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Single mode EDF fiber laser using an ultra-narrow bandwidth tunable optical filter

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ABSTRACT

Single longitudinal mode (SLM) erbium-doped fiber (EDF) laser operation using a commercialized ultra-narrow bandwidth optical filter has been demonstrated. A 2-m long EDF with an absorption coefficient of 24 dB m^{-1} at the pump wavelength is used as gain medium. The ultra-narrow tunable filter is used for selection of a single longitudinal mode from the available spectrum of multiple modes, which originally exist in the FBG's reflection spectrum. Our approach provides a relatively simple and direct method for realization of SLM operation. A high-resolution optical spectral analyser with a resolution of 0.16 pm is used to observe the output spectrum. To verify the SLM operation, the delayed self-heterodyne method is used, giving a measured laser linewidth of 61.5 kHz.

1. Introduction

Single longitudinal mode (SLM) fiber lasers have become an essential tool in various fields of application, including optical spectroscopy, modern instrumentation, fiber optic sensors, fiber communications and microwave photonic systems [1]. To achieve SLM operation in a fiber laser is a challenging task, due to the multimode laser oscillation that readily exists in a fiber laser. This multimode oscillation originates from several factors; such as the long cavity length, the consequently small spacing between the longitudinal modes and mode-hopping [2]. The frequency noise that can occur may forbid SLM operation. In previous work, these difficulties have been overcome using a variety of techniques – such as employing external injection locking [3], multiple-ring cavity structures [4], using an unidirectional loop mirror configuration [5] and implementation of an un-pumped erbium doped fiber (EDF) as a saturable absorber [6]. A more practical method, in terms of providing durably stable SLM operation is the use of a stable ultra-narrow bandwidth optical filter [7]. In this regard, phase-shifted fiber Bragg gratings (FBGs) [8–10] have been proposed for the optical filter required, in order to suppress mode-hopping and multimode oscillation in the fiber laser [11]. A similar mechanism to that of ultra-narrow bandwidth optical filter, that is by introducing an equivalent phase shift (EPS) into the fiber Bragg grating (FBG) has been reported in Refs. [7] and [12]. Although this technique is able to offer a much narrower transmission bandwidth, depending on the precision of the phase shifts used, a shortcoming of this technique is that a complex FBG fabrication process is required, involving control of the sampling period during fabrication of the FBG [7]. In addition, another limitation associated with this technique is that FBGs are typically temperature sensitive, which correspondingly degrades the laser performance when the environmental temperature varies. We believe and demonstrate that a better alternative for the realization of ultra-narrow bandwidth optical filtering is the use of a fiber-coupled free-space optical system that includes a diffraction grating operated in either a Littrow or a Littman Metcalf configuration, giving high selectivity, low insertion losses and low dispersion.

In this paper, we report the demonstration of an ultra-narrow linewidth SLM erbium-doped fiber laser. A 2-m EDF with an absorption coefficient of 24 dB m^{-1} at a 980 nm pump wavelength is used as the gain medium. The ultra-narrow linewidth optical filter is used for selection of a single mode from the available spectrum of multiple modes,. This working mechanism provides a simple and direct way to realize SLM operation in a fiber laser. A high-resolution optical spectral analyser with a resolution of 0.16 pm is used to observe the output spectrum. To verify the SLM operation, the delayed self-heterodyne method is used, giving an estimated laser linewidth of approximately 61.5 kHz. Although this linewidth is not as narrow as some of the values reported in the literature [13–15], the mechanism for realizing this ultra-narrow linewidth SLM erbium-doped fiber laser is simple, direct and reliable. In Ref.

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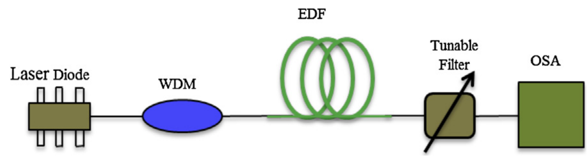

Fig. 1. The experimental setup for characterize of optical tunable filter.

[13], an ultra-narrow linewidth of 109 Hz is obtained by using EDF as a saturable absorber (SA). However, optimization of the parameters of the SA and the low output power level obtained render this approach unsuitable for typical applications.

