Feasibility study of a fiber ring laser working on the SLM regime in a BOTDA sensor

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***Abstract*—A feasibility study of the employment of a fiber laser working as the laser source of a Brillouin distributed sensor is presented in this paper. The Erbium Fiber Ring Laser structure designed works on the Single Longitudinal Mode regime. The main parameters of the ring cavity are analyzed in terms of the laser requirements and the performance of a Brillouin Optical Time Domain Analysis sensor using the fiber laser as light source.**

***Index Terms*—Stimulated Brillouin scattering, distributed systems, BOTDA, ring laser, SLM regime, optical fiber sensors.**

I. INTRODUCTION

RESEARCH efforts in the field of optical fiber sensors have considerably increased over recent years. In particular, distributed optical sensors based on different scattering phenomena have been a very active area of research due to their characteristics to carry out measurements over large sensing distances, several tens of kilometers, with high spatial resolutions, typically around 1 m [1]. In particular, Brillouin based solutions have been widely explored to enable different solutions exploiting both spontaneous (SpBS) and stimulated (SBS) Brillouin scattering due to their ability to provide temperature as well as strain measurements. Different solutions have been employed since the appearance of the proposal to measure distributed temperature using the nonlinear Brillouin effect [2]. One of the most popular solutions is the implementation based on the analysis of the SBS generated in the optical fiber in the time domain. Brillouin optical time domain analyzers (BOTDAs) have been extensively used in different applications, most of them related to structural health monitoring [3] or to the energy sector, for example in the detection of leakage in oil pipes [4]. SBS phenomenon appears when counter-propagating pump and probe waves interact within the optical fiber due to acoustic phonons [5]. Given that the pump wave in BOTDA sensors is pulsed, it is possible to retrieve distributed information along the optical fiber coming from the interaction between these two counter-propagating signals. The backscattering wave recovered provides information about the temperature or strain affecting the optical fiber with a given spatial resolution, determined by the duration of the pump pulse, which is normally reduced to 1 m due to the limitation imposed by the phonon lifetime [5]. Recently, different solutions have been proposed in an attempt to bypass that limitation and to reach higher spatial resolutions [6]–[8]. Another important improvement in BOTDA is the increase in the sensing ranges, reaching distances up to 100 km by means of coding techniques [9], or via Raman [10] or Brillouin assistance [11]. These systems have also limitations with the pump and probe powers injected into the optical fiber, as some detrimental effects could appear such as non-local effects [12] or pump depletion [13]. New strategies have been developed to overcome these limitations and to improve the performance of BOTDA sensors [14]. Increasing the probe power enables the improvement of the signal-to-noise ratio (SNR) of the sensor, which also implies an enhancement in its performance.

As mentioned before, increasing the SNR is a main goal in these systems due to its relationship with the estimation of the Brillouin frequency shift (BFS). It is also important to analyze the impact of different noise sources and their influence on the resulting SNR in BOTDA sensors. The different noise sources taking place on these sensors have been studied and modeled [15], concluding that they are very dependent on the fiber length and on the optical powers injected into the fiber, both pump and probe waves. The fiber length determines the nature of the dominating noise source, making it different for short and long sensing distances. The first is dominated by the phase-to-intensity noise conversion induced by the SBS process and the second is ought to a combination of sources, basically dominated by probe double Rayleigh scattering. The influence of some laser parameters on the noise of Brillouin sensors has also been analyzed in other works. In [16], the effect of laser phase noise has been studied when pump and probe are both continuous waves. This study concludes that the final performance of stimulated Brillouin amplification setups considerably depends on the coherence of the chosen laser source. The coherence of the laser source is responsible for reduced gain and gain fluctuations of the signal, originating from source phase noise. Moreover, laser sources employed in BOTDA sensors should have a high coherence, with linewidths narrower than the natural Brillouin gain spectrum (BGS) of the sensing optical fibers. In the case of single-mode fibers (SMF) the bandwidth of the BGS is around 35 MHz. This enables the usual employment of lasers with linewidths ranging typically from tens of kHz to a few MHz. It has also been analyzed how

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the laser linewidth affects the noise system for different pump pulse durations and fiber lengths [17]. This work demonstrates that the power spectral density of the laser frequency noise increases the system noise, thus showing a linear increase with the linewidth of the laser until it reaches a linewidth around tens of MHz, where noise saturates.

