detect BGS under all sensing fiber strain/temperature conditions, a large probe tuning range is sought after. In our scheme, tunability of generated probe light was achieved through piezo actuators acting on the Brillouin ring fiber coil, driven by a DC-voltage generator. Actually, PZT actuators imparting tensile strain (up to ~4 mε) can enable a large tuning range over ~200 MHz, thus allowing one to monitor most sensing fiber strain/temperature conditions. Moreover, the generated probe light should be narrow linewidth enough to allow for a correct reconstruction of BGS without affecting the sensor resolution (therefore it should be much narrower than BGS linewidth). Linewidth was assessed through a delayed self-heterodyne technique [5, 8], providing an accurate worst-case characterization for MHz-wide sources. The light full-width half power was measured to be ~2.5 MHz, indicating a small value enabling an accurate BGS reconstruction in BOTDA sensing. The extracted power is measured by means of an optical power meter, resulting in a maximum output power of ~ 0.5 mW with the available 25mW input pump power.

3. BOTDA SENSOR EXPERIMENT

In order to demonstrate the ability of the developed source to be successfully employed in Brillouin sensing, we set up a BOTDA system incorporating the novel source. Figure 2 shows the experimental set-up of the BOTDA-based sensor employing the proposed BRL source. The common light source is a standard distributed-feedback (DFB) laser at 1.55 nm (see previous Section). The CW-light is first split into pump and probe branches by using an optical splitter. One of the outputs of the splitter is used as pump signal, and hence amplified by an Erbium-doped fiber amplifier (EDFA) and coupled into a Mach-Zehnder modulator (MZM), driven by a low-frequency pulse generator, in order to create high-power pump pulses (we employed 40 ns pulse width corresponding to a minimum spatial resolution of 4 meters.

[†] Patent pending

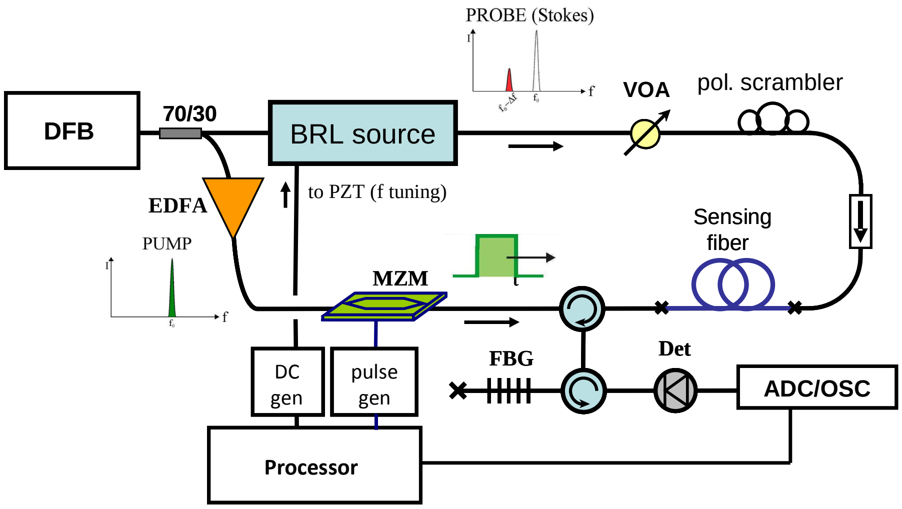
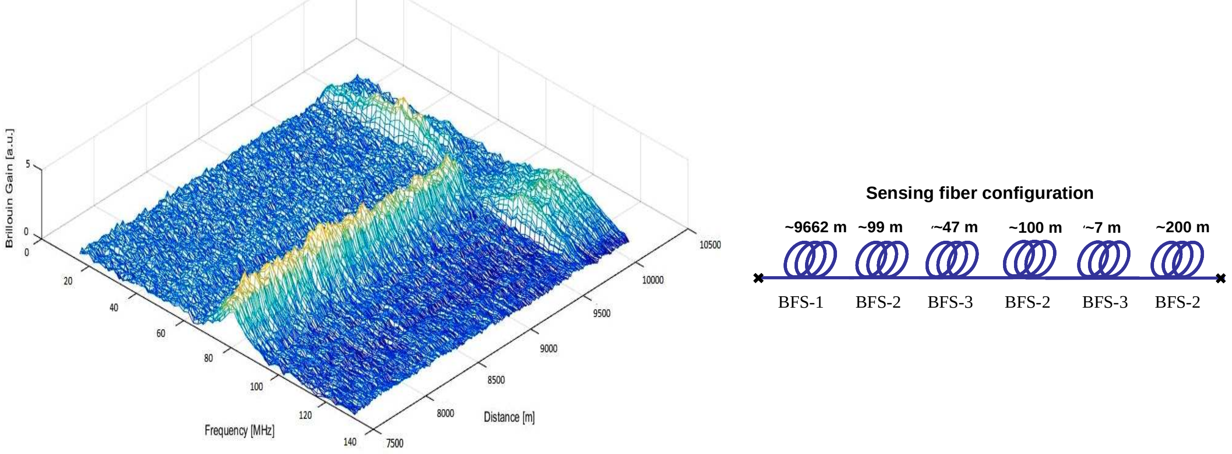


