

# Single-longitudinal mode laser structure based on a very narrow filtering technique

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**Abstract:** A narrow filtering technique based on the spectral overlapping of two uniform FBGs and applied to obtain a Single Longitudinal Mode (SLM) laser is proposed and demonstrated in this work. The two FBGs are spectrally detuned to reduce their coincident reflection response narrowing the equivalent filter bandwidth. A proof-of-concept linear laser has been built and tested exhibiting SLM operation even with temperature and strain variations.

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**OCIS codes:** (140.3510) Lasers, fiber; (140.3500) Lasers, erbium; (140.3570) Lasers, single-mode; (140.3425) Laser stabilization; (050.2770) Gratings.

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## 1. Introduction

Fiber lasers are important for practical engineering applications, such as: remote sensing, communications, microwave photonics systems or spectroscopy [1,2]. In a simplified way, a fiber laser structure requires two key elements: an active medium to provide the amplification and an optical cavity that causes the positive feedback. The active medium determines the

output power and the cavity design, the resulting laser modes. In many applications, fiber lasers should operate in single longitudinal mode regime (SLM) because their output line width becomes narrower and their power stability improves. These conditions are particularly useful to achieve high resolutions in sensing systems based on fiber lasers.

Several laser configurations have been proposed to ensure a stable SLM operation. A ring cavity configuration is often employed, but complex techniques are required to achieve the SLM operation, this resulting unsuitable for applications that require a small size [3–5]. A linear fiber laser becomes another option to achieve this operation mode. Short SLM linear fiber lasers using fiber Bragg grating (FBG) have been demonstrated in erbium doped fiber [6–9], however the cavity length must be short to obtain a SLM operation. The fiber shortening implies the use of rare-earth ion doped fibers with a high unit length gain to achieve a high output power. The phosphate glass fiber with a high Er-doping concentration (5dB/cm) was suited to short linear SLM fiber lasers [10]. However, this glass is expensive and the required splices to standard fiber introduce high losses and mechanical weakness. A different custom made Er-doped silica fiber has been also employed [11] in a linear cavity obtaining a SLM laser but, this fiber exhibits the same drawbacks as the phosphate one.

Moreover, for real sensor systems, relying in custom made doped fibers is not a practical solution and using commercial Er-doped fibers (with a lower gain) implies a larger cavity. The achievement of SLM operation with a larger cavity implies the employment of a very narrow optical filter. In this work, a very narrow filtering technique based on the spectral overlap of two uniform Fiber Bragg Gratings (FBGs) is presented and demonstrated. The spectral overlapping of odd FBGs has been already applied [12,13] but, to the best of our knowledge, this is the first time that two uniform FBGs are combined to reduce the final bandwidth of the achieved filter. The proposed technique has been employed to build a SLM linear laser. The proposed structure maintains the SLM operation even under strain and temperature variations.

## 2. Spectral overlapping principle

The filtering required for the SLM operation can be obtained by combining two matched FBGs. The narrowing effect is produced by detuning one FBG, but keeping it partially overlapped with the other. In this way, the two filters are matched just when the wavelength of the optical signal is within the overlapped section, thus narrowing the whole spectral response. An example of the FBG detuning is depicted in Fig. 1.

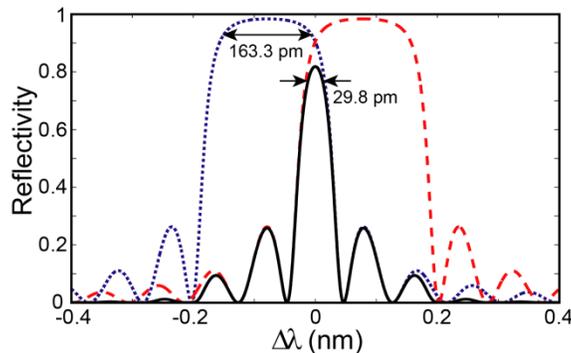


Fig. 1. One FBG is detuned (dashed line) in terms of the other (dotted line). The overlapped spectrum (solid line) gives rise to a filter narrower than both individual FBGs.

