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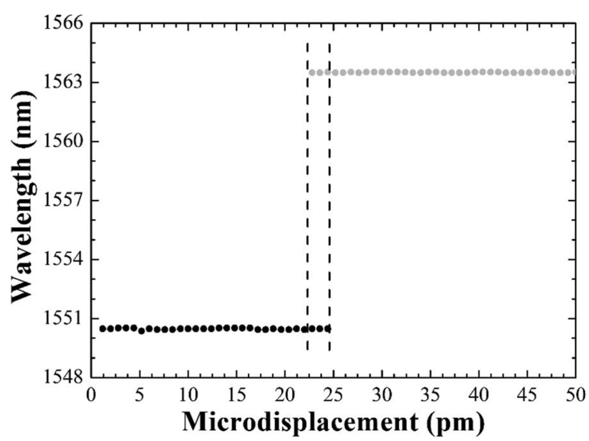

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Single-Longitudinal-Mode Dual Wavelength-Switchable Fiber Laser Based on Superposed Fiber Bragg Gratings

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Abstract: In this work, a simple switchable dual-wavelength short-cavity fiber laser operating in a single-longitudinal-mode regime at room temperature and based on superposed fiber Bragg gratings is proposed and experimentally demonstrated. Only by introducing stress into one of the overwritten FBGs, single- or dual-wavelength laser oscillations can be attained. Either single- or multimode operation of the laser can be easily achieved. Single-longitudinal-mode emission has been verified in two different ways: the first corroboration has been conducted by the heterodyne detection of the output signal, and the second one has been carried out by using a high-resolution optical spectrum analyzer.

Index Terms: Cavity laser, dual overwritten grating, erbium-doped fiber, single-longitudinal mode, superposed fiber Bragg gratings.

1. introduction

Switchable multi-wavelength fiber lasers have been widely investigated due to the fact that they are becoming an important component in the areas of optical fiber communications and sensing [1], [2]. A variety of different methods have been employed for the design of multiwavelength-switchable fiber lasers [1]–[5] such as highly birefringence loop mirrors [6], cascaded fiber grating [7], cascaded birefringence fiber Bragg grating [8] and acoustic waves modulation [9]. In most of these methods, the lasing wavelengths are switched by adjusting the polarization in the cavity, which is a complex optical technique and they have some obvious disadvantages. Another important aspect to take into account of the multi-wavelength erbium doped fiber laser (MEDFL) is their output power instability and mode competition [10]. These instabilities as well as a multi-longitudinal mode (MLM) operation can degrade the performance characteristics of a sensor array based on a tunable ring laser interrogation scheme.

On the other hand, superposed fiber Bragg gratings (SFBG) provide a novel and simple method to achieve switchable fiber lasers due to the possibility to create multiwavelength cavity lasers exactly in the same length of fiber. These SFBG have found use in multiple applications

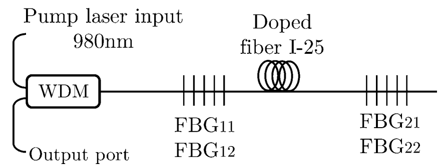

Fig. 1. Schematic configuration of the dual-wavelength single-longitudinal-mode fiber laser cavity.

such as sensors [1], [11], for generating high repetition-rate pulse trains [12], or extremely small time-delay steps [13], telecommunications [14], filters [15] or implementing microwave multi-frequency measurement and signal detection [16] among others [17], [18]. Additionally, dual overwritten FBG sensor scheme is one of the most suitable schemes of discrimination between thermal effects and strain in fiber gratin sensors. By solving a matrix equation, which includes temperature and strain coefficient depending on wavelengths of two gratings, the Bragg wavelength shift of each fiber gratin can be easily obtained [19]. Likewise, superposed fiber Bragg gratings can generate interesting and short devices for optical communications and measurement applications [18], [20].

In this work a single-longitudinal mode (SLM) dual wavelength-switchable erbium doped fiber laser (EDFL) based on SFBG is presented and experimentally demonstrated. This method presents some advantages compared with other techniques based on polarization and there is no insertion loss from optical switches. The lasing wavelengths and the wavelength spacing can be easily controlled by changing the properties of the FBGs. The obtained experimental results of this switchable laser present a significant improvement compared with previous works in terms of output power stability [2] or switching time [3]. In this laser configuration the switching time is not limited by the specifications of the commercial switch but for the high precision motorized stage, which can be selected to work faster. Furthermore, the number of wavelengths simultaneously lasing can be carried out superposing more FBGs but without changing the laser working conditions (pump power or cavity losses).

