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# Single Longitudinal Mode Lasers by Using Artificially Controlled Backscattering Erbium Doped Fibers

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**ABSTRACT** In this work, we propose and experimentally demonstrate a new distributed short linear cavity fiber laser. At one of the cavity ends, fabricated by a commercial femtosecond fiber laser chirped pulse amplifier, an artificially controlled backscattering erbium doped fiber section has been connected. This distributed reflector acts also as a saturable absorber, leading to the generation of tunable and switchable single longitudinal-mode laser emissions. The distributed reflector consists of 9 micro-drilled sections of about 1cm each one and randomly spread throughout 2 meters of highly doped erbium fiber. The total length of the fiber laser is 9.5 m and the laser shows a single mode behavior at all the emitted wavelengths. Using this new kind of reflecting saturable absorber, single and multiple single-mode emissions can be obtained. The achieved laser presents a pump threshold as low as 45 mW and shows up to 8 different single-mode emission lines with an optical signal to noise ratio of 45dB.

**INDEX TERMS** Distributed amplifier, erbium-doped fiber amplifier, fiber laser, laser cavity resonator.

## I. INTRODUCTION

Stable erbium-doped fiber (EDF) lasers are attractive sources that have many applications, such as optical sensing, microwave photonics, optical testing, and optical communications [1]. EDF lasers would present unstable multimode oscillation that comes from homogeneous broadening effects, long fiber cavities or spatial hole-burning among others. Some of the techniques that have been used to guarantee a single-longitudinal-mode (SLM) operation in EDF lasers are related with the Rayleigh backscattering feedback [2] or the use of saturable absorbers (SA) to suppress multiple modes in the cavity [3].

Since the advent of random distributed feedback fiber lasers, optical fiber distributed reflectors have been used as a new kind of laser mirrors. These mirrors use Rayleigh backscattering, improves output power stability and generates modeless behavior [4]. Due to the low Rayleigh backscattering coefficient of the single mode fiber (SMF), high pump power levels for Raman amplification were initially needed for the operation of all random fiber lasers by using Raman gain. Recently [5], artificially controlled backscattering (ACB) techniques that do not require Raman amplification or technical conditions and processes as complex as those required to fabricate, for example, random fiber gratings (RFG) [5] have been demonstrated. However, they can generate a distributed mirror using the random feedback from Rayleigh scattering [6]. In addition to this, by using a rare-earth doped fiber to fabricate this reflector, the power of the pump source can drop to the level of few milliwatts [7]. Thus, EDF-based amplification can be used to fabricate random lasers.

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This random feedback from Rayleigh scattering can be improved by drilling the fiber using a femtosecond laser with ultrashort pulses width and very strong instantaneous power. It induces a nonlinear multi-photon absorption of material to modulate the refractive index along an optical fiber, so the position and reflectivity of the scattering points can be controlled [8].

An approach of introducing strong backscattering as well as decreasing the pump power threshold and shorten the cavity length of fiber lasers is shown in this work. Another remarkable advantage of this distributed reflector is that can be also used as a saturable absorber, leading to the generation of tunable and switchable single longitudinal-mode laser emissions.

In this paper, we combine both concepts to achieve a new cavity for stable multiwavelength single-mode lasers.

So here it is reported, to the best of our knowledge, the first experimental demonstration of a short cavity fiber laser assisted by an ACB-EDF which acts both as a saturable absorber and as a compact distributed reflector. The experimental fiber laser properties in terms of multiwavelength emission, single-longitudinal mode behavior and obtained output power levels are here presented.

Single and multiple single-mode laser emissions have been achieved using this new kind of reflecting saturable absorber; with average measured optical signal to noise ratios (OSNRs) of 45 dB.

## II. EXPERIMENTAL SETUP

In order to fabricate the artificially controlled backscattering erbium doped fiber (ACB-EDF), a commercial femtosecond fiber laser chirped pulse amplifier (FLCPA) was employed [9]. The operating wavelength is 1030nm, with a 370fs pulse duration.

All the inscriptions were made using a pulse energy of 4.5$\mu$J and a pulse repetition rate (PRR) of 100Hz. The laser beam was tightly focused with an objective lens from Mitutoyo (NA=0.42), and the EDF was placed on a high-precision air-bearing XYZ stage from Aerotech. The distributed reflector consists of 9 micro-drilled sections of ~1cm each one and they were randomly spread throughout 2 meters of highly doped erbium fiber.

