DBR fiber laser sensor with polarization mode suppression

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***Abstract*—A Distributed Bragg Reflector (DBR) fiber laser sensor based on a commercial high-birefringence Er-doped fiber has been proposed. The spectral overlap of two uniform Fiber Bragg Gratings has been employed as filtering technique to achieve a sensing head that operates in the Single Longitudinal Mode regime. The high-birefringence Er-doped fiber has been employed to remove a polarization mode, only allowing the oscillation of a single polarization mode. In this way, a single frequency operation with a very stable laser output has been achieved. The proposed fiber laser exhibits a linear response for both strain and temperature variations, keeping the SLM regime and the polarization mode suppression.**

***Index Terms*—Fiber lasers, Erbium, Single Longitudinal Mode, Fiber Bragg Grating**

I. Introduction

Fiber Bragg gratings (FBG) [1], [2] have played an important role in the development of optical fiber sensors and telecommunication systems among other fiber optic devices. The performance of FBG sensors must be improved, covering more complex requirements for specific applications. Particularly, fiber grating laser sensors have been proved to be a reliable technology for sensing devices. Short fiber laser sensors can be mainly found under two basic configurations: Distributed Bragg Reflector (DBR) or Distributed Feedback lasers (DFB) [3], where both the active medium and the filtering elements are included within the sensing head. Fiber laser sensors exhibit the same advantages of passive FBG sensors such as linearity or multiplexing capabilities, but they also improve the signal-to-noise ratio in comparison to other approaches.

Usually, the Single Longitudinal Mode (SLM) regime is required for high precision fiber laser sensors; however, some of their characteristics have to be improved to allow very high resolution sensing systems, particularly the stability of the output signal and the laser linewidth. SLM Fiber lasers based on DBR and DFB structures typically exhibit two orthogonal polarization modes caused by the fiber birefringence [4], what can be attractive to develop polarimetric fiber sensors [5], but limits their final resolution.

Single Polarization Mode (SPM) fiber lasers, where only a single orthogonal polarization mode is active, can improve these limitations, but achieving a robust SPM behavior may prove difficult. Some methods for ensuring a SPM in fiber lasers have been experimentally reported (especially for DFB lasers) [6]–[9]. A particular approach is based on provoking an external birefringence [6], [8] to allow only a single polarization mode. However, this birefringence should be uniformly distributed along the laser cavity, what limits its final robustness.

In this work, two techniques have been combined to obtain a Fiber Laser Sensor working on SLM regime with a single polarization mode. Employing a spectral overlapping technique [10] and a commercial high-birefringence (Hi-Bi) Er-doped fiber, a proof-of-concept Fiber Laser Sensor with a SPM has been manufactured and experimentally tested. The experimental results exhibit the same linearity of Fiber Bragg Gratings (FBGs) with strain and temperature but with a very stable laser output.

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II. Working principle

The spectral overlap technique has been proved a reliable method to achieve SLM lasers [10]. This method is based on combining two uniform FBGs of matched Bragg wavelengths, being one slightly detuned and keeping its reflection spectrum partially overlapped with the other. In this way, the whole spectral overlapped response of both FBGs becomes narrower than those associated with the two individual FBGs (Fig. 1). However, a DBR cavity inherently emits in two different lasing wavelengths due to the existence of the two orthogonal polarization modes. These competition between the polarization modes can provoke fluctuations in the output power.

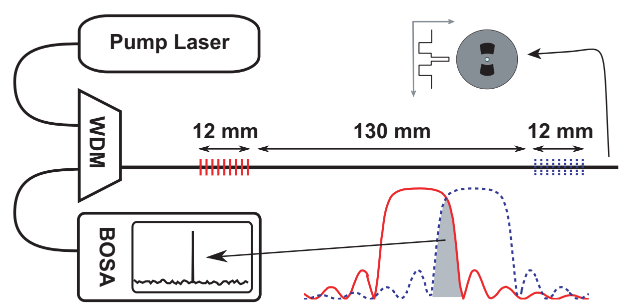

Fig. 1. Setup employed during the manufacture process. The DBR fiber laser structure is also depicted: two uniform FBGs of 12 mm length separated 130 mm.