On the other hand, Erbium fiber ring lasers are devices that have attracted attention due to their potential applications in optical fiber sensing, sensor network multiplexing schemes and instrument testing due to their advantages: they are simple structures with narrow linewidths and compatibility with other optical fiber components. Over recent years, several techniques have been proposed to achieve a stable single longitudinal mode (SLM) operation in fiber lasers, such as the employment of a laser configuration based on serial connection of FBGs using optical circulators [18], or saturable absorbers operating as autotracking ultranarrow-band filters that always select the dominant mode [19].

In this paper, we propose the use of a stable configuration of Erbium Fiber Ring Laser (EFRL) as the source of a BOTDA system. The EFRL is based on an uniform fiber Bragg grating (FBG) working on the SLM regime. The laser features will be initially analyzed, especially its spectral linewidth and stability in terms of both optical power and wavelength. The proposed design overcomes some typical fiber ring laser problems such as multimode operation and wavelength instability. The inherent ability of FBG-based EFRLs to be tuned over a wide spectral range and to show very narrow linewidths might be of great interest for BOTDA implementations. Afterwards, the ring laser will be employed as the source of a BOTDA sensor. The performance of our design will be compared to the performance of a standard BOTDA employing a commercial distributed feedback laser (DFB). The feasibility of using EFRLs will be demonstrated measuring hot spots at the end of a 50 km fiber under test (FUT).

II. Theory

Brillouin sensors are based on the SBS process generated via the interaction of the counter-propagating probe and pump waves, where, in the case of time domain implementations, the latter is pulsed. In these systems, there is a linear relation between the BFS and the local temperature variation Δ_T and the applied strain Δ_ϵ, which can be expressed as follows [20]:

$$\nu_B(T,\epsilon) = C_\epsilon \Delta_\epsilon + C_T \Delta_T + \nu_B(T_0,\epsilon_0), \qquad (1)$$

where ν_B is the BFS, C_ϵ and C_T are the strain $(MHz/\mu\epsilon)$ and temperature $(MHz/^\circ C)$ coefficients and T_0 and ϵ_0 the reference temperature and strain. These values are mainly determined by the fiber composition and external protections (coatings and jackets) [21].

The first BOTDA implementation was proposed in 1989 by Horiguchi et al. [22]. In this first approach, two independent laser sources were employed to generate the pump and the probe waves respectively and, by measuring the amplification of the probe, the BGS could be determined. This system presents the inconvenience that it is complex to simultaneously adjust both lasers in power and frequency to generate the SBS process. For this reason, a new configuration appeared with only one laser source to avoid these problems [5]. This configuration, with the laser source and an electro-optic modulator (EOM), has been the base in most of the new BOTDA configurations. Nowadays, it is possible to find new implementations with more than one laser, but these proposals are related to amplification effects. There are different contributions based on using first [23] or second order [24] Raman amplification to improve the performance of BOTDA sensors. An alternative solution is based on injecting into the fiber the signal of a distributed Brillouin amplifier (DBA) to compensate the attenuation and amplify the BOTDA pump pulses to achieve large measurement distances [11]. Finally, an additional study has been carried out using a modified Brillouin ring laser instead of using traditional techniques based on phase-locked loops or optical side-band generation methods with EOMs. This technique has the advantage of enabling a cost-effective solution given that more expensive and complex devices are not required, such as the RF generator. Using this approach it is possible to tune the probe wave for a tuning range of 200 MHz without modulators, enough to analyze the BGS of a fiber and measure the BFS over a 10 km single mode fiber with 4 m of spatial resolution [25].

