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Compact optical fiber lasers and optical fiber sensors assisted by femtosecond laser inscription of plane-by-plane FBGs

P. Roldán-Varona[1,*], D. Pallarés-Aldeiturriaga[1,2], L. Rodríguez-Cobo[2], R. A. Pérez-Herrera[3], M. Bravo[3], M. López-Amo[3], and J. M. López-Higuera[1,2,4]

[1] *Photonics Engineering Group, University of Cantabria, 39005, Santander, Spain*
[2] *CIBER-bbn, Instituto de Salud Carlos III, 28029, Madrid, Spain*
[3] *Dpto of Electrical Electronic and Communication Engineering and Institute of Smart Cities (ISC), Public University of Navarra, 31006 Pamplona, Spain*
[4] *Instituto de Investigación Sanitaria Valdecilla (IDIVAL), 39011, Santander, Spain*

[*] *Corresponding author: pablo.roldan@unican.es*

Abstract: Development of a high temperature sensor based on optical fiber laser generated from a cavity of reduced dimensions (43 mm) in Er-doped fiber. The mirror FBGs have been inscribed with femtosecond laser using the slit beam technique (Pl-b-Pl).
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1. Introduction

In industry, there is a growing number of applications (e.g., laser-assisted 3D synthesis, high power lasers, nuclear plants, steel production) that require characterization and monitoring in harsh environments. Here, optical fiber sensors (OFS) are of particular interest due to their electromagnetic immunity and compact design. Among the OFS, fiber Bragg gratings (FBGs), are a mature technology with an enhanced potential to withstand harsh environments thanks to the regeneration process [1] and ultrafast lasers [2].

In addition to sensing, their selective reflection properties are widely employed on fiber laser cavities [3]. These lasers are well known for exhibit high efficiency, good beam quality and being compact. Combining the temperature properties of FBGs to this technology, fiber laser sensors can measure temperature (among other parameters) with an outstanding signal-to-noise ratio, being suitable for sensing applications requiring long distances and high precision [4].

In these kinds of lasers, Type I-UV FBGs are commonly employed, which exhibits two drawbacks. First, they can only be inscribed in photosensitive fibers [5], where erbium concentrations are usually low. Thus, FBGs must be inscribed in regular SMF [6], inevitably increasing cavity length. Second, Type I-UV FBGs are completely erased at high temperatures [7].

Femtosecond (fs) laser inscribed FBGs solve both issues thanks to its nonlinear absorption process that overcome photosensitivity limitations and produce refractive index changes (RIC) that can easily withstand 1000°C or even more depending on modification type.

There are high-temperature fiber laser sensors employing fs-FBGs as part of the cavity that work up to 1000°C [8]. However, laser cavity is achieved by means of a sagnac loop which increases its length and complexity. Moreover, only the FBG is actually exposed to high temperatures. Besides, moderate erbium dopant fibers are employed (55 dB/m).

In this work, a centimeter-scale erbium-doped fiber laser sensor is presented. Here, laser cavity is integrated in a heavily Er-doped fiber by means of two FBGs acting as a simple Fabry-Perot cavity. This laser exhibits a length as low as 4.3 cm which is lower than [6] and can withstand up to 500°C. Besides, as the cavity is directly written into the active fiber, there are no splices that would introduce losses or distort performance under high optical pump or laser signal. For this purpose, a parameter optimization for FBG inscription in Er-doped fiber will be performed first. There are few works reporting fs-FBG inscription in non-photosensitive, heavily Er-doped fiber. The plane-by-plane (Pl-b-Pl) writing method will be employed instead of typical point-by-point (PbP) inscription, as the latter exhibits less reflectivity and more losses, which may compromise cavity performance. Then, this optimization will be employed to achieve a fiber cavity as short as possible, characterizing its output spectrum and wall-plug efficiency. Finally a temperature study will be performed to the laser cavity.

2. Experimental setup

In order to manufacture the distributed Bragg reflector (DBR) laser sensor. First, a proper gain media must be selected. For this, a commercial Er-doped fiber (Er110 of LIEKKI) has been used, which has an absorption ratio of 110 dB/m at 980 nm. As mentioned, the high concentration of erbium induces a greater gain, enabling a reduction in the laser cavity length. The cavity has a total length of 43 mm: 2 FBGs of 1.5 mm separated 40 mm.