On the other hand, the Polarization Hole Burning (PHB) effect introduces an inhomogeneous broadening of the gain, what modifies the amplification properties of each polarization mode. This effect can be defined as Polarization Dependent Gain (PDG) [11] and has influence on the active lasing modes. Trying to model the PDG within Er-doped fiber laser cavities, the erbium ions can be split into two groups [12]: ions that are "parallel" to the polarization of the signal and ions that are "orthogonal" to the polarization of the signal. For these groups the emission and absorption coefficients can be defined as (Eq. 1):

$$\begin{aligned} \alpha_{\parallel}(\lambda) = &\ \alpha(\lambda)(1+\epsilon); \quad g^{*}_{\parallel}(\lambda) = \ g^{*}(\lambda)(1+\epsilon); \\ \alpha_{\perp}(\lambda) = &\ \alpha(\lambda)(1-\epsilon); \quad g^{*}_{\perp}(\lambda) = \ g^{*}(\lambda)(1-\epsilon); \end{aligned} \tag{1}$$

where $\alpha(\lambda)$ and $g^{*}(\lambda)$ are the absorption and the emission coefficients, respectively. Symbols $\|$ and $\perp$ indicate "parallel" and "orthogonal" ion groups and ϵ is the anisotropy parameter. From Eq. 1, it can be deducted that if some anisotropy is provoked to the fiber, there will be different oscillation conditions between the two polarization modes and, consequently, a stable oscillation of a single polarization mode (SPM) can be achieved.

Trying to take advantage of both effects, the spectral overlap technique and PDG, two FBGs written into a commercial Hi-Bi Er-doped fiber can be employed to build a DBR structure. The SLM regime can be obtained by slightly detuning a FBG, while the fiber birefringence just allows a single polarization mode. Based on this combination, a proof-of-concept DBR fiber laser has been manufactured into a commercial HiBi Er-doped fiber.

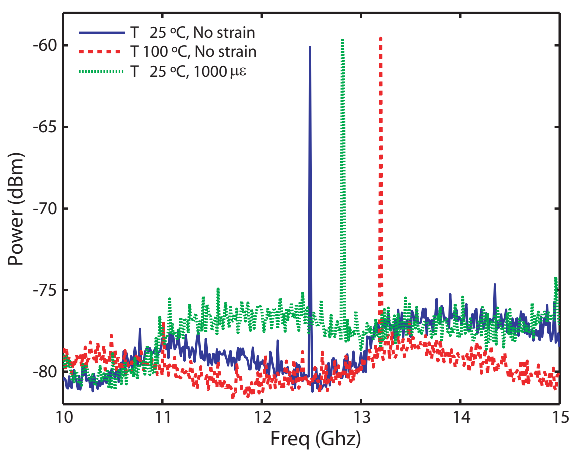

Fig. 2. SLM operation measured for different conditions. The laser signal is mixed with a TLS source obtaining a single peak

III. Manufacture process

Two matched FBGs have been written into a commercial Bowtie Er-doped fiber of Fibercore (DHB1500), using the phase mask technique with a continuous laser emitting at 244 nm. A small Gaussian apodizing function has been applied to reduce the secondary lobes of both FBGs. After writing both FBGs, one of them has been post-exposed to drift its Bragg wavelength and reduce the overlapping area, consequently achieving a narrower equivalent filter. The achieved FBGs have a reflectivity around 100% with a FWHM bandwidth of 0.6 nm. The employed fiber has an absorption ratio of 10dB/m at 980 nm

During the FBG post-exposition, the DBR fiber laser has been pumped at 980 nm to generate the laser emission. The laser signal has been monitored by using a high resolution optical spectrum analyzer (BOSA-C Aragon Photonics) to measure the behavior of the longitudinal modes. The FBG drift has been stopped when the SLM behavior has been measured at the BOSA. During the manufacture, the Single Polarization Mode (SPM) response has been verified even when more than a single longitudinal mode was active. The proposed DBR structure has a total length of $L \approx 154\ mm$ and it is depicted in Fig. 1.

