© 2020 Optica Publishing Group. One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this paper for a fee or for commercial purposes, or modifications of the content of this paper are prohibited.

Enhanced Optical Fiber Lasers and Optical Fiber Sensors Assisted by Micro-drilled Optical Fibers

R. A. Perez-Herrera[1,*], M. Bravo[1], P. Roldan-Varona[2,3], D. Leandro[1], L. Rodriguez Cobo[3], J. M. Lopez-Higuera[2,3,4], M. Lopez-Amo[1]

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

Abstract: Enhanced OFS assisted by micro-drilled optical fibers acting as mirrors are demonstrated. Strain sensitivity improved more than one order of magnitude in comparison with FBG sensors using a 50 µm-waist micro-drilled taper as distributed reflector.
OCIS codes: (140.3510) Lasers, fiber; (060.2370) Fiber optics sensors; (140.3500) Lasers, erbium; (060.2430) Fibers, single-mode

1. Introduction

Today, fiber Bragg grating sensors are well stablished transducers for a great number of sensing applications [1]. They are especially well-suited for strain and temperature measurements. Thus, they are extensively used for civil works monitoring or for sensing platforms including a high number of this kind of sensors [2]. Their main advantage is that the measured parameter is coded in a wavelength shift, immune to optical power fluctuations. Moreover, because they are wavelength selective reflectors, they can be of part of an optical laser cavity. Because of this, sensing systems based on lasers using FBGs as sensing mirrors have been developed since 1993 [3]. These lasing sensors have demonstrated a high sensitivity and a high optical signal to noise ratio (OSNR) [4].

Typically, FBG-based sensing systems offer a temperature sensitivity of 11 pm/ºC and a strain sensitivity of 1.2 pm/µε [5, 6]. These measurement sensitivities have been enough to establish this kind of sensors as a flagship in sensing along two decades or more.

In this work we demonstrate how to use the current micro-drilling techniques, also used for FBGs writing [7], to develop more sensitive sensing structures. A preliminary study of a micro-drilled SMF fiber reflector for laser sensors was recently presented in [8]. Now in order to complete the study, we have compared two different kind of quasi-randomly distributed reflectors. The first ones were written into standard single-mode fibers, and the other ones, in tapered optical fibers with different waist dimensions. Their performance as sensing mirrors in a fiber laser are experimentally evaluated. By using this type of mirrors, it is possible to develop short cavity fiber optic laser sensors which offers higher strain sensitivity than regular FBG transducers. Those distributed reflectors have been fabricated using a femtosecond (fs) commercial Fiber Laser Chirp Pulse Amplifier (FLCPA) from CALMAR lasers, operating at 1030 nm, with a 370 fs pulse duration and a variable Pulse Repetition Rate (PRR) from 1 Hz to 120 kHz. It provides inhomogeneity enhancement of the refractive index of the fiber, increasing the distributed scattering. The fiber is located on a slide and covered with a coverslip. Between them an index-matching oil has been deposited in order to eliminate the spherical aberration of the fiber [9], favoring the focusing of the laser pulses through a 100x/NA=0.5 objective lens from Mitutoyo.

In this experimental study, three different distributed reflectors based on tapered optical fibers and micro-drilled optical fibers were employed. For the drilling process of these optical fibers, a standard transversal inscription setup, similar to the one previously employed in [10] was selected.

2. Experimental setup

In the first study, a micro-drilled standard single-mode optical fiber (MDF), with a 125 µm diameter was used. Figure 1 shows a photograph of the quasi-randomly distributed reflector along the fiber, showing the dimensions of some micro-modifications induced along the SMF. As it is depicted in this figure, the randomness of the inscribed fiber was achieved by randomly modulating the pulse repetition rate at every pulse (which corresponds to 100 ms approximately). Consequently, quasi-random physically structure with several micro-drilled points was attained. However, the repetition rate of the femtosecond laser could not be simultaneously modulated at the same rate as the pulse inscription speed. Thus, direct random inscription was not possible, but quasi-randomly spaced spots was. Specifically, the pulses are separated by a pseudo-random period between 1 and 10 µm.

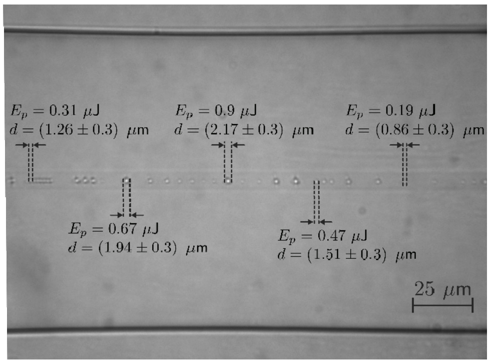

Fig. 1. Photograph of the quasi-randomly distributed reflector along the SMF.