The setup used is shown in Fig. 1, with the 976 nm pump laser (JDSU S26-7602-340), the Er-doped fiber laser cavity, and a high resolution optical spectrum analyzer (OSA) (Anritsu MS9740A with 30 pm resolution) to collect the generated laser spectrum. A wavelength division multiplexer (WDM) 980/1550 nm is used to decouple the pumping and the generated signal.

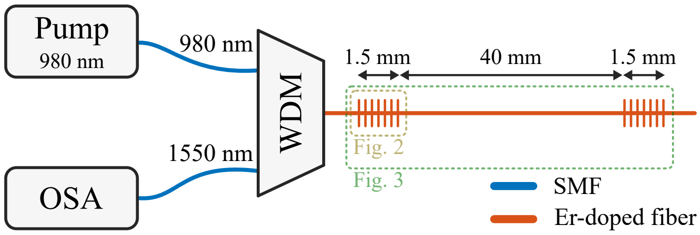

Fig. 1. Characterization setup during the DBR laser fabrication process.

The FBGs presented in this work have been inscribed using a commercial femtosecond Fiber Laser Chirp Pulse Amplifier (FLCPA) from CALMAR laser. It operates in 1030 nm, with pulse duration of 370 fs and a maximum pulse energy (E_p) of 5 μJ. The FBG inscription method Pl-b-Pl has been used due to the slit beam technique [9]. In this way, the refractive index changes induced in the core of the fiber are two-dimensional, in width and depth, controlled by the width of a slit located prior to the objective lens, and the E_p, respectively. This long-distance working lens ($\times 50/\text{NA} = 0.42$ from Mitutoyo) focuses the pulses on the fiber, which is located on a nm-accuracy, air-bearing XYZ translation stage from Aerotech. In order to avoid aberrations due to the geometry of the fiber, an index-matching oil and a coverslip have been used above the sample [10].

A series of inscriptions were performed to investigate the optimal FBG conditions. The two FBGs have a length of 1.5 mm, and have been inscribed with a period $\Lambda = 1.588$ μm, which generates the third order of the FBG around 1530 nm, the optimum amplification point in Er-doped fibers. The writing speed has been set at 80 μm/s. Regarding the pulse energy, $E_p = 4.47$ μJ has been used in the laser. However, the slit beam technique with a slit width of 300 um has been used [9], so that only 18.9% of the energy reaches the objective lens. This is done, in order to make planar modifications of the refractive index and thus uniformly cover the cross section corresponding to the 4 μm core of the Er-doped fiber. The reflectivity is approximately $\sim 62\%$.

A longitudinal image of the FBG inscribed in the Er-doped fiber can be seen in Fig. 2a. The plane generated by each laser pulse is easily observable, which completely covers the 4 μm core. Likewise, Fig. 2b spectrally characterizes the transmission spectrum of the FBG. For this purpose, the configuration shown in Fig. 1 has been used, through which the amplified spontaneous emission (ASE) is used as the light source. In order not to induce errors derived from the amplification of the Er-doped fiber, the FBG must be inscribed at the beginning of it for its characterization.

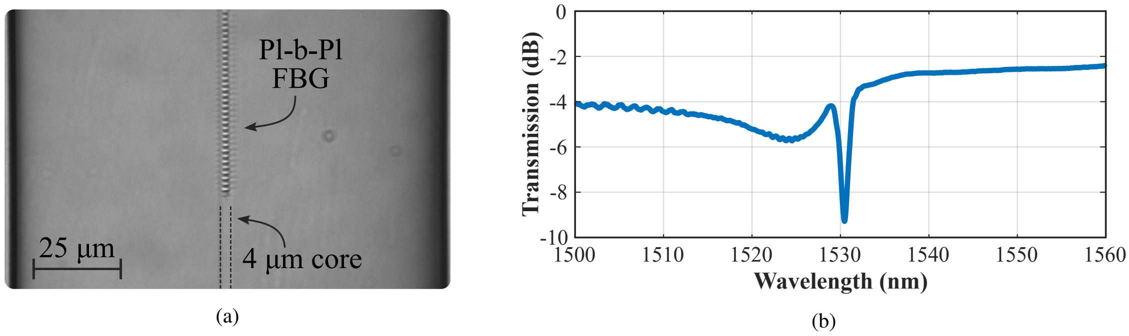

Fig. 2. Two uniform FBGs of 1.5 mm length were inscribed into Er-doped fiber with a distance between them of 40 mm. (a) A longitudinal image of the inscribed FBG is shown, (b) as well as the transmission spectral response of each FBG. For this, the amplified spontaneous emission (ASE) of the Er-doped fiber is used as the light source, and the FBG is inscribed at the beginning of it.