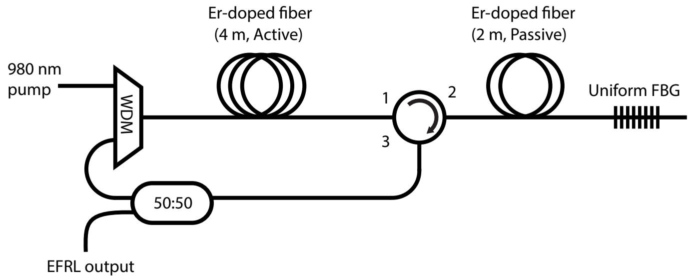

Fig. 1. Fiber Ring Laser configuration employed to achieve a SLM output. A 2 m section of Er-doped fiber is introduced before the FBG as saturable absorber to narrow the FBG response.

III. Experimental Issues

The proposed fiber laser configuration is depicted in Fig.1. The proposed setup uses two sections of commercial Er-doped fiber (I25 from Fibercore). The first 4 m long Er-doped fiber is pumped with a 980 nm pump laser to generate an erbium amplification around 1550 nm with a bandwidth of tens of nanometers. This amplification effect is launched through a 2 m non-pumped Er-doped fiber acting as saturable absorber to narrow the FBG response due to the Spatial Hole Burning (SHB) effect [26] and reaching the single longitudinal mode regime. After that, the resulting signal returns to the ring configuration via an optical circulator. One of the arms of the 50/50 optical coupler is used for the propagation of the signal within the ring and the other arm is the output of the EFRL that will be employed in the BOTDA setup.

The system employed to validate the feasibility of the EFRL as a laser source for distributed measurements is based on a conventional dual probe sideband BOTDA implementation. Fig. 2 shows the proposed setup. This sensor is the most

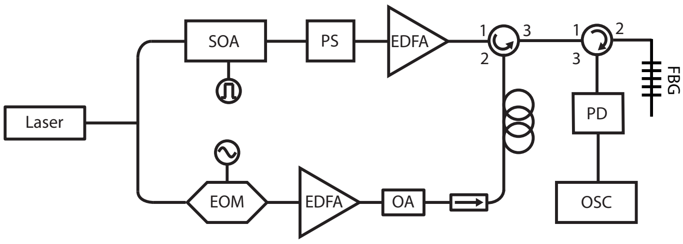

Fig. 2. Schematic setup of the BOTDA system used in the experimental tests: semiconductor optical amplifier (SOA), polarization scrambler (PS), erbium-doped fiber amplifier (EDFA), electro-optical modulator (EOM), optical attenuator (OA), fiber Bragg grating (FBG), photodetector (PD) and oscilloscope (OSC).

popular BOTDA configuration employed in the literature, where the light from a laser source working around $\lambda = 1550$ nm is divided using an optical coupler into two branches, obtaining the probe and pump waves. The upper branch of Fig. 2 is responsible for generating the optical pump pulses. To achieve this, a semiconductor optical amplifier (SOA) is employed with an external pulse generator. The duration of the electrical pulses determines the duration of the optical pulses that determine the spatial resolution of the sensor. The use of the SOA allows to reach extinction ratios above 40 dB. The frequency of the pulses defines the maximum length of the FUT, given that only one pump pulse can be transmitted within the fiber at any given moment. A polarization scrambler (PS) and an erbium-doped fiber amplifier (EDFA) are used to avoid the polarization dependence of the SBS gain along the fiber and to boost the pump pulse power, respectively. The probe wave, lower branch of BOTDA depicted in Fig. 2, employs an electro-optical modulator (EOM) driven by a RF generator to generate the modulated probe. It uses the double-sideband suppressed-carrier technique to generate the two sidebands. The probe is then amplified and afterwards attenuated with the help of an EDFA and a variable optical attenuator to establish a constant power and it is then launched into the FUT. For these measurements, the optical fiber employed to verify the performance of the sensor is a 50 km long SMF. The detection scheme employed is based on the direct detection of one of the two sidebands (Stokes or anti-Stokes) [27]. This means that, once the SBS process has taken place within the FUT, the resulting optical signals are circulated and filtered with a narrow FBG. In this case, the Stokes component is reflected by the FBG and detected with a 125 MHz photodetector (PD). Finally, the electrical signal is acquired and averaged with an oscilloscope.

