Stable L-band Fiber Laser Sensor using a Backscattering-Based Multimode Fiber Reflector

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Abstract: A new and highly stable L-band fiber laser for sensing is demonstrated. An emission line at 1575.47 nm, was achieved using a special reflector. Good strain sensitivity, optical signal to noise ratio and output power stability were measured. © 2022 The Authors.

1. Introduction

Optical fiber lasers have been intensively developed over the last years. These lasers, in their compact version, use high gain from highly doped optical fibers as well as fiber Bragg gratings (FBGs) or other filtering mirrors, leading us to stable and robust single wavelength operation in different telecommunication bands.

L-band telecommunication lasers have been mainly demonstrated with Er^{3+}-doped or Er^{3+}/Yb^{3+} co-doped silica fibers [1]. These erbium doped fiber lasers (EDFL) can be used in sensing or in spectroscopic analysis, among other applications, attracting research interest on them. However, in L-band, the number of reported optical fiber lasers in comparison with C-band ones is short, particularly, in optical fiber lasers for sensing. Some few examples can be found in [2-4]. This is due to the high cost of some components compared to C-band. However, this band is essential for some sensing applications, e.g., gas detection for both pollution monitoring and safety reasons, such as carbon dioxide and hydrogen sulphide [5]. Therefore, further efforts should be made to achieve good light sources for the L-band, being the stability and optical signal-to-noise ratio (OSNR) critical parameters for optical sensing.

In recent years, a new family of reflectors has been developed for optical fiber lasers. These reflectors are fabricated using femtosecond (fs) laser writing systems [6]. Ultrafast laser writing allows artificially controlled backscattering (ACB) to be generate in optical fibers. The behavior of these reflectors improves in several parameters, those generated by Raman amplified distributed random mirrors [7]. Another important aspect in high-quality fiber lasers is their polarization behavior, and polarization-maintaining (PM) laser cavities are required for long-term stability of the laser [8]. In this paper, we demonstrate a new high-quality L-Band laser strain sensor that shows high OSNR and stability levels, using ACB mirrors and a polarization maintaining structure.

2. Inscription process

The optical fiber inscription was carried out using a Cazadero fiber laser (Calmar Laser) that delivers 370 fs laser pulses at a central wavelength of 1030 nm. However, the light absorbed non-linearly by the fiber has a wavelength of 515 nm, due to the second harmonic generation (SHG) introduced in the setup, as shown in [9]. A pulse repetition rate of 150 Hz and a pulse energy of 0.75 µJ were used during the inscription. The laser pulses were tightly focused into the Ø50 µm core of a multimode fiber (MMF) using a 0.42 NA, 50× objective lens from Mitutoyo. The fiber was translated through the laser focus using a motorized nano-resolution XYZ stage from Aerotech. This ACB-MMF reflector was written on the axial axis of the fiber, and it had a random period between Λ_{min}=1.61085 µm and Λ_{max}=1.64230 µm and a total length of 17 mm. Although this is a random fiber grating (RFG) [10], the almost total periodicity of the optical structure gives rise to Bragg resonances which, in the third order (m=3), present reflection in the spectral band centered at around 1575.4 nm.

3. Experimental setup

The schematic diagram of the experimental setup used to characterize the L-band linear cavity fiber laser is presented in Figure 1. At one of the polarization-maintaining (PM) fiber laser cavity ends, an ACB-MMF reflector was connected (Fig.1 (g)), acting as a quasi-distributed laser mirror. At the other end of the PM fiber cavity, there was a 3-port PM fiber optic circulator (PM-FOC, Fig.1 (d)) in which ports 3 and 1 were connected to conform a PM fiber loop mirror (PM-FLM) [11]. Between these two ends of the cavity, a PM 980/1550nm wavelength-division multiplexer (PM-WDM, Fig.1 (b)) injected the PM pump laser (Fig.1 (a)), centered at 976-nm, into the linear cavity. In the common port to the PM-WDM was the gain medium, which consisted of 5 meters of polarization-maintaining erbium-doped fiber (PM-EDF, Fig.1 (c)) with a peak core absorption ranging from 12 to 27 dB/m at 1531 nm and optimized for PM-EDFAs and ASE light sources (DHB1500, Fibercore Inc.).