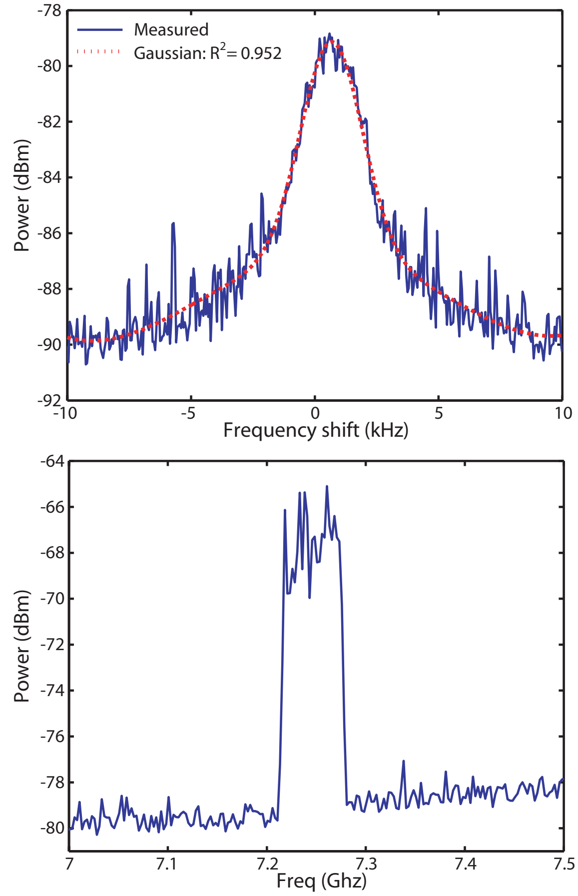

Fig. 3. Linewidth of 1.66 kHz (3dB) measured using self- heterodyne detection with a modulation frequency of 10 GHz (top). Wavelength stability (57.5MHz) of the mode measured during 10 minutes (bottom)

IV. Experimental response

After finishing the proposed device, different properties have been experimentally obtained. The proposed device has been conceived to achieve a very stable response due to its SLM operation with polarization mode suppression thus, the first tests have been employed to verify this SLM operation.

Employing a heterodyne detection system, the DBR fiber laser output has been mixed with the signal of a Tunable Laser Source (TLS) using a 3 dB coupler. The TLS (Agilent 8164B) has a full-width at half maximum (FWHM) linewidth of 100 kHz and its wavelength has been placed close to the manufactured laser. This combination has been translated to the electrical domain using an Optical Converter (HP11982A) and an Electric Spectrum Analyzer (HP8592L). In Fig. 2, a single peak is shown, proving the SLM operation with polarization mode suppression of the tested device.

The SLM verification has been performed at room temperature (25 $^{\circ}C$). Moreover, the laser temperature has been risen in a climatic chamber up to 100$^{\circ}C$, verifying the SLM and SPM operation at higher temperatures. On the other hand, when some strain has been uniformly applied being the room temperature maintained at 25 $^{\circ}C$, the proposed fiber laser also keeps its very stable behavior. The achieved electric-domain captures depicted in Fig. 2 prove the SLM operation of the manufactured device even with temperature or strain variations.

A. *FWHM linewidth and wavelength stability*

The heterodyne setup has been changed to the delayed self-heterodyne detection scheme [13], in order to measure the FWHM linewidth of the emitted wavelength. A phase modulator (Photoline MPZ-LN20) has been employed to perform the 10 GHz modulation. A 130 km length standard optical fiber has been employed as delayed line. An EDFA (Photonetics BT17) has been introduced in the setup to amplify this delayed line. According to [13], the measured (FWHM) linewidth was the square root of two times the real linewidth, so the achieved linewidth was under 2 kHz as shown in Fig. 3 (top), improving the results achieved with a similar structure in [10] (1.66 kHz vs. 4.5 kHz). This narrow linewidth suggests a very stable SLM operation of the fiber laser, being an important factor to achieve high resolution in sensing systems, what is related to the linewidth and stability of the emitted laser wavelength.

Fig. 3 (bottom) also shows the wavelength stability measured using the heterodyne detection method.The laser signal was mixed with the TLS and the single laser mode was held in the ESA for 10 minutes. The measured wavelength stability of the single mode was under 58 MHz (0.46 pm) even without being isolated from environmental vibrations, which is comparable to the 62 MHz achieved in [10] for a polarization mode.

B. *Power stability*

The output laser signal was directly connected to an OSA (HP70952B) to study the power behavior of the manufactured laser. Maintaining the pump current at 100 mA, the output generated optical power was monitored during 30 min using the OSA.

In Fig. 4 (top), the power stability measured each 30 seconds (bottom) is depicted, achieving a drift of 0.12 dB with a 90% confidence interval during 30 minutes. For the pump current employed to the stability test (100 mA), the output laser exhibited an optical signal-to-noise ratio (OSNR) greater than 45 dB.

The proposed device exhibited a great power stability even without being isolated from environmental vibrations (0.12 dB vs 0.91 achieved in [10]). This stability is originated by a very stable SLM operation that has been improved by the lack of competition between polarization modes, proving the benefits of the polarization mode suppression for achieving high performance devices.