IV. Experimental results

A set of experimental tests was carried out to study the feasibility of using the proposed EFRL to perform distributed measurements within a BOTDA sensor. Some key laser parameters have initially been measured, such as the optical and electrical output spectra and the wavelength and power stability in time, in order to check the SLM working regime of the EFRL. These results have been compared with those obtained using a commercial DFB laser diode manufactured by EMCORE, with both lasers working around 1550 nm. One of the advantages of the EFRL structure is that the operating wavelength could be easily modified between 1500 to 1600 nm only by changing the chosen uniform FBG.

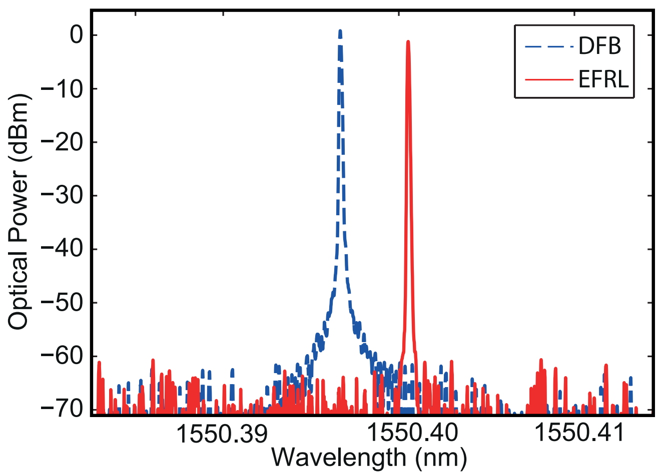

Fig. 3. Optical spectrum comparison between DFB (blue dashed line) and EFRL (red solid line) lasers.

Fig. 3 presents the comparison of the spectra associated with both lasers using a Brillouin optical spectrum analyzer (BOSA) with a high spectral resolution of 0.082 pm. In order to equalize the output power of both lasers, an optical attenuator has been employed with the DFB to reduce the optical power down to 0 dBm for a better comparison. It is important to note that the wavelength of the EFRL is easily modifiable by simply changing the temperature/strain conditions of the FBG. For a fair comparison, the FBG has been tuned to achieve an EFRL wavelength (red solid line) very close to the one produced by the EMCORE laser (blue dashed line). This fine-tuning is achieved using a mechanical setup formed by a fiber holder and a single-axis positioner, with a separation of tens of cm between them. The FBG is attached to these two positioning elements and it is stretched to the desired position via the single-axis positioner to establish the desired wavelength. The results show a very similar optical spectrum for both lasers, with a narrow spectrum and monomode behavior.

As explained in [17], the phase noise of the laser is directly proportional to its linewidth, and the noise of a BOTDA sensor increases linearly with the power spectral density of the laser frequency noise, so a narrower laser source would enable an improved performance. In this regard, an analysis of the linewidth of each laser has been carried out with the help of an electrical spectrum analyzer (ESA).