The inscriptions consist of several hundred of refractive index changes (RICs) whose spacing is pseudo-random between 2 and 20$\mu$m, as depicted in Fig. 1. In order for each RIC to be induced in the entire core cross-section, the slit beam shaping technique is used [10], with a slit width of 400$\mu$m (2.5mm beam diameter).

After being fabricated, this MD-EDF was characterized by using an optical backscatter reflectometer (OBR). The time-domain acquisition mode with a spatial resolution of 10 $\mu$m was employed to evaluate the backscattered light [11] through this 2-meter-long piece of MD-EDF.

Because of that ultra-high spatial resolution, the employed OBR (LUNA OBR 4600) can be used for internal component and fiber testing [11]. Figure 2 shows the backscattered

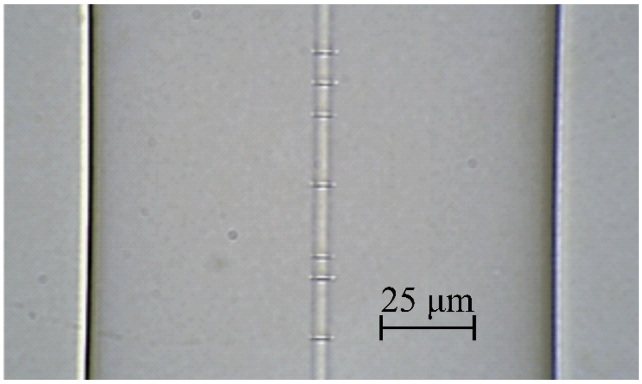


**FIGURE 1.** Microscope image of one of the nine quasi-randomly distributed reflectors inscribed along the erbium doped fiber.

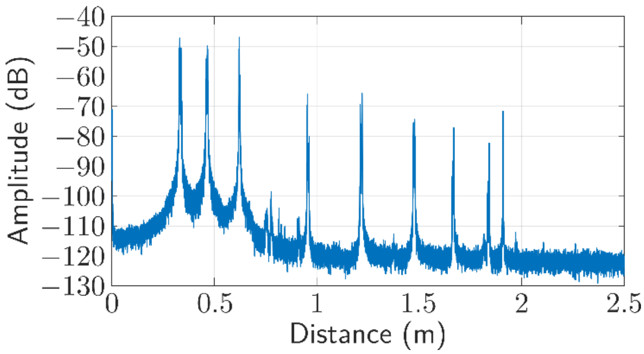


**FIGURE 2.** Backscattered optical power as a function of fiber length for a 2-meters-long micro-drilled erbium-doped fiber section.

optical power as a function of the total reflector fiber length when the MD-EDF is connected to the OBR. Here, nine intensity spikes spaced a random distance between them can be seen, corresponding to the nine micro-drilled reflecting sections-carried out into the 2 meters long highly doped erbium fiber section. The free termination of this MD-EDF was angle-cleaved to avoid end Fresnel reflection.

Different backscattered light amplitudes for each peak can also be observed at the location of the micro-drilled reflecting sections. Each one of these micro-drilled sections presents a pseudo-random reflected Rayleigh backscatter because of the refractive index fluctuations and their pseudo-random spacing between them. As the number of random reflectors increases, the random feedback is enhanced but together with larger loss in the total ACB-EDF section. Amplitudes from about 40 to around 50dB over the noise floor were recorded. Those high backscattered light amplitudes are due to the Rayleigh backscattering (RBS) that occurs when the fiber is micro-drilled.

Figure 3 shows a schematic diagram of the experimental linear short-cavity fiber laser setup, in which the ACB-EDF was used both as saturable absorber and as a distributed reflector. The pump laser was centered at 976nm so a 980/1550 nm wavelength division multiplexer (WDM) was used to inject this pump into the fiber laser cavity. Two pieces of EDFs, both M12 (980/125, from Fibercore Inc.) with a

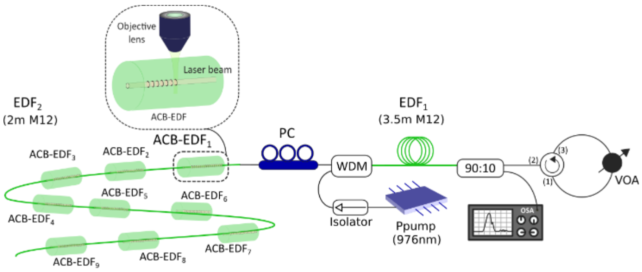


**FIGURE 3. Schematic diagram of the experimental linear cavity fiber laser setup, in which the MD-EDF ($EDF_2$) was also used as saturable absorber.**