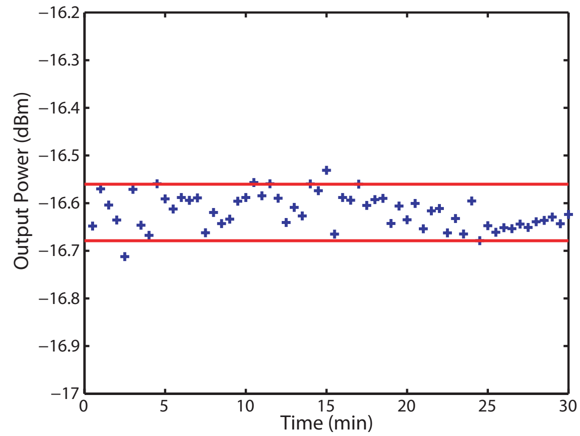

Fig. 4. Power stability measured during 30 minutes.

C. *Temperature and strain responses*

After measuring the behavior of the manufactured laser, it has been tested for sensing purposes by obtaining its temperature and strain responses. Employing a climatic chamber to perform a temperature sweep from 20 $^{\circ}C$ to 100 $^{\circ}C$ and a micrometric linear motor stage to apply different strain values to the laser, both sensitivities have been experimentally obtained by measuring the laser output using an OSA.

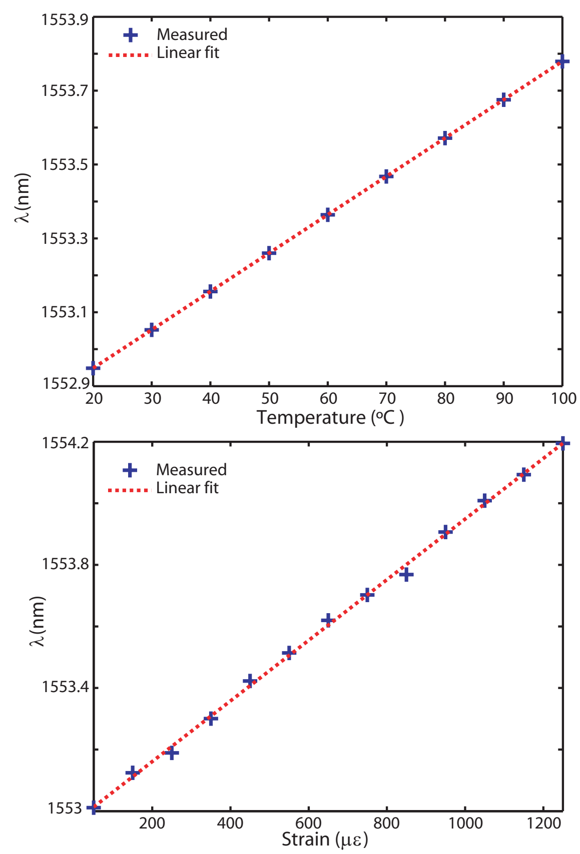

Fig. 5. Power stability measured during 30 minutes (top) and output power against the pump current (bottom).

The laser response to the temperature sweep is depicted in Fig. 5 (top). The whole DBR structure behaves as its mirror FBGs, exhibiting a linear response with a 0.8 nm drift within the 80 $^\circ C$ sweep (similar to a FBG written into standard fiber). After its thermal characterization, the manufactured device has been monitored during the strain sweep and the results are depicted in Fig. 5 (bottom). As happens with temperature variations, the whole DBR structure behaves as its mirror FBGs, also exhibiting a linear response with strain. The SLM operation has been also verified during the temperature and strain sweeps and the achieved results have been previously depicted in Fig. 2. The manufactured laser can be also employed as a high resolution sensing head, improving the working distance of passive transducers (e.g. FBGs).

V. Conclusions

In this work, a DBR fiber laser sensor working in SLM regime has been designed to achieve a very stable laser output by only allowing the oscillation of a single polarization mode. Combining the spectral overlapping technique with a commercial Hi-Bi Er-doped fiber, a proof-of-concept fiber laser sensor has been manufactured and experimentally tested. The SLM regime has been achieved by the partial overlap of two uniform FBGs while, using a Hi-Bi fiber to modify the oscillation conditions between the two polarization modes, the SPM has also been obtained.

The SLM regime has been maintained even under high temperatures and deformations, exhibiting the same linearity as single FBGs for both parameters (strain and temperature). The manufactured device also showed a very stable laser output, mainly caused by the lack of competition between active modes. This structure can enhance the present FBG based sensor performance by improving their interrogation distance and peak discrimination, enabling this technology for telecom and sensing fields, where high stability and precision are required.

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