In order to measure the FWHM linewidth of the emitted wavelength, the delayed self-heterodyne detection scheme [28] has been employed. The measured electrical spectrum of the ERFL is depicted in Fig. 4 with a blue dashed line, while the associated Lorentzian fitting has been represented with a red solid line. The laser linewidth is half of the 3-dB linewidth of the measured electrical spectrum due to self-convolution. According to this procedure, the measured laser

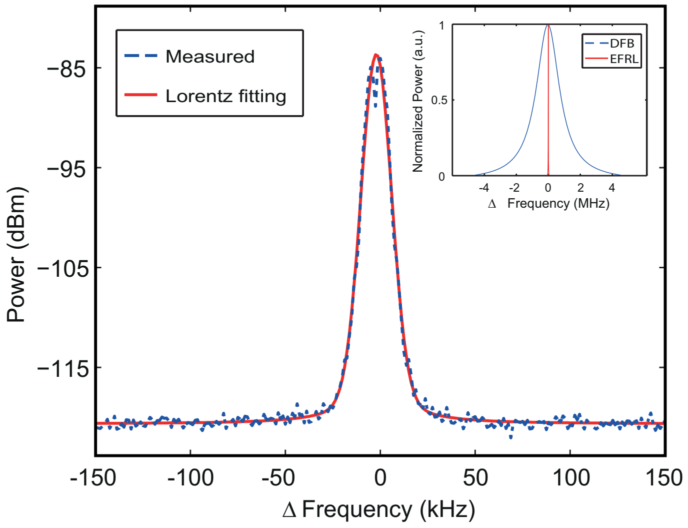

Fig. 4. Measured data of electrical spectra of EFRL (blue dashed line) and the resulting Lorentzian fitting (red solid line). The inset shows a comparison of the electrical output spectra of DFB (blue dashed line) and EFRL (red solid line) lasers.

linewidth is around 3 kHz. Moreover, a comparison between the electrical spectra of the commercial DFB (blue dashed line) and the EFRL (red solid line) lasers are shown in the inset of this figure. Both spectra have been represented after applying a Lorentzian fitting process and normalizing it in terms of their maximum, showing that the proposed fiber laser is considerably narrower than the commercial one, which exhibits an estimated linewidth of 700 kHz.

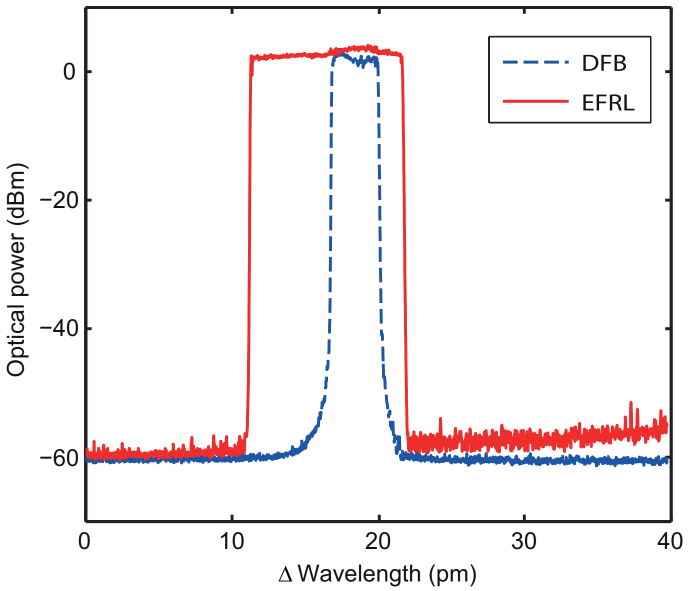

Fig. 5. Optical spectral stability of DFB (blue dashed line) and EFRL (red solid line) lasers after 4 hours.

Stability, in terms of wavelength and power, is another key parameter associated with laser performance. Some initial measurements, depicted in Fig. 5, were carried out with the proposed setup explained in the previous section. We realized that, with this setup, the output wavelength of the EFRL

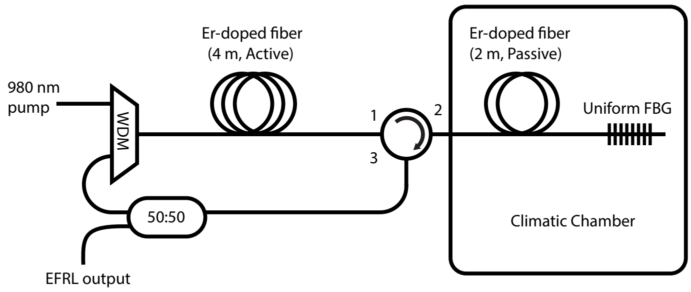

Fig. 6. Fiber Ring Laser configuration employed to achieve a better wavelength stability. A 2 m section of Er-doped fiber and the FBG are inside a climatic chamber.