In Fig. 1, a simulation of the proposed spectral filter is shown. Two uniform FBGs of  $L = 9\text{mm}$  length with a 1 dB bandwidth of  $W_{1\text{dB}} = 163.3\text{ pm}$  are detuned  $\Delta\lambda = 156.4\text{ pm}$  obtaining an equivalent filter of By employing this structure, as the detuning increases (maintaining some spectral overlapping) the narrowing of the equivalent filter also improves. The main

drawback of this scheme is the power drop due to the equivalent reflection reduction of the overlapped filter. This effect can be minimized by employing FBGs with a higher reflectivity (even being saturated) because their side slopes are steeper thus, maintaining the same bandwidth, a higher equivalent reflectivity can be achieved. This spectral filtering scheme can be applied to different fiber laser structures however, a trade-off between reflectivity (limited by the medium gain) and bandwidth (limited by the modal spacing) has to be reachable to get SLM operation. In this work, a proof-of-concept laser has been manufactured by writing two uniform and spectrally displaced FBGs into Er-doped fiber creating a DBR structure.

### 2.1 Laser manufacturing

The two matched FBGs were written into a commercial erbium doped fiber (Fibercore M12 which has an absorption ratio of 12dB/m at 980 nm) 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. In comparison to the laser structures where two FBGs are spliced to the active fiber, the writing of the FBGs directly to the Er-doped fiber reduces the power losses (lower threshold power) and avoids mechanical weak points. Once the FBGs have been written, one of them was post-exposed to drift its Bragg wavelength and reduce the overlapping area, narrowing consequently the equivalent filter bandwidth. The achieved FBGs have a reflectivity of 99% with a FWHM bandwidth of 240pm and the final wavelength drift is 180 pm.

During the FBGs post-exposition, the DBR fiber laser has been pumped at 1480 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. The proposed DBR structure is depicted in Fig. 2.

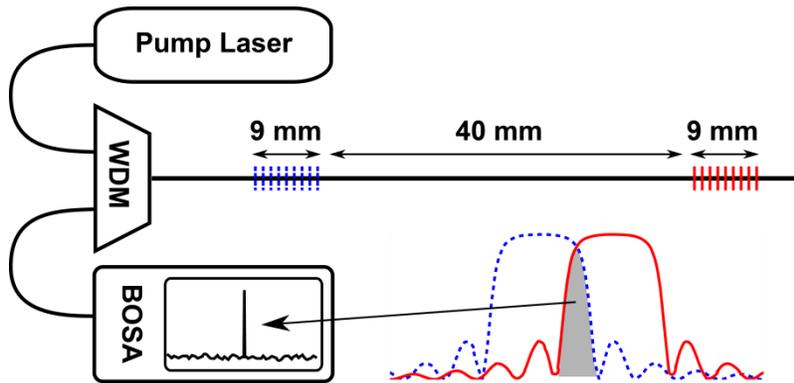


Fig. 2. Employed setup during the fabrication process. The DBR fiber laser structure is also shown: two uniform FBGs of 9 mm length were inscribed into Er-doped fiber with a distance between them of 40 mm.

### 3. Experimental characterization

Since the wavelength selective effect is given by the equivalent filter bandwidth that results from the partial FBG's reflection bands overlapping, the wavelength of the obtained laser is centered at the Bragg wavelength of the equivalent filter. This value matches the upper and lower edges from the lower and upper FBG's bands respectively (1552.2 nm).

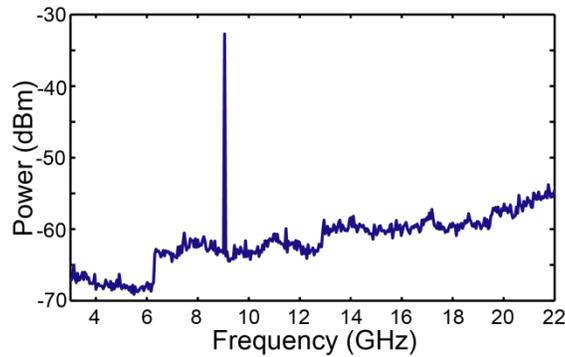


Fig. 3. SLM operation measured at 25°C. The laser signal is mixed with a TLS source obtaining a single peak.

The SLM operation was verified with a heterodyne detection system. A polarization splitter has been connected to the laser output to remove one of the orthogonal polarization modes. The measurements have been performed using an Optical Converter (HP11982A) and an Electric Spectrum Analyzer (HP8592L). A single polarization mode of the lasing signal from the manufactured laser was combined 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. In Fig. 3, a single peak is shown proving the SLM operation of the tested device.