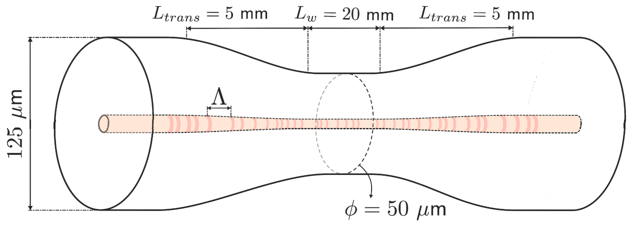

Fig. 2. Schematic illustration of the SMF microwire, in which micro-holes were applied using the femtosecond laser micromachining system.

Secondly, two different micro-drilled tapered optical fibers (MDTF) were developed. The fabrication of the tapered fibers was carried out by means of a Taper Manufacturing Station TMS-01-0400 (3SAE) (NorthLab Photonics, Sweden), which allows manufacturing tapered fibers with arbitrary shapes, low losses, and excellent repeatability, as has been previously reported [11]. The transitions between the original optical fiber and the uniform waist of the taper have a length of about 5 mm each for a total taper length of about 30 mm as can be seen in Figure 2.

The first inscription process was carried out from a 50 µm–waist tapered fiber and for the second one, a 100 µm-waist was employed, both were fabricated from standard single-mode fiber. A schematic illustration of this micro-drilled 50 µm–waist tapered optical fiber is shown in Figure 2.

Figure 3 shows a schematic diagram of the experimental setup used to evaluate the laser generation properties when using these distributed reflectors within a short-linear-cavity fiber acting as a mirror. In this figure it can be seen the three types of distributed reflectors employed: an un-drilled tapered optical fiber (a), a micro-drilled tapered fiber (b) or a micro-drilled optical fiber (c). A 1480/1550 nm wavelength division multiplexer (WDM) injects the Raman pump laser centered at 1480 nm into the linear cavity fiber laser. The gain medium, located at the common port of the WDM, consists of 4 m of erbium-doped fiber (EDF). The EDF was the I25 (980/125) (Fibercore Inc.), suitable for C amplifiers with a core composition optimized for erbium-doped fiber amplifiers (EDFASs) in dense wavelength division multiplexing (DWDM) networks; the peak core absorption ranges from 7.7 to 9.4 dB/m at 1531 nm. The linear cavity of the laser ends at a fiber loop mirror (FLM) comprising an optical circulator in which ports 3 and 1 are connected. After this, the recirculating signal travels through the 1500-nm port of the WDM to an optical coupler. At the optical coupler (OC), 10% of the signal was monitored by an optical spectrum analyzer (OSA) with a resolution of 0.03 nm, and the other 90% was guided to the distributed reflectors. All the experimental measurements were carried out at room temperature, and no vibration isolation or temperature compensation techniques were employed.

3. Results

Previous works [9] demonstrate that the micro-drilling has an enhancing effect on the laser generation properties. In that case, a micro-drilled tapered fiber (MDTF) with 50 µm–waist diameter was experimentally analyzed. In this occasion the objective was to broaden and deepen the analysis for a 100 µm-waist and using a Raman pump laser. Figure 4 shows a comparison between the results attained when using an un-drilled tapered fiber (Fig. 4 (a)) or a micro-drilled tapered fiber (Fig. 4 (b)), both with 100 µm-waist and being pumped with 37 dBm at 1480-nm light. As it was previously pointed out, the micro-drilling, even with a higher waist diameter and using a different pump laser, dramatically enhances the laser generation properties.

A single-wavelength laser centered at 1558.5 nm was measured employing the 100 µm-waist micro-drilled optical fiber. The output power level attained from this single-laser oscillation when pumped with 37 dBm of light at 1480 nm was about 10 dBm, and it was measured an OSNR higher than 55 dB as Fig. 4 shows.

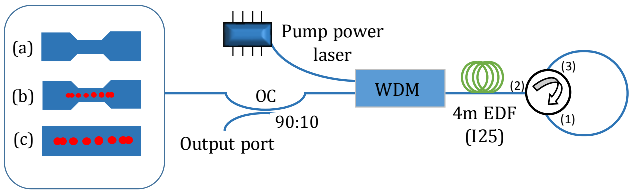

Fig. 3. Schematic diagram of the experimental lineal short-cavity fiber laser setup, in which an un-drilled tapered optical fiber (a), a micro-drilled tapered fiber (b) or a micro-drilled optical fiber (c) were used to reflect an amplified signal.