Fig. 2. Set-up of BOTDA sensor employing BRL light source

The pump pulses are hence coupled into one end of the sensing fiber. The other output port of the splitter is used in the BRL scheme to generate the probe signal (which is inherently locked to pump wavelength) as explained in previous Section. The generated CW probe power is then coupled at the other end of the sensing fiber. Tuning of the probe wavelength-shift with respect to pump wavelength is simply achieved by adjusting the tensile strain of the fiber ring coil, thus accomplishing BGS trace reconstruction. Since the efficiency of StBS is polarization dependent, a polarization scrambler has been used to depolarize the probe light, so that fluctuation of the Brillouin gain due to polarization changes along the fiber are highly suppressed. At one fiber-end, the probe light amplified by pump through StBS is collected, through an optical circulator, and coupled into a photo-detector (100 MHz bandwidth), with subsequent analog-to-digital sampling and data storage.

Fig. 3(a) shows the BGS measured along the last part of sensing fiber, by sweeping the modulation frequency of the probe signal. The sensing fiber itself is given by several spools of different single-mode fibers, each having different BFS characteristics, in order to emulate the typical BFS variation in presence of temperature (or strain) modifications, i.e. to estimate the sensing performance for a total of ~10 km SMF. The length of each fiber spool is shown in Fig. 3(b); in particular two very short spools of SMF (47 m and 7 m) exhibit BFS values (i.e. BFS-3) which are down-shifted by about 30 MHz from the initial long fiber spool BFS (BFS-1), and are interleaved with ~100 m fiber spools whose BFS (BFS-2) is ~20-MHz up-shifted with respect to initial fiber, providing a valid assessment for spatially-resolved sensing estimation in case of hot spots or short strained fiber sections.



(a) (b)

Fig. 3. (a) Brillouin gain spectrum (BGS) measurements as a function of the distance for last sensing fiber kilometers. (b) Sensing fiber configuration highlighting the different fiber spools with different BFS characteristics

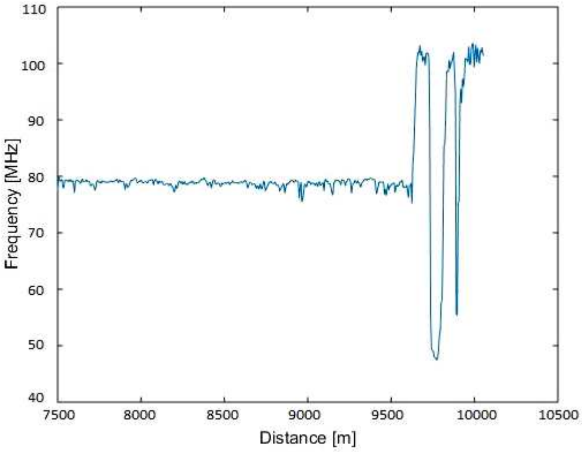


Fig. 4. Brillouin frequency shift (BFS) parameter versus distance.

The BFS parameter is then calculated from BOTDA traces by Lorentzian fitting of the gain spectra (BGS) for each fiber location. The result of BFS along fiber distance is hence shown in Fig. 4; in this figure, the ability of BOTDA to detect BFS variations in short fiber spools can be clearly observed (particularly in the 7 m fiber spool). The frequency accuracy attained by BOTDA sensing with our proposed probe source can be calculated as the standard deviation of the BFS trace in Fig. 4, and results to be ~0.5 MHz throughout the fiber length, representing a resolution in temperature and strain equivalent to ~0.5 °C and ~10 με, respectively.

In conclusion we have successfully applied our proposed optical source to distributed temperature and strain measurements in BOTDA-based sensing. The optical source, based on a modified Brillouin fiber ring laser, can be a cost-effective solution to overcome the limitations affecting conventional BOTDA systems (given by expensive and complex components and techniques) to provide a tunable, pump-locked narrow-wavelength probe signal. The BFRL source showed an adequate probe output power (~0.5 mW), large tunability (up to ~200 MHz), and a narrow linewidth (<2.5 MHz). This feature allowed us to successfully set-up a cost-effective BOTDA sensor scheme providing down to 4 meter spatial resolution over ~ 10 km single mode optical fiber with strain and temperature resolutions of ~ 10 με and ~ 0.5 °C respectively.

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