After this signal recirculated through the PM-FLM and passed through the PM-EDF section again, it arrived to the 1550 nm port of the PM-WDM up to a polarization-maintaining optical coupler (PM-OC, (Fig.1 (e)). At the PM-OC, 10% of the signal was extracted to be monitored by an optical spectrum analyzer (OSA, (Fig.1 (f)) with a resolution of 0.03 nm, while the other 90% reached the multimode-fiber-based reflector.

The spectrum analyzer employed features a wavelength resolution determined by the built-in grating of 30 pm. However, by increasing the number of points within the sweep width where data is captured, the waveform can be displayed at a minimum internal resolution of 1 pm.

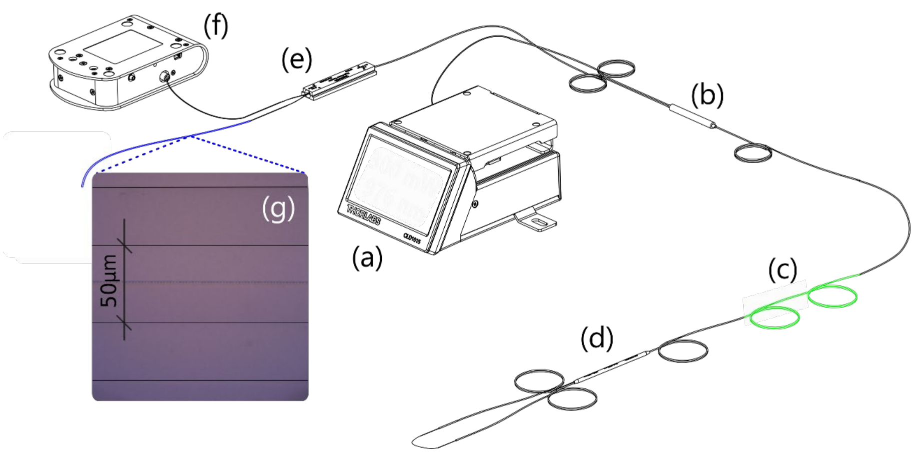

Figure 1. Schematic diagram of the experimental linear cavity polarization-maintaining (PM) fiber laser setup. (a) PM pump laser; (b) PM wavelength-division multiplexer; (c) PM erbium-doped fiber; (d) PM fiber optic circulator; (e) PM optical coupler; (f) optical spectrum analyzer; (g) artificially controlled backscattered multimode-fiber reflector.

4. Experimental results

First and foremost, the exit amplified spontaneous emission (ASE) measured in the amplifier configuration was analyzed. Figure 2 depicts the ASE spectrum when the free end of the DHB1500 PM-EDF was directly connected to the OSA and 5 meters of this doped-fiber was pumped at 500 mW.

The optical spectrum of the laser when pumped by a 976-nm at power of 500 mW and measured by the OSA is depicted in Figure 3. A single-laser emission line centered at 1575.47 nm, with an output power level of 7.75 dBm and an optical signal-to-noise ratio (OSNR) of 68 dB was measured. Previous studies indicate that these values are fairly good for the majority of sensor applications [12].

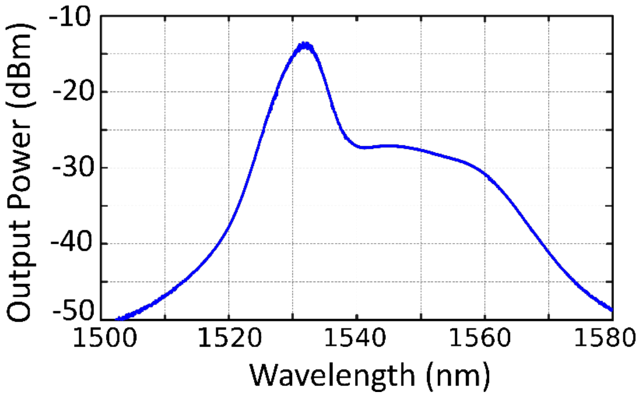

Figure 2. Amplified Spontaneous Emission (ASE) spectrum obtained when a 5 m length section of PM-Er-80 was pumped by a 980 nm PM light source.