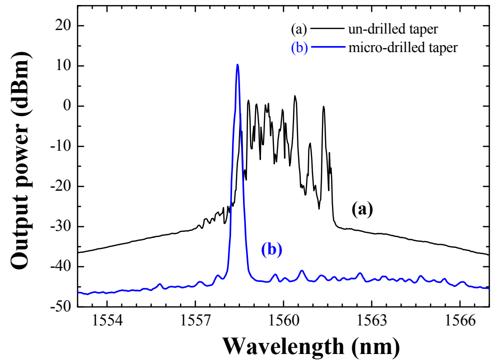

Fig. 4. Output spectra of the short-linear-cavity fiber laser pumped with 37 dBm at 1480 nm for the 100 µm–waist un-drilled tapered fiber (a) or a micro-drilled tapered fiber (b).

Then, this structure was characterized as temperature sensor when no strain was applied. In this case, the pump laser employed was centered at 980 nm and the 1480/1500 nm WDM was substituted by a 980/1500 nm one. The wavelength shift sensitivity to the temperature was characterized using the MDF, the 100 µm-waist MDTF and the 50 µm-waist MDTF distributed reflectors. This characterization was carried out by using a climatic chamber in the range of 35ºC to 100ºC and taking samples each 2ºC.

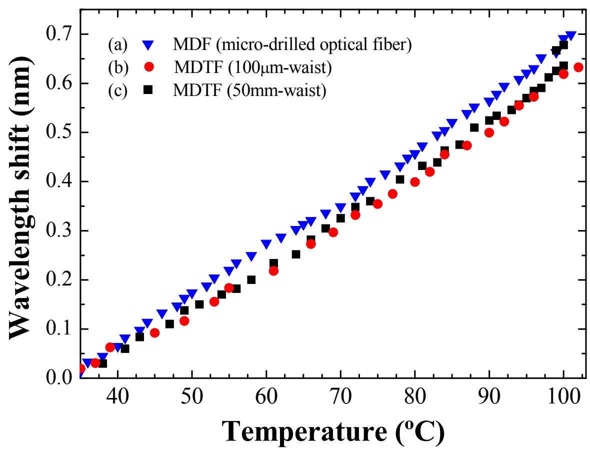

Fig. 5. Wavelength shift as function of temperature when using the MDF (a), or the MDTFs with 100 µm-waist (b) or 50 µm-waist (c).

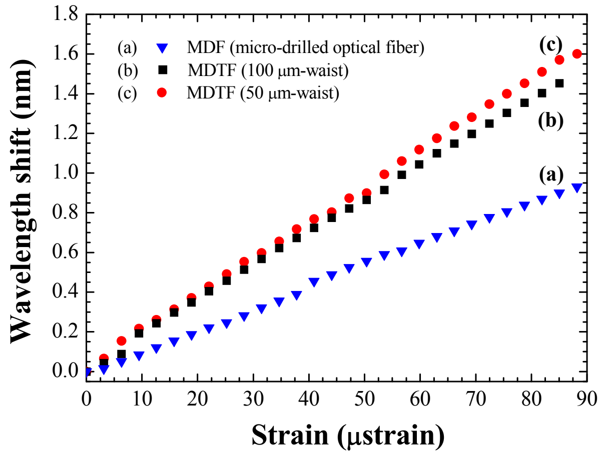

Fig. 6. Wavelength shift as a function of strain change when using a MDF (a), or a MDTF with 100 µm-waist (b) or 50 µm-waist (c).

As shown in Fig. 5, the center wavelength shift for these three single-wavelength lasers when using a MDF (Fig. 5 (a)), a MDTF with 100 µm-waist (Fig. 5 (b)) or a MDTF with 50 µm-waist (Fig. 5 (c)) present a clear linear behavior (the mean square errors were equal to 0.9983, 0.9953 and 0.9976 respectively) and a temperature sensitivity of about 10pm/ºC, 9.1pm/ºC and 9.6pm/ºC was measured, in that order. The attained values were close to the typical value for temperature-induced Bragg wavelength shift in silica fibers operating at 1550 nm, which is around 11 pm/ºC [5].

Next, these sensor heads based on micro-drilled optical fibers, were placed in a high precision single-axis motorized stage (MS) in order to evaluate the wavelength shift produced by straining them. The sensor heads characterization consisted of 29 steps of 3.15 µε per step.

Figure 6 presents the central emission wavelength shift when the structure was subjected to the above-mentioned strain variations using a MDF (Fig.6 (a)), a MDTF with 100 µm-waist (Fig.6 (b)) or a MDTF with 50 µm-waist (Fig.6 (c)). These results show linear response as evidenced by the mean square errors, very close to 1 (0.9983, 0.9991 and 0.9992 respectively), showing sensitivities as good as 10.9 pm/µε, 17 pm/µε and 18.1 pm/µε for the MDF, the MDTF with 100 µm-waist or the MDTF with 50 µm-waist, in that order.