Another point to highlight, and of great importance, is that the required splice between the SMF and the Er-doped fiber usually introduces high losses and mechanical weakness. In this way, the most suitable parameters for splice have been determined experimentally.

3. Results and discussion

3.1. Spectral characterization

Fig. 3a shows the spectral characterization of the generated laser, with the pump laser fed with 340 mA (156 mW), together with a real image of the cavity with the characteristic green fluorescence of the erbium (Fig. 3b). The laser has a multimodal behaviour, being centered in 1529.8 nm with a full width at half maximum (FWHM) of $\sim$ 870 pm, due to the filtering generated by the FBGs of the cavity. It should be noted that the FBG properties have not optimized to a greater extent. Subsequently, the behavior of the laser as an optical fiber sensor will be evaluated.

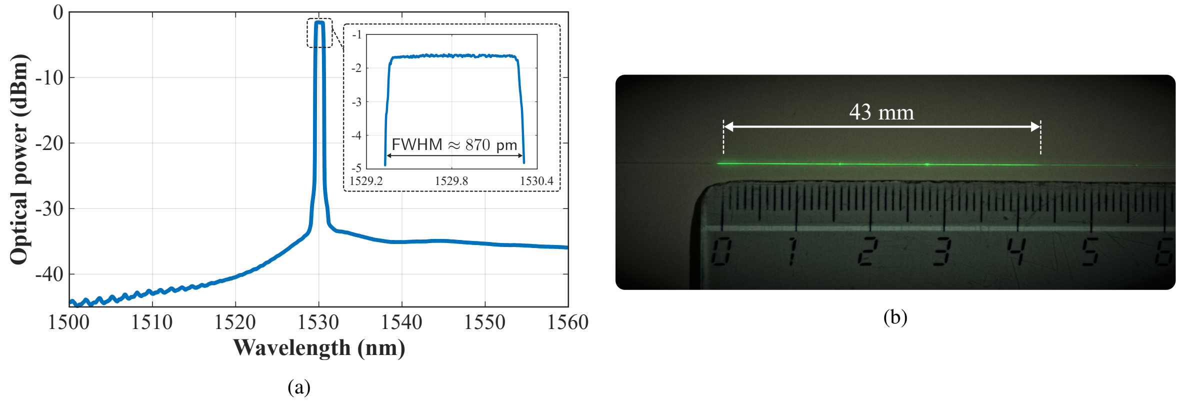

Fig. 3. (a) Laser spectrum characterized by the setup of Fig. 1 with the pump laser diode fed with 340 mA. (b) Image of the part corresponding to the laser cavity of the Er-doped fiber, with the dimensions mentioned above.

The laser characteristics were measured with respect to laser threshold. It has been determined that the pumping value from which the laser effect begins to be generated is 250 mA (114.8 mW). In Fig. 4 an evaluation of the laser's optical power is performed as a function of the 980 nm pump applied.

According to the quadratic fit made ($R^2 = 0.941$), a saturation trend in the optical power of the laser is observed. By discriminating the different zones, a linear operating region can be perceived from the threshold of the laser (between 250 and 335 mA of the pumping laser supply). In this region the laser power increases at a rate of 0.1628 dB/mA pumping ($R^2 = 0.919$).