2. Network Configuration

The experiment was conducted using the set-up shown in Fig. 1. This distributed Bragg reflector (DBR) fiber laser consists of a short piece of erbium doped fiber (I-25 by Fibercore, with absorption of 35–45 dB/m at 1531 nm) and two pairs of wavelength-matched overwritten gratings at different Bragg wavelengths. The set-up was pumped by light from a laser source at 980 nm through a WDM configuration and the output was monitored by using an optical spectrum analyzer (OSA). This pump laser diode was temperature controlled to make sure the laser output was as stable as possible.

These SFBGs have been overwritten using a continuum UV laser and two different phase mask into standard telecommunication fiber, having a similar cost of a single FBG. The use of overwritten FBGs has also similar costs to a DFB structure based on standard ones, but guaranteeing a uniform applied strain, that also has its influence on laser stability. This technique can be limited by the photosensitivity exhibited by the employed fiber, however, it can be enhanced with a hydrogen loading process, achieving reduced costs, which are irrelevant in comparison to the total cost of the whole laser (active fiber, pump laser...).

The first SFBG is composed of two FBGs centered at 1550.17 nm and 1562.65 nm (FBG_{11} and FBG_{12} respectively), with a corresponding full-with at half maximum (FWHM) of 0.097 nm and 0.109 nm and a reflectivity of 42% and 40% at room temperature in that order. The second one comprises two FBGs (FBG_{21} and FBG_{22}) centered at 1549.98 nm and 1562.43 nm, with a FWHM of 0.156 nm and 0.178 nm and a reflectivity of 95% and 96% at room temperature respectively. The erbium doped fiber was spliced between these two pairs of overwritten FBGs, creating a short cavity fiber laser. The length of this doped fiber was around 30 cm and the length of SMF where these superposed FBGs was written were about 60 cm each one, creating a cavity length of about 150 cm long.

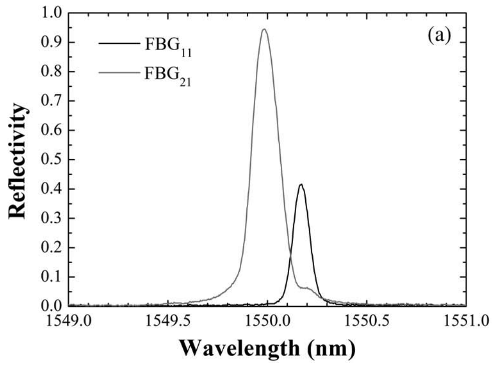

Fig. 2. (a) Normalized reflection spectra of FBG_{11} and FBG_{21} measured by an optical spectrum analyzer. (b) Normalized reflection spectra of FBG_{12} and FBG_{22} measured by an optical spectrum analyzer.

Fig. 2(a) and (b) illustrate the normalized reflection spectra of the central Bragg wavelengths of these two SFBGs. As can be seen, first cavity laser was created by means of FBG_{11} and FBG_{21} and the second cavity was formed by FBG_{12} and FBG_{22}. The central Bragg wavelength difference between both couples of gratings ($FBG_{11} - FBG_{21}$ and $FBG_{12} - FBG_{22}$) was about 0.188 nm and 0.216 nm, respectively.

First pair of SFBG was glued to two stress inducing plates (SP) motionless in one specific position in order to maintain their wavelength emissions as fixed as possible. The micro-displacements applied to the SP could be controlled by a high precision motorized stage in order to modify their wavelength emission. In this case, the induced stress was selected to be the one for the first wavelength fiber laser emitting at about 1549 nm. Albeit, the second pair of superposed FBGs of the laser cavity has been stretched using a motor stage (Newport MM4005), achieving very precise control of its Bragg wavelength. This scheme has been proposed trying to increase the repeatability and accuracy of the experimental setup, attaining a final resolution of about 0.4 pm and also avoiding the need of adjust the polarization inside the cavity for switching the lasing wavelength.

3. Results

By straining the second SFBG of the set-up shown in Fig. 1 a wavelength shift is produced that permits to switched among three different lasing combinations: lasing one by one separately or two wavelengths simultaneously. The experimental results of this work were evaluated by using an OSA as well as a high-resolution optical spectrum analyzer (BOSA-C from Aragon Photonics) located in the output port, as can be noticed in Fig. 1, which offers high resolution (0.08 pm) and high dynamic range ($>$ 80 dB) simultaneously.