These values, when compared with the typical value for strain induced Bragg wavelength shift, that is approximately 1.2 pm/µε [5,6] presents a significant enhancement of more than one order of magnitude. This represents a substantial improvement of the strain sensitivity.

Finally, Table 1 provides a summary of the data acquired over this experimental study. This table shows a temperature and strain comparison for the sensor heads of interest.

Although temperature sensitivities achieved were similar to the FBGs ones, the strain sensitivity presents more than one order of magnitude enhancement in comparison with a FBG sensor.

Table 1. Comparison of temperature and strain sensitivity when a FBG, a micro-drilled fiber or a micro-drilled tapered fiber were employed.

Optical fiber structure	Waist Diameter (μm)	Temperature sensitivity (pm/ºC)	Strain sensitivity (pm/μstrain)
FBG [5]	125	11	1.2
MDF	125	10.5	10.9
MDTF	100	9	17
MDTF	50	9.5	18.1

4. Conclusions

In conclusion, this work presents an experimental performance analysis of different kind of quasi-randomly distributed reflectors written into single-mode fiber when they are used as sensing mirrors in a short-linear-cavity fiber laser. In particular, the features of the laser generation when optical tapered fibers (TF), micro-drilled optical fibers (MDF) or micro-drilled tapered fibers (MDTF) are presented. When the 100 μm-waist micro-drilled tapered optical fiber was used, a single-wavelength reflector laser centered at 1558.5 nm with an output power level of about 10 dBm and an optical signal to noise ratio (OSNR) greater than 55 dB were measured. The achieved temperature sensitivities were similar to FBGs. However, the strain sensitivity improved more than one order of magnitude in comparison with FBG sensors; highlighting the 18.1 pm/με when the 50 μm-waist MDTF was employed as distributed reflector.

Funding. This work was supported by the Spanish AEI project TEC2016-76021-C2, FEDER Funds, and the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 838143.

5. References

[1] A. Cusano, A. Cutolo, "Fiber Bragg Grating Sensors: Recent Advancements, Industrial Applications and Market Exploitation," Ed. Bentham Science Publishers (2013).

[2] V.G. Annamdas, Y. Yang, Yaowen, H. Liu, "Current development in fiber Bragg grating sensors and their applications," in Proceedings of SPIE-Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, 6932 (2008).

[3] A. D. Kersey and W. W. Morey, "Multi-element Bragg-grating based fibre-laser strain sensor," Electron. Lett. **29**, 964-966 (1993).

[4] S. Avino, A. Giorgini and G. Gagliardi, "Fiber-Optic Cavities for Physical and Chemical Sensing," Open Opt. J. **7** (Suppl-1, M8) 128-140 (2013).

[5] L. S. Grattan, B. T. Meggit, Optical Fiber Sensor Technology: Devices and Technology, Vol. 2 (Optoelectronics, Imaging and Sensing, Springer Science & Business Media, 2012).

[6] C. E. Campanella, A. Cuccovillo, C. Campanella, A. Yurt, V. Passaro, "Fibre Bragg Grating Based Strain Sensors: Review of Technology and Applications," Sensors **18**, 3115, (2018).

[7] B. Malo, K. O. Hill, F. Bilodeau, D. C. Johnson, J. Albert, "Point-by-point fabrication of micro-Bragg gratings in photosensitive fibre using single excimer pulse refractive index modification techniques," Electron. Lett. **29**, 1668-1669 (1993).

[8] R. A. Pérez Herrera, M. Bravo Acha, Pablo Roldan-Varona, D. Leandro, L. Rodriguez Cobo, J. M. Lopez-Higuera, M. Lopez-Amo, "Micro-drilled optical fiber for enhanced laser strain sensors," in Proceedings of SPIE 11199, Seventh European Workshop on Optical Fibre Sensors, 111992R (2019).

[9] K. Zhou, F. Shen, G. Yin, and L. Zhang, "Optical fiber micro-devices made with femtosecond laser," in Advanced Photonics 2016 (IPR, NOMA, Sensors, Networks, SPPCom, SOF), OSA Technical Digest (online) (Optical Society of America, 2016), paper SeW3D.1.

[10] R. A. Perez-Herrera, D. Pallarés-Aldeiturriaga, A. Júdez, L. Rodriguez Cobo, M. Lopez-Amo, and J. M. Lopez-Higuera, "Optical fiber lasers assisted by microdrilled optical fiber tapers," Opt. Lett. **44**, 2669-2672 (2019).

[11] A. Judez, D. Leandro, R. A. Perez-Herrera, M. Galarza, and M. Lopez-Amo, "High sensitivity fiber-optic liquid level sensor using biconical tapered fibers," in Proceedings of 26th International Conference on Optical Fiber Sensors, OSA Technical Digest (Optical Society of America, 2018), paper TuE45.