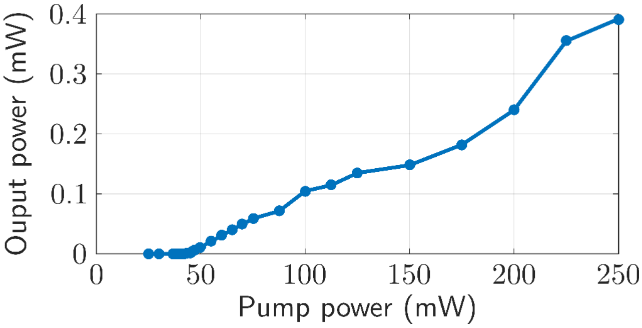


**FIGURE 4. Output power versus pump power for the linear cavity fiber laser.**

theoretical peak core absorption range from 16 to 20 dB/m at 1531 nm, were located into the setup. The first one ($EDF_1$), with 3.5 m long, was used as an active gain medium of the cavity and placed at the common port of the WDM. The second one ($EDF_2$), with about 2 m long and where the nine micro-perforated inscriptions were carried out, was located at one of the cavity ends, that is, after the polarization controller (PC) which was also connected to the 1550 nm WDM port. The PC provided an intracavity mechanism to compensate for the slight polarization dependent gain or adjust the polarization states of the feedback light-wave [12]. The free end of $EDF_2$ was immersed in refractive-index-matching gel to avoid undesired reflections. The other end of the linear laser cavity ends at a fiber loop mirror (FLM) including a 3-port optical circulator where a variable optical attenuator (VOA) is connected between ports 3 and 1. This recirculating signal travels to an optical coupler where 10% of the reflected signal is headed into an optical spectrum analyzer (OSA) with a resolution of 0.1nm. The remaining 90% passes through the 3.5 m long of EDF to the end of the linear short cavity fiber laser.

The following experimental measurements were developed at room temperature and in addition to this, no temperature compensation techniques or vibration isolation were employed.

Figure 4 illustrates the output power as a function of pump power for the linear cavity fiber laser. As this figure shows, the achieved laser presents a pump threshold of about 45 mW, and an efficiency of 0.15%.

Figure 5 (a) shows the optical spectrum, measured by an OSA, of the short-linear-cavity fiber laser with MD-EDF

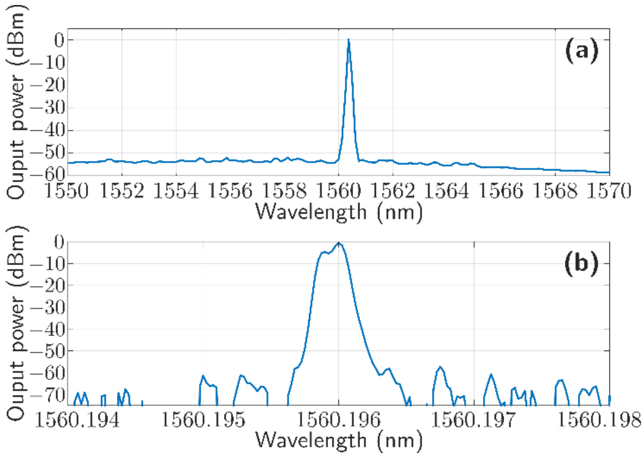


**FIGURE 5. Output optical spectrum of the linear-cavity fiber laser with MD-EDF pumped by a 976nm laser at power of 100mW without using the optical variable attenuator, measured by the OSA (a) and the BOSA (b).**

pumped by a 976 nm laser at power of 100 mW without using a VOA. In this case, the attenuator was disconnected from the optical circulator, and ports 3 and 1 were connected. When operating above this threshold, a single-wavelength laser centered at 1560.1 nm and a pump threshold as low as 45 mW were achieved as Fig. 4 illustrates.

The output power level obtained from this single-laser oscillation when pumped at 100 mW was around 0 dBm, as Fig. 5 (a) illustrates. An OSNR as high as 55 dB was measured by properly tuning the polarization controller (PC) in order to maximize this value. Several previous studies show that these values are reasonably good for most sensor applications [13].

After that, the behavior of the longitudinal modes of this linear cavity fiber laser was experimentally analyzed by using a high-resolution optical spectrum analyzer (BOSA-C Aragon Photonics) which offers simultaneously a high resolution (0.08 pm) and a high dynamic range (>80 dB). This spectral resolution has a lower value than the mode spacing between the longitudinal modes of the linear cavity laser so, as Fig. 5 (b) illustrates, single-longitudinal mode (SLM) operation condition of this laser can be verified, showing only one mode at the central wavelength emission. In addition to this, a laser linewidth at full width at half-maximum (FWHM) of 0.05 pm was measured. This value was limited by the BOSA's resolution and corresponds to a linewidth of the electric beat signal of around 6.2 MHz as presented in Figure 6.