The output spectrum of the cavity laser for a 100 mA pump power is presented in Fig. 3. The pumping threshold needed to obtain laser emission was around 60 mA. However, a higher pump power level was used in order to increment the output power stability, as it was previously reported by the authors in [21].

As can be seen in Fig. 3(c) and (d), a single-wavelength laser centered at 1549 nm or 1562 nm respectively can be distinguished. Fig. 3(a) and (b) correspond to a dual-wavelength switch operation measured by a BOSA or an OSA respectively, showing the possibility of single or dual lasing wavelengths combinations. The power obtained from each of the output channels was around -30 dBm and an optical signal to noise ratio (OSNR) of about 40 dB was measured. As depicted in Fig. 3(a), output power levels are lower than the ones measured by the OSA. The reason is that, in order to protect the BOSA, a variable optical attenuator was inserted before this device reducing the output power level in around 10 dB. Nonuniformity of the channel-to-channel output power was less than 3 dB when the dual-wavelength lasing configuration was used. Several previous studies establish that these values are equitably good for most sensor applications [22].

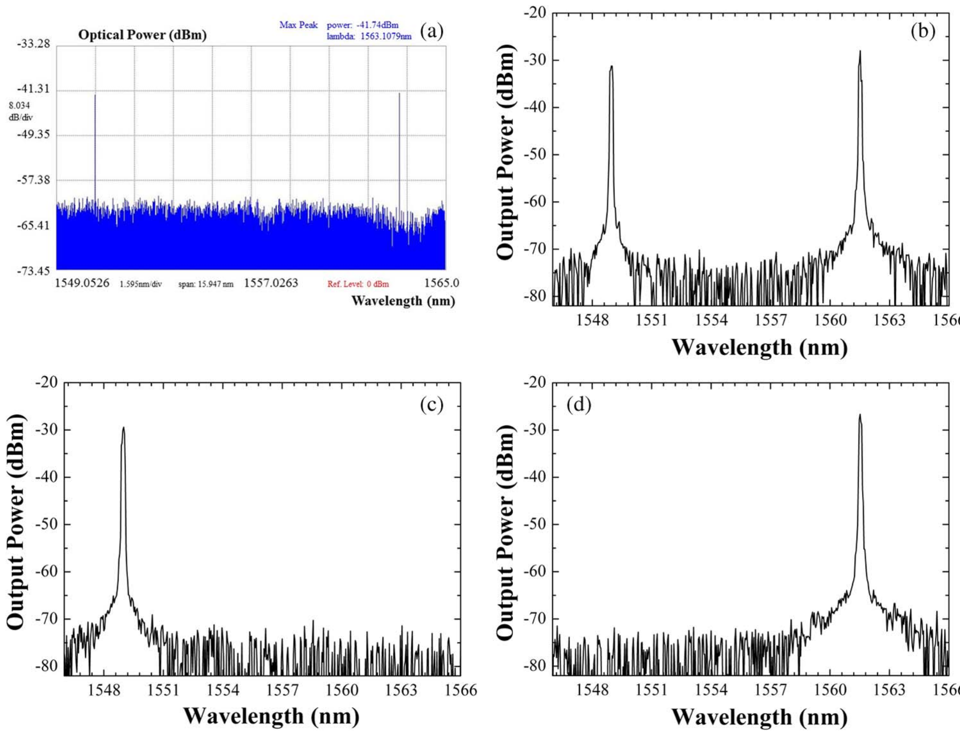

Fig. 3. Output spectra of the laser cavity with dual-wavelength measured by a BOSA (a) or an OSA (b) and single-wavelength at 1549 nm (c) or 1562 nm (d) lasing configuration when it is pumped by a 980 nm laser at 100 mA.

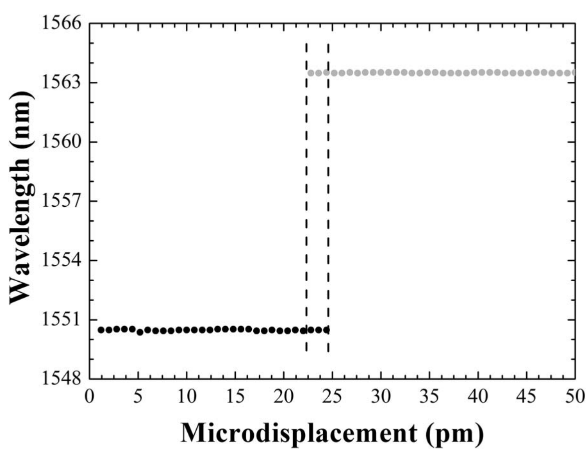

Fig. 4. Wavelength laser emission as a function of the applied micro-displacement on the second pair of superposed FBGs of the laser cavity.