### 3.1 FWHM linewidth and wavelength stability

In order to measure the FWHM linewidth of the emitted wavelength, the setup is changed to the delayed self-heterodyne detection scheme [14]. A phase modulator (Avanex IM10-P) has been employed to perform the 1GHz modulation. A 100 km of standard optical fiber has been employed as delayed line. An EDFA (MPB-EFA-P18F) has been introduced in the setup to amplify the delayed line. According to [14] the measured (FWHM) linewidth was square root of two times the real linewidth, so this was less than 5 kHz as is shown in Fig. 4. This narrow linewidth indicates a stable SLM operation of the fiber laser, being this very important to achieve high resolution in sensing systems that depends on the linewidth and stability of the emitted laser wavelength.

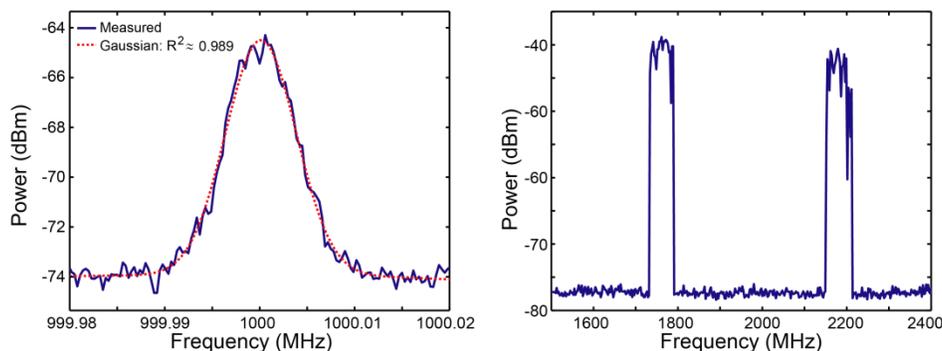


Fig. 4. Linewidth of 4.5 kHz (3dB) measured using self-heterodyne detection with a modulation frequency of 1GHz (left). Wavelength stability (62.2MHz) of both orthogonal polarization modes measured during 10 minutes.

Figure 4 (right) also shows the wavelength stability measured using the heterodyne detection method (without the polarization splitter). The laser signal is mixed with the TLS and both polarization modes are held in the ESA during 10 minutes. The orthogonal

polarization mode spacing of 400 MHz (3.2 pm) corresponds to the typical fiber birefringence. The higher wavelength drift of both polarization modes is under 65 MHz (0.52 pm).

### 3.2 OSNR and power stability

The output laser signal was connected directly to an OSA (HP70952B) to study the power behavior of the fabricated laser. Maintaining the pump power emitting at 26 dBm, the output generated optical power was monitored during 1 hour using the OSA.

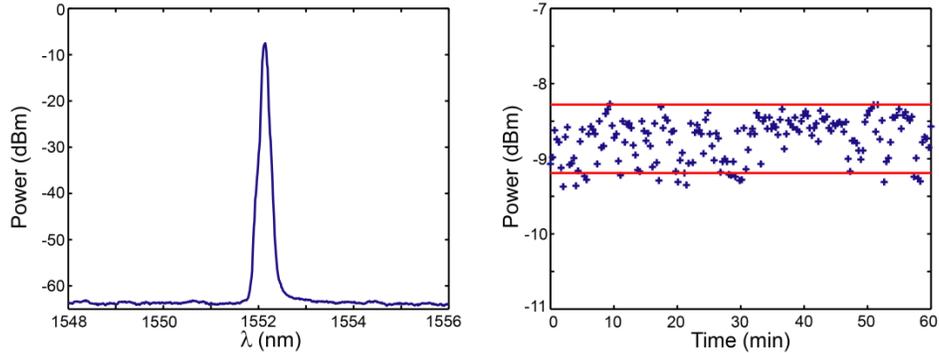


Fig. 5. Measured OSNR for a 26dBm power pump (left) and power stability measured during 1 hour (right).

In Fig. 5, output spectra (monitored by an optical spectrum analyzer (OSA)) of the proposed laser emitting at the Bragg wavelength of the equivalent filter is depicted (left) exhibiting an optical signal-to-noise ratio (OSNR) greater than 55 dB. The power stability measured each 20 seconds (right) is also depicted. The achieved stability was 0.91 dB with a 90% confidence interval during 1 hour.

### 3.3 Temperature response

As the laser wavelength is given by the spectral overlapping of the reflected bandwidths of the FBGs, the wavelength laser response should follow the FBG thermal response. A temperature sweep between 0 and 100 °C has been performed while the laser wavelength was measured using the OSA.