(red solid line) was very variable during the 4 hours of the test, due to room temperature changes in the laboratory. The commercial DFB (blue dashed line) does not present this problem, as it is always thermally controlled.

The setup was modified to improve the stability. Both non-pumped Er-fiber and FBG were put into a climatic chamber where temperature is under control. The modification of the setup is shown in Fig 6.

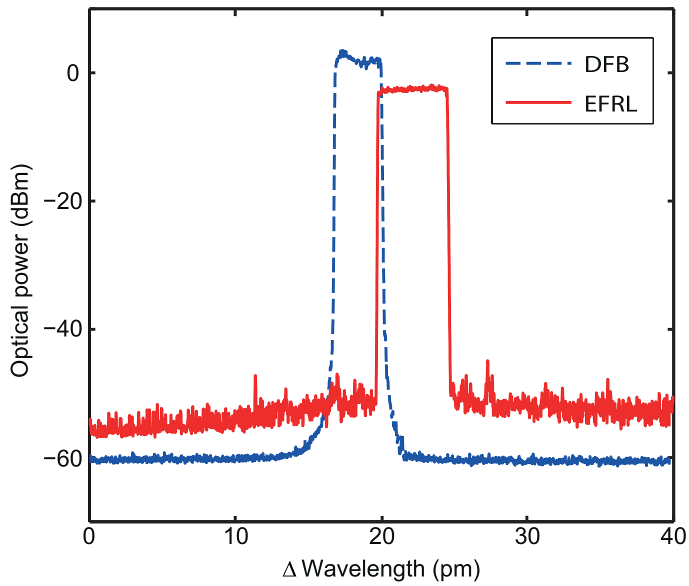

Fig. 7. Optical spectral stability of DFB (blue dashed line) and EFRL (red solid line) lasers after 4 hours using the climatic chamber.

With this new configuration, it might be feasible to use the EFRL as the source of a BOTDA sensor, given that a fixed and stable operation wavelength is required. In the BOTDA configuration employed for this study (dual probe sideband implementation), one of the sidebands is filtered out using a narrow FBG (after the interaction takes place) and the other is photodetected and analyzed. For this reason, it is essential that the wavelength of the probe wave, dependent on the laser source, and the filtering FBG exhibit wavelength consistency. As can be appreciated in Fig. 7, now the results present a similar behavior for both DFB (blue dashed line) and EFRL (red solid line) lasers, with a fluctuation of approximately 5 pm