Fig. 4 illustrates the wavelength laser emission as a function of the applied micro-displacement on the second pair of superposed FBGs of the laser cavity. As it was expected three different situations can be distinguished. When a micro-displacement smaller than 23 pm is applied, a wavelength laser emission centered at 1549 nm is attained [see Fig. 3(c)]. Increasing this micro-displacement, dual wavelength emission is obtained [see Fig. 3(a) and (b)] as can be seen in the center of Fig. 4; and finally only a wavelength laser emission centered at 1562 nm is achieved [see Fig. 3(d)].

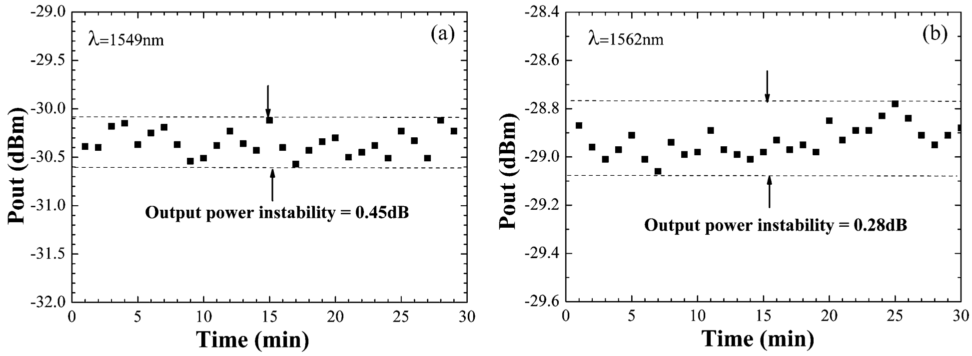

Fig. 5. Output power fluctuations of the first (a) and second (b) wavelengths measured every minute along 30 minutes.

An output power instability study at room temperature of these configurations (single- and dual-wavelength lasing operation) was carried out. The spectral characteristics of the lasers were measured using an optical spectrum analyzer (OSA) at the output port with 0.1 nm resolution. In this work, the instability was defined as the output power and wavelength variations (measured in dB and nm) for a given interval of time and a specific confidence level (CL), that is the probability value associated with a confidence interval, given as a percentage [23]. In these experiments a confidence level of 90% was used and each configuration was tested 30 times during 30 minutes so, the measured data were recorded once each minute. Fig. 5(a) and (b) exhibit the output power fluctuations of both wavelengths. A small power fluctuation was observed and the variation was about 0.45 dB and 0.28 dB for the first and second wavelengths respectively, much better than stabilities measured for SLM ring configurations or another short cavity lasers [24], [25]. Thus, the experimental results demonstrated the stability of the laser.

As it is well known, in this type of topologies, multiple longitudinal modes are supported by the cavity, however due to the high resolution of this scheme, about 0.4 pm, solely by varying the applied strain in the second superposed FBGs the reflection wavelength of the FBGs can be shifted. As it was aforementioned by only straining the second SFBG of the set-up the wavelength shift produced allows switching among three different lasing combinations. Taking into account that configuration, a single or multimode operation of the laser can be easily achieved.

Single-longitudinal-mode (SLM) or multi-longitudinal-mode (MLM) operation in each wavelength laser emission has been verified in two different ways. The first corroboration has conducted by the heterodyne detection of the output signal. Each laser line was combined with the output of a commercial tunable laser source (TLS) with a linewidth of 100 KHz closely located in the spectrum. By doing that, the beating signal was detected after a photodetector by means of an electrical spectrum analyzer (ESA), whose resolution bandwidth can be as good as 1 Hz.

Fig. 6(a) illustrates the output optical spectrum when the tunable laser was tuned to the first wavelength laser emission and the applied strain was selected to create a SLM operation. Fig. 6(b) shows how only by varying the applied strain a MLM operation can be attained for the same wavelength laser. These measurements were also carried out for the laser centered at 1562 nm obtaining similar results. This behavior can be explained by the fact that the accuracy of the experimental setup is high enough to tune the laser emission wavelength to obtain only one mode inside itself.