To fully verify the number of lasing modes of the linear cavity fiber laser, a heterodyne detection was also performed by mixing the signal of a tunable laser source (TLS, Agilent 8164B) with the laser output by means of a 50:50 coupler. The FWHM linewidth of the TLS was 100 kHz and its wavelength has been placed close to the obtained laser. Figure 6 depicts the achieved result and confirms the measures attained with the BOSA-C and depicted in Fig. 5 (b). This measurement has been repeated at different emission wavelengths and, in all cases, a SLM operation was achieved

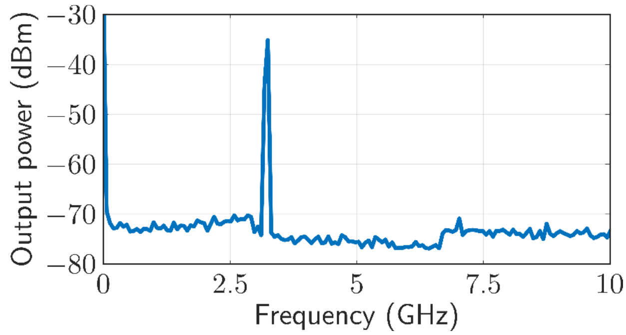

**FIGURE 6.** Electric beat with a tunable laser source (TLS) of the laser output showing the SLM operation condition.

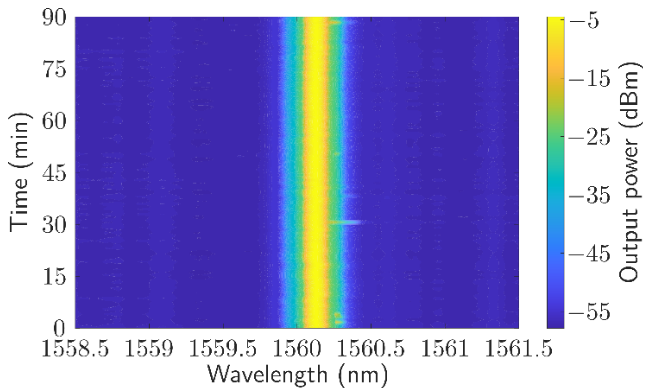

**FIGURE 7.** Output power fluctuations versus time, measured at room temperature generated for one lasing wavelength with SLM behavior.

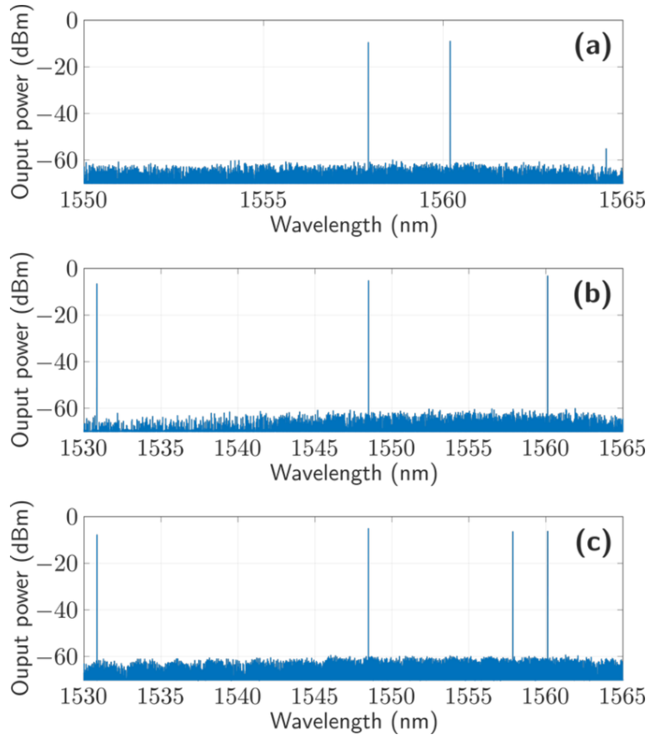

**FIGURE 8.** Output spectrum of the linear cavity fiber laser with a (a) dual-wavelength, (b) three-wavelength or (c) four-wavelength laser operation by using a high-resolution optical spectrum analyzer (BOSA).