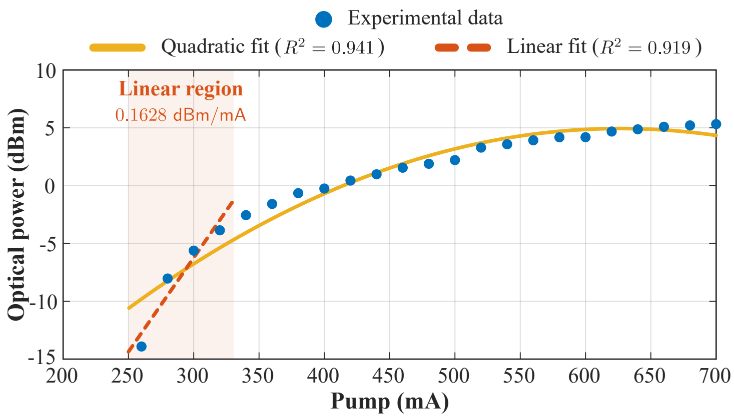

Fig. 4. Variation of the optical power of the laser depending on the intensity that feeds the pumping laser. A quadratic fit of the experimental values is shown, as well as the linear operating range of the laser (no saturation).

3.2. Thermal response

Once the spectral behavior and efficiency of the laser has been characterized, its use as a fiber laser sensor is undertaken. Due to the outstanding signal-to-noise ratio, its use as a sensor is highly recommended in applications in which the optical power is likely to be reduced. High temperature sensing is one of these cases. Thus, a 2-hour temperature cycle has been carried out, rising to 500ºC, with intermediate steps of 15 min every 100ºC. Fig. 5 depicts both wavelength (Fig. 5a) and output power (Fig. 5b) behavior in the temperature cycle with a pump generated with an electrical intensity of 500 mA. Wavelenght response exhibits an expected linear behavior and slightly higher sensitivity compared with traditional FBGs: 13.14 pm/ºC ($R^2 = 0.9997$). Optical power follows a decreasing linear trend that might be attributed to several factors, for example, reflectivity decrement with temperature. This trend is abruptly increased above 400°C. Regardless this decrement, output power is strong enough to perform reliable measurements.

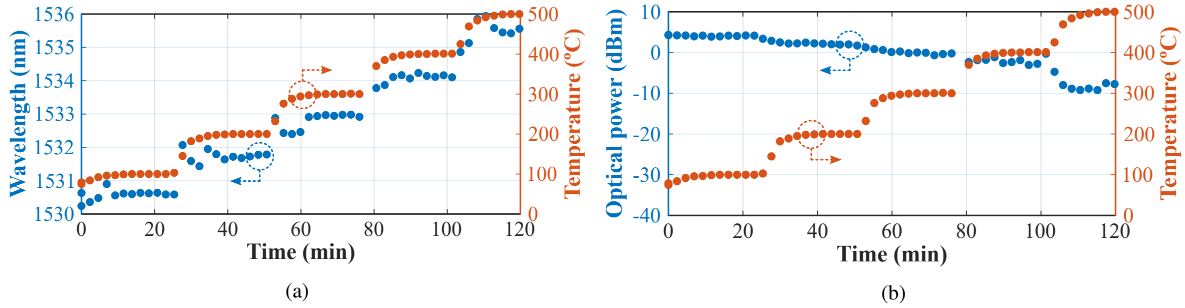

Fig. 5. (a) Laser wavelength variation, (b) and associated optical power for the temperature cycle shown, which reaches 500°C after 2 hours.

4. Conclusions

In this work an ultra-compact laser has been developed, with a total length of 43 mm, and is entirely in Er-doped fiber. The cavity mirrors are based on FBGs (1.5 mm each) inscribed with femtosecond laser using the plane-by-plane method (slit beam technique). The Pl-b-Pl inscription method offers great control of the FBG parameters, such as refractive index changes, period, losses and reflectivity. This makes it suitable for generating cavity mirrors. Also, the fact of not needing photosensitive fibers, necessary for the inscription of UV-FBGs, allows to use fibers with a significantly higher concentration of erbium (110 dB/m absorption at 980 nm), and reduce the cavity length due to the large induced gain.

The laser, generated in 1529.8 nm and with 870 pm of FWHM, can be used as an optical fiber sensor in extreme temperature environments due to its great signal-to-noise ratio. It has a sensitivity of 13.14 pm/°C, having been subjected to temperatures of up to 500°C, with great stability in power up to that point.As a future line, the incorporation of other types of dopants in the cavity is foreseen, as well as the optimization of the FBG parameters, which will allow significantly higher temperatures (as well as discriminate another series of parameters).

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