2. Characterization of ultra-narrow bandwidth optical filter

For this work, a Yenista XTM-50 ultra-narrow bandwidth optical filter is used as the mechanism to generate the desired SLM output. The optical filter consists of a triangular mirror, grating and a reflector, where the triangular mirror is the main component for controlling the wavelength and bandwidth tunability. The triangular mirror is a crucial component of the filter as it is used to select a portion of the spectrum, with the narrow end of the triangular mirror creating a narrow bandwidth filter while the wide end creates a wide bandwidth filter.

Characterization of the optical filter is carried out using the setup as shown in Fig. 1. An amplified spontaneous emission (ASE) output is first generated using an EDF pumped by a 980 nm laser diode operating at a power of 63 mW. The EDF used is a conventional EDF, approximately 2 m long with an absorption rate of 24 dB m^{-1} at 980 nm. The 980 laser diode is connected to the EDF using a wavelength division multiplexer (WDM), with the 980 nm laser diode connected to the 980 nm port of the WDM and the EDF connected to the common output. The opposite end of the EDF is connected to the optical filter, so that the ASE generated will pass through the optical filter and subsequently be channelled into an ANDO AQ6317C optical spectrum analyser (OSA) for analysis.

The spectrum of different bandwidth and wavelength from the characterization of the optical filter are shown in Fig. 2(a) and (b).

From Fig. 2, it can be seen that the bandwidth and wavelength of the output spectrum is changing variably with the screw graduation of a tunable filter. The bandwidth of the optical filter is tunable from 50 to 850 pm, which is shown in Fig. 2(a) while a wide wavelength tunability is observed from 1485 nm to 1615 nm and this is depicted in Fig. 2(b), with the power of the wavelengths filtered corresponding to the relative power of that particular wavelength in the ASE spectrum.

3. Experimental setup

The setup of the proposed SLM EDF ring laser is shown in Fig. 3. In this setup, a 2-m long EDF with an absorption coefficient of 24 dB m^{-1} at 980 nm acts as the gain medium. A 980-nm laser diode is used as a pump wavelength source, and the pump wavelength is injected into the ring cavity through the 980 nm port of a 980/1550-nm WDM. The common port of the WDM is connected to the 2-m long EDF, with the other end of the EDF now connected to Port 1 of an optical circulator (OC).

When pumped by the 980 nm laser diode, the 2-m long EDF generates an ASE spectrum, which will travel though Ports 1 to 2 of the OC and thus encounter the first wavelength mechanism, which in this case is formed by a fiber Bragg grating (FBG) with a central wavelength of approximately 1546.5 nm. Although this filter does not yet generate the desired SLM output, it is still a crucial component of the setup as it restricts the number of wavelengths that are allowed to oscillate in the cavity. The output filtered by the

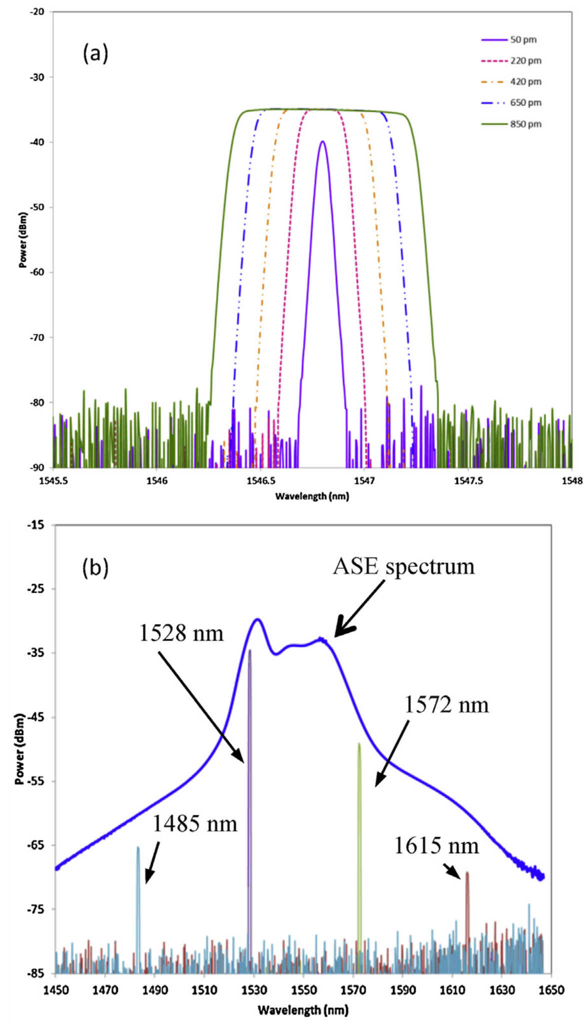

Fig. 2. Characterization of optical filter (a) bandwidth tunability from 50 to 850 pm; (b) wavelength tunability from 1485 to 1615 nm.