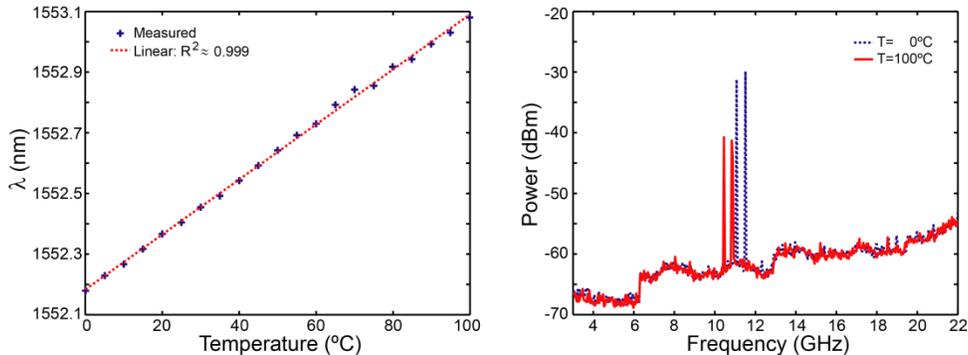


Fig. 6. Emitted wavelength displacement during the temperature sweep (left) and the two orthogonal polarization modes at the extreme temperatures (0°C and 100°C) (right).

The laser response to the temperature sweep is depicted in Fig. 6 (left). The whole DBR structure behaves as their mirror FBGs, exhibiting linear response with a 0.9 nm drift within the 100°C sweep (similar to a FBG written into standard fiber). The SLM operation has been

also studied during the temperature sweep. The measurements associated with the sweep limits are depicted in Fig. 6 (right). The same single modal behavior (polarization modes) can be observed in both temperature limits.

### 3.4 Strain response

The manufactured device is attached to a micrometric linear motor stage to perform a strain sweep. If the applied strain is the same for both FBGs, the laser properties should be maintained while the structure is being stretched.

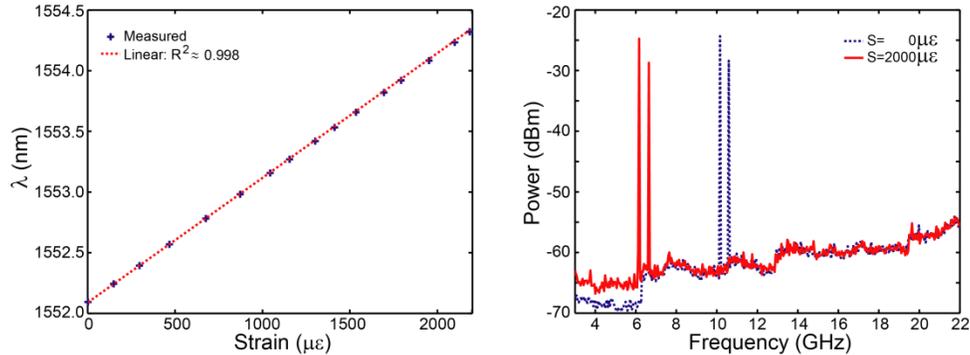


Fig. 7. Emitted wavelength displacement during the strain sweep (left). The two orthogonal polarization modes are depicted in both extremes (right).

A strain sweep up to 2000  $\mu\epsilon$  has been performed while the laser wavelength was measured obtaining a peak drift of 2.2 nm. These results are shown in Fig. 7 (left) and they exhibit the same linear behavior as a single FBG. The SLM condition has been also evaluated during the sweep using the heterodyne detection. Results are shown in Fig. 7 (right) and the SLM is maintained for the highest achieved deformation.

## 5. Conclusions

In this work, a narrow filtering technique based on the spectral overlapping of two uniform FBGs has been proposed to achieve a SLM regime in a fiber laser. The two uniform FBGs are spectrally detuned during the fabrication process to reduce the equivalent filter bandwidth. In order to verify this proposed technique, a DBR fiber laser was fabricated by directly inscribing the two spectral overlapping FBGs in a commercial erbium doped fiber. The total length of fiber laser, including the two FBGs, is 58 mm. This laser operated in robust SLM regime for different working conditions and in two orthogonal polarization modes. The FWHM was less than 5 kHz and the higher signal wavelength variation is under 65 MHz (0.52 pm). The OSNR was better than 55 dB and the power stability of 0.91 dB for a pump power of 26 dBm. It has been also confirmed that the fiber laser maintains a SLM behavior over the whole temperature and strain range discussed.

From the experimental results, we can conclude that the proposed narrow filtering technique provide a simple approach to achieve a stable SLM fiber laser where a precise control for the cavity length and a custom made erbium doped fibers are not required. These fiber lasers can be particularly appealing for applications requiring high resolution and small size sensors.

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