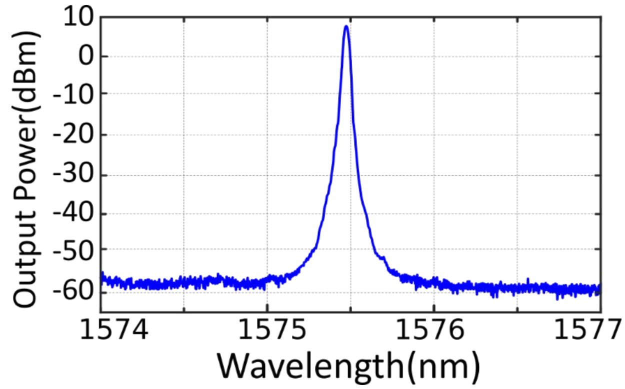

Figure. 3. Output optical spectrum of the linear-cavity PM fiber laser when pumped by a 976-nm PM laser at power, measured by an OSA.

Next, this sensor head, based on a multimode-fiber-based reflector, was placed in a high precision single-axis motorized stage in order to evaluate the wavelength shift produced by straining the same. The sensor heads characterization consisted of 20 steps of 20 με per step.

Figure 4 presents the central emission wavelength shift when the ACB-MMF was subjected to the abovementioned strain variations. This result shows a linear response as evidenced by the mean square error, very close to 1, showing a sensitivity of 1.02 pm/με. This value is similar to the typical value for strain induced Bragg wavelength shift, that is approximately 1.2 pm/με [13], [14].

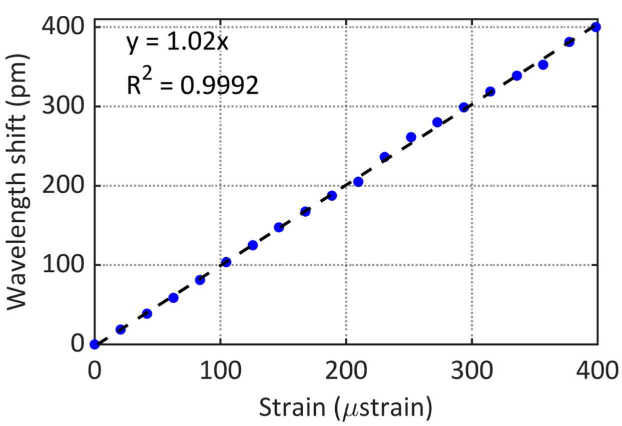

Figure. 4. Wavelength shift as a function of strain change when using an ACB-MMF as sensor head.

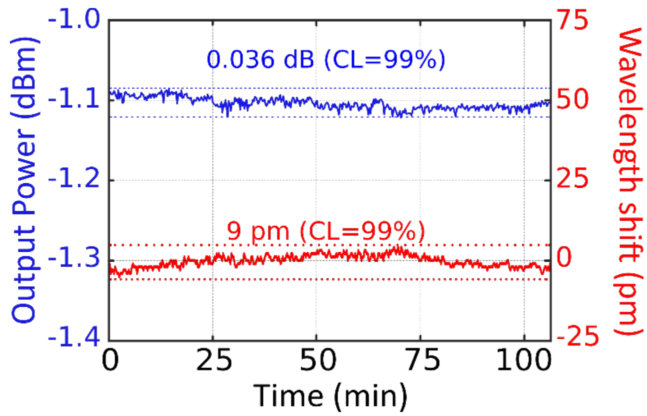

Figure. 5. Output power stability (blue) and wavelength shift (red) when pumped for 2 hours, with a confidence level of 99%.

Figure 5 shows the output power level stability (blue line) and wavelength shift (red line) of the linear cavity PM fiber laser, when pumped at 500 mW, for 2 hours. The measured data was stored each 10 seconds and a confidence level (CL) of 99% was considered. The output power level, measured at room temperature, showed a variation as low as 0.036 dB, when pumped at 500 mW, which is a marked improvement when compared to similar configurations previously reported [15], [16]. On the other hand, the central emission wavelength of the laser showed a variation of 9 pm during the same period of time and under the same circumstances.