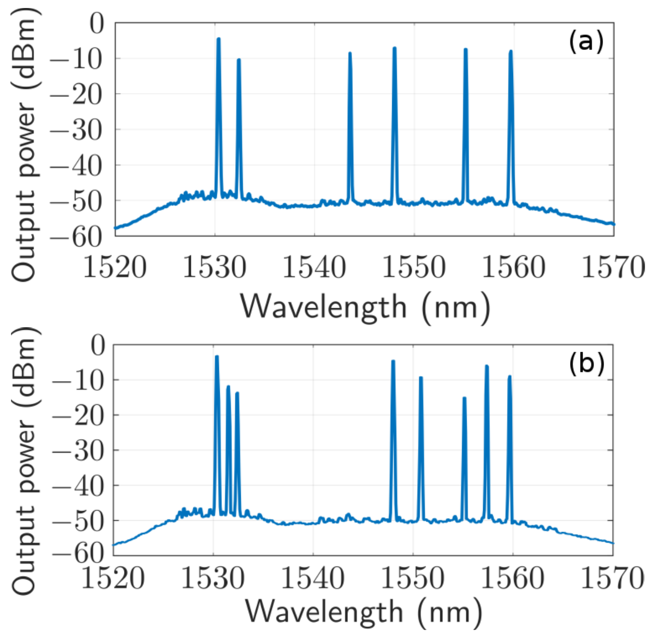

**FIGURE 9.** Output spectrum of the simultaneous (a) six-wavelength or (b) eight-wavelength laser oscillations in the linear short-cavity fiber laser.

even when several lasing wavelengths were oscillating simultaneously.

After verifying the SLM operation, the system output stability was experimentally analyzed. As it has been previously demonstrated, when a SLM behavior is achieved lower output power fluctuations are obtained [14]. Figure 7 shows the output power fluctuation of the lasing wavelength centered at 1560.1 nm for the SLM operation. The measured data were recorded during a period of 90 minutes each 15 seconds and a confidence level (CL) of 95% was considered. It was noticed that at room temperature, the maximum output power variation was around 0.66 dB.

Once the natural oscillation of this linear cavity fiber laser was experimentally studied, a variable optical attenuator was connected between the ports 1 and 3 of the optical circulator. By doing that, the reflectivity at one end of the linear cavity could be easily tuned. Therefore, both the number of laser emissions and their central wavelengths can be selected.

By varying the optical attenuation of the VOA shown in the schematic set up of Fig. 3, the laser can be switched among different lasing wavelengths, lasing up to eight wavelengths simultaneously. As it well known, by reducing the number of lasing wavelengths the gain competition among the different wavelengths is also reduced, increasing the output power and stability values of the remaining ones. Likewise, multiwavelength emission is needed in some applications.

Figure 8(a) illustrates the output spectrum of a dual-wavelength laser operation with an output power level of around -10 dBm and an OSNR of 40 dB. Here it is presented only one of the possible dual-wavelength laser configurations that could be tuned, showing all of them similar characteristics but different central emission wavelengths. Figure 8(b) corresponds to a three-wavelength laser operation, where an output power level obtained from each one of the output channels was around –8.5 dBm and OSNRs about 50 dB were measured. Finally, Fig. 8(c) represents the output spectrum of a four-wavelength lasing configuration with an average output power level of around –5 dBm and an OSNR of about 55 dB.

By combining the reflection provided by the VOA and the variation of the PC, more than four wavelength emission lines can be attained. However, the equalization of all these emission wavelengths was not always possible due to the lack of elements capable of equalizing these powers individually. Figure 9(a) illustrates the output spectrum of this distributed cavity fiber laser when six-wavelength lasing oscillations were obtained. In these cases, the average output power level was around -8 dBm and an OSNR of at least 40 dB was measured for each channel. In Fig. 9(b) the optical spectrum of eight-wavelength lasing oscillations can be seen. As it has been previously pointed out, the higher the number of simultaneous emission wavelengths, the harder their equalization. In this case, OSNR values from 35 to 45 dB were measured.

## III. CONCLUSION

In this work, it is proposed and experimentally demonstrated a new distributed short linear cavity fiber laser. At one of the cavity ends, an artificially controlled backscattering erbium doped fiber section has been connected. This distributed reflector acts also as a saturable absorber, leading to the generation of tunable and switchable single longitudinal-mode laser emissions. The 2-meter-long distributed reflector consists of 9 micro-drilled sections of ∼1cm each one. These nine sections are randomly spaced into one of the highly doped erbium fibers employed into the linear cavity fiber laser. The total length of the fiber laser is 9.5 m and shows a single mode behavior at all the emitted wavelengths. The new laser structure can emit up to 8 wavelengths with an OSNR of 45 dB.

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