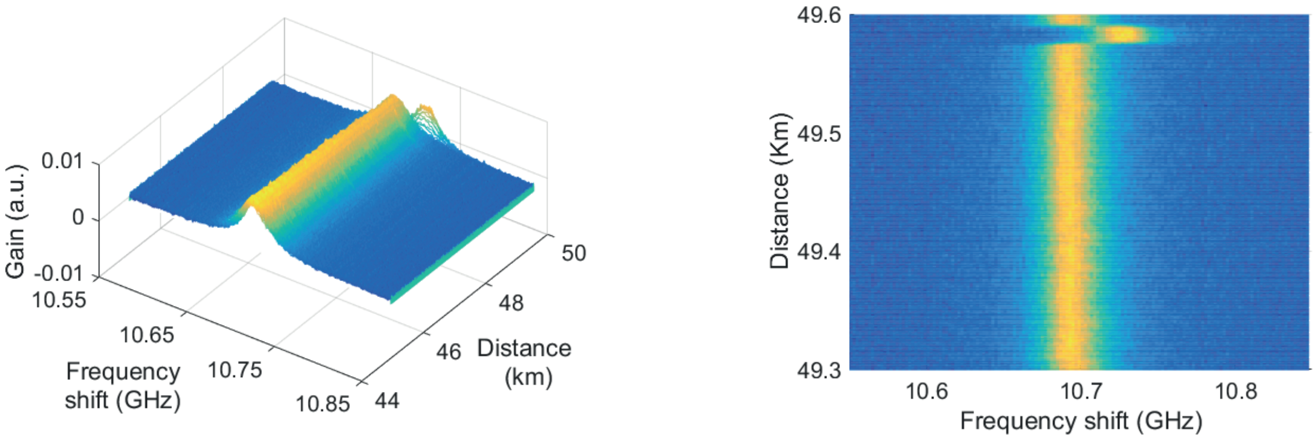

Fig. 8. 3D map (a) and top view (b) of Brillouin gain measured employing the EFRL: (a) Last 5 km of the sensing fiber and (b) last 300 m where the hot spot can be better observed.

with respect to the center wavelength. This value is measured recording the optical spectra with the BOSA during 4 hours.

Once a suitable performance of the EFRL was achieved, some distributed measurements were carried out over a long FUT to check the feasibility of the proposed solution. The sensing fiber is an uniform 50 km single mode fiber at room temperature, where the last 20 m have been placed inside a climatic chamber at 50°C to measure a hot spot. The spatial resolution of the sensor was set to 5 m, and the frequency of the probe wave was swept from 10.55 to 10.85 GHz with a frequency step of 2 MHz.

Fig. 8(a) shows the retrieved 3D data of the BGS measured using the BOTDA sensor with the EFRL. Only the last 5 km of the sensing fiber are shown for a better understanding of the achieved results. The changes of the central frequency of the BGS are clearly identified at the end of the fiber due to the presence of the hot spot. A zoomed version of the last 300 m of the gain data is shown in Fig. 8(b) using a top view of the 3D map. The shift of the Brillouin frequency (around 30 MHz) can be easily identified at the hot spot section.

After the BOTDA traces are obtained, a Lorentzian fitting is applied to the BGS measured at each spatial point along the 50 km fiber estimating the resulting BFS. The same process is put into practice with other measurements made with the DFB laser at the same conditions, and the results are depicted in Fig. 9. Again, the 3D map only presents the last 10 km of the FUT. As can be observed, the distribution of the BFS along the fiber is practically the same for both lasers, DFB and EFRL (blue and red lines, respectively). An inset with the BFS over the last 300 meters has also been included in the figure to verify that the hot spot is correctly resolved, showing a difference of about 30 MHz, corresponding to a temperature change of about 30°C, as expected.

Fig. 8 and 9 demonstrate that the EFRL can be used as the laser source of a BOTDA sensor to perform distributed measurement with similar results to those obtained with a DFB laser diode.

Finally, an analysis of the error in the determination of the BFS along the optical fiber is performed when the fiber spool

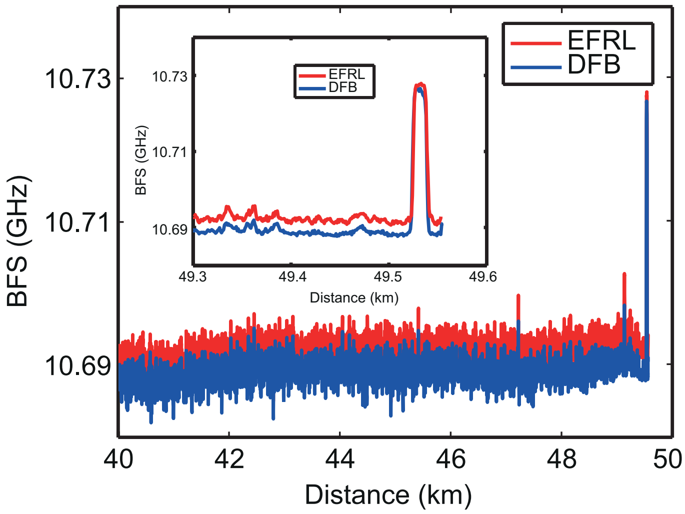

Fig. 9. Estimated BFS over the last 10 km of the FUT. The inset only shows the BFS near the hot spot section. The red line represents the BFS measured with the EFRL and the blue line with the DFB.