The second verification of the single or multi-longitudinal mode operation condition was done by using a BOSA. Its spectral resolution has a lower value than the mode spacing between the longitudinal modes of the cavity given by

$$\Delta\lambda = \frac{\lambda^2}{2 \cdot n \cdot L} \tag{1}$$

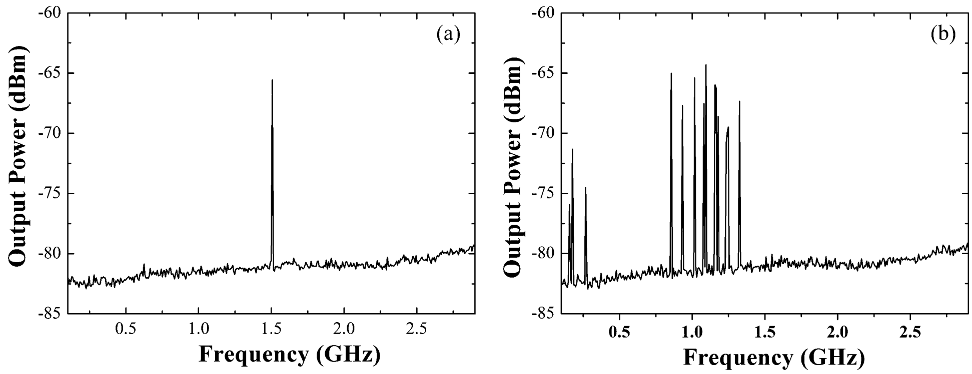

Fig. 6. (a) Output optical spectrum measured by the ESA when the tunable laser was tune close to 1549 nm at a SML operation. (b) Output optical spectrum measured by the ESA when the tunable laser was tune close to 1549 nm at a MLM operation.

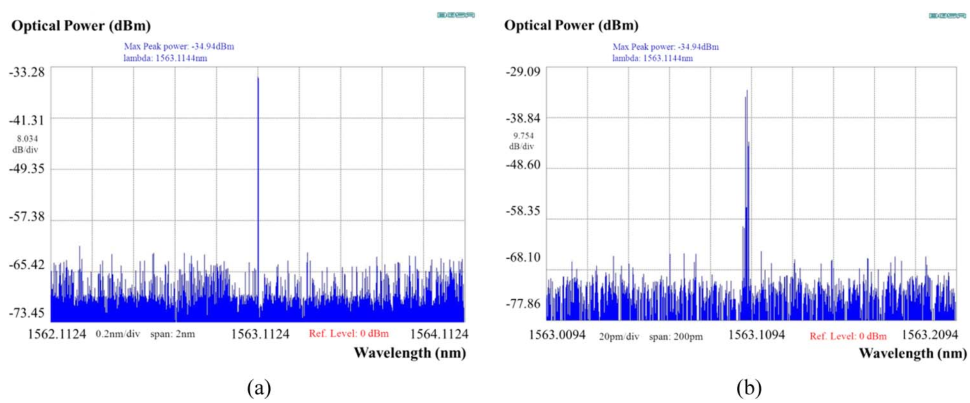

Fig. 7. (a) Output optical spectrum measured for the second channel at SLM operation measured by a BOSA. (b) Output optical spectrum measured for the second channel at MLM operation measured by a BOSA.

where λ is the central mode wavelength, n is the refractive index of the fiber and L is the cavity length. Bearing in mind that: $n = 1.476$, and $L \approx 150$ cm, the mode spacing between the longitudinal modes is about 0.54 pm. This value corresponds to a spectral separation of around 63 MHz that fits with the obtained results showed in Fig. 6(b). Consequently, we can account for the SLM operation condition by using this device, which resolution is as high as 0.08 pm. Obtained results can be seen in Fig. 7(a) and (b). This analysis was also carried out for the laser centered at 1549 nm attaining analogous results.

V. Conclusion

In this work, a switchable dual-wavelength short cavity fiber laser operating in single-longitudinal-mode at room temperature and based on superposed fiber Bragg gratings is proposed and experimentally demonstrated. Due to the high resolution of this proposed scheme, as good as 0.4 pm, solely by varying the applied strain in the second superposed FBGs the reflection wavelength of the FBGs can be shifted, and both single-mode or multi-mode operation of the laser can be easily achieved. Single-longitudinal mode operation could be also obtained because of their resolution so the accuracy of the experimental setup was good enough to tune the laser emission wavelength in order to obtain only one mode inside itself. The laser stability was also analyzed obtaining a power fluctuation as small as 0.45 dB and 0.28 dB for the first and second wavelength respectively.

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