4. Conclusions

A highly stable L-band linear cavity polarization-maintaining fiber laser is proposed and experimentally characterized in this work. A quasi-distributed mirror, inscribed into a 50/125 multimode fiber, was the only exception in this laser, which was entirely composed of polarization-maintaining fiber components. An L-band single-laser emission line, centered at 1575.47 nm, with an optical signal-to-noise ratio of 68 dB and an output power level of 7.75 dB was obtained. Strain measurements were carried out using this laser, showing a remarkable stability, with an output power level and central wavelength variations of 0.036 dB and 9 pm were obtained respectively, both measured at room temperature with a 99% confidence level. Strain sensitivity was 1.02 pm/με, comparable with that of FBGs based laser sensors, showing ours a better stability in measurements.

5. Acknowledgements

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6. References

[1] S. Fu et al., "L-Band Wavelength-Tunable Er3+-Doped Tellurite Fiber Lasers," J. Lightw. Technol. **38**(6), 1435-1438, (2020).

[2] L. Yu, T. Liu, K. Liu, J. Jiang, L. Zhang, Y. Jia, and T. Wang, "Development of an intra-cavity gas detection system based on L-band erbium-doped fiber ring laser," Sensors and Actuators B: Chemical **193**, 356-362, (2014).

[3] W. Li, A. Zhang, Q. Cheng, C. Sun, and Y. Li, "Theoretical analysis on SPR based optical fiber refractive index sensor with resonance wavelength covering communication C+L band," Optik **213**, 164696, (2020).

[4] R. A. Perez-Herrera, A. Ullan, D. Leandro, M. Fernandez-Vallejo, M.A. Quintela, A. Loayssa, J. M. Lopez-Higuera, and M. Lopez-Amo, "L-band multiwavelength single-longitudinal mode fiber laser for sensing applications," J. Lightw. Technol. **30** (8), 1173-1177, (2012).

[5] J. Marshall, G. Stewart, and G. Whitenett, "Design of a tunable L-band multi-wavelength laser system for application to gas spectroscopy," Meas. Sci. Technol. **17** (5), 1023–1031, (2006).

[6] H. Huang, L.-M. Yang, and J. Liu, "Micro-hole drilling with femtosecond fiber laser," Proc. SPIE 8607, 86070K (2013).

[7] X. Wang, L. She, D. Chen, and Q. Wu, "Theoretical and experimental study of artificially controlled backscattering fiber using femtosecond laser fabrication," Opt. Laser Technol. **113**, 6–10 (2019).

[8] O. Deparis et al., "Polarization-maintaining fiber Bragg gratings for wavelength selection in actively mode-locked Er-doped fiber lasers," IEEE Photonics Technol. Lett. **13** (4), 284-286 (2001).

[9] P. Roldán-Varona, M. Lomer, J. F. Algorri, L. Rodríguez-Cobo, and J.M. López-Higuera, "Enhanced refractometer for aqueous solutions based on perfluorinated polymer optical fibres," Opt. Express **30**, 1397-1409 (2022)

[10] R.A. Perez-Herrera, P. Roldán-Varona, L. R. Cobo, J. M. López-Higuera and M. Lopez-Amo, "Single Longitudinal Mode Lasers by Using Artificially Controlled Backscattering Erbium Doped Fibers," IEEE Access **9**, 27428-27433 (2021)

[11] R.A. Perez-Herrera, D. Pallares-Aldeiturriaga, A. Judez, 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)

[12] S. Pevec, D. Donlagić, "Multiparameter fiber-optic sensors: a review,"' Opt. Engineering **58** (7), 072009 (2019)

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

[14] 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).

[15] T. Feng, F. Yan, W. Peng, S. Liu, S. Tan, X. Liang, and X. Wen, "A high stability wavelength-tunable narrow-linewidth and single-polarization erbium-doped fiber laser using a compound-cavity structure," Laser Phys. Lett. **11** (4), 045101 (2014).

[16] Z.Wang, J. Shang, K. Mu, S. Yu and Y. Qiao, "Stable single-longitudinal-mode fiber laser with ultra-narrow linewidth based on convex-shaped fiber ring and Sagnac loop," IEEE Access **7**, 166398-166403 (2019).