is maintained at a constant temperature of 25°C. 10 measurements were performed with each BOTDA configuration always with the same temperature and strain conditions. The error is calculated as the standard deviation of the BFS at each spatial point of the FUT. The results are not as good as expected, showing that the EFRL setup exhibits an almost double BFS error estimation in comparison to the DFB. These results have been represented in Fig. 10, where it is possible to appreciate the whole FUT length. The error varies from 0.4 to 1 MHz for the EFRL (red line) and from 0.2 to 0.5 MHz when the resulting BFS is measured employing the DFB (blue line).

V. Conclusion

The feasibility of using a Erbium fiber ring laser as the laser source in a BOTDA sensor has been analyzed in this work. These systems typically employ DFB lasers to generate the SBS process. Our proposal is to use an Erbium fiber ring laser working on the Single Longitudinal Mode regime instead

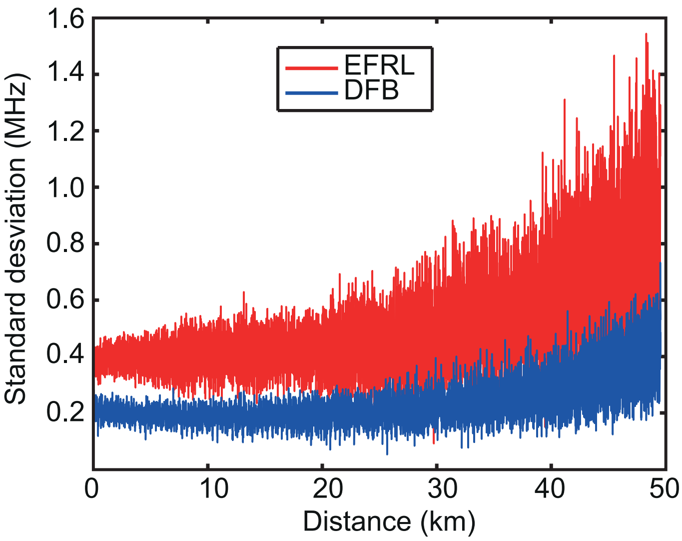

Fig. 10. Standard deviation of the estimated BFS vs fiber distance for both lasers (EFRL in red and DFB in blue)

of the DFB to perform distributed measurements based on Brillouin scattering. Initially, some key laser parameters like the output spectrum and the wavelength and power stability were measured and also compared with the DFB. These results can be considered suitable after performing a temperature stabilization of the EFRL structure.

Afterwards, the feasibility of using this laser in a BOTDA system was verified by measuring a hot spot of 20 m at 50°C at the end of a 50 km fiber spool and comparing the results with those provided by a commercial DFB laser. The results achieved at the hot spot section prove that the proposed laser implementation is able to correctly estimate the BFS, although it exhibits a higher noise level than the DFB. Nevertheless, the results are promising and the viability of using a fiber laser in BOTDA implementations has been demonstrated. This could open up the possibility of improving the EFRL configuration or using other Erbium fiber laser approaches to improve the final performance of the sensor. Among other possible advantages, the proposed structure has the ability to be tuned over a wide spectral range, from 1500 to 1600 nm, only by changing the uniform FBG and also to be fine tuned modifying the temperature or strain conditions surrounding the FBG. Moreover, these are flexible structures allowing the possibility of including the laser modulation within the ring structure, thus giving rise to interesting solutions for some implementations.

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