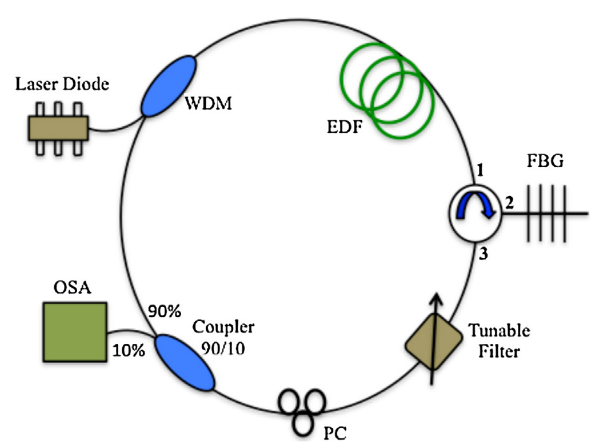

Fig. 3. Schematic diagram of the SLM EDF laser.

FBG now travels back through Port 2 to Port 3 of the OC where it re-enters the lasing cavity. Travelling along the cavity, the lasing wavelengths now encounter the ultra-narrow bandwidth tunable optical filter, which further filters the oscillating wavelengths and allows only a SLM to continue propagating along the cavity. Further along the cavity, a polarization controller (PC) is used to adjust the polarization of the propagating wavelength, thereby optimizing the

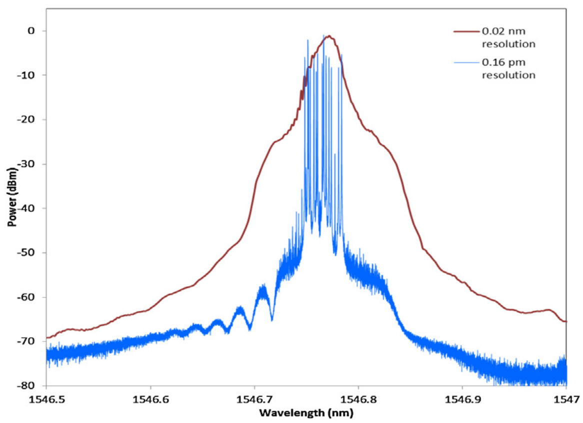

Fig. 4. Output spectrum observed from 0.02 nm resolution OSA and 0.16 pm resolution OSA.

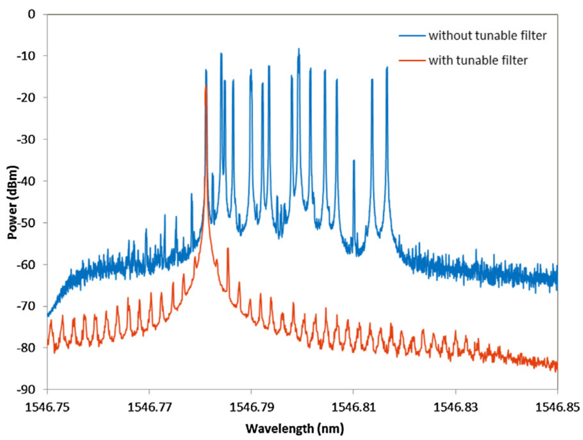

Fig. 5. Obtained spectrum with and without filtering by the tunable, high resolution optical.

power of the output, before it encounters a 90:10 coupler that are used to extracts a portion of the propagating signal for analysis. The 90% port of the coupler is attached to the 1550 nm port of the WDM, thus completing the cavity. The output is analysed using a conventional ANDO AQ6317C OSA that has a resolution of 0.02 nm, as well as an APEX AP2051A OSA that has a very high resolution of 0.16 pm. The total cavity length of this configuration is measured to be approximately 20 m.

4. Results and discussion

The output spectrum of the laser cavity, obtained with the tunable optical filter removed from the cavity, is shown in Fig. 4. The output obtained is analysed using both OSAs, thus giving comparable spectra obtained as resolutions of 0.02 nm and 0.16 pm. Analysis of the spectrum obtained at a resolution of 0.02 nm gives a peak power of −1.027 dB m at 1546.8 nm and a full-width at half-maximum (FWHM) bandwidth of 0.186 nm. The spectral output obtained from the high resolution OSA under the same conditions on the other hands shows that the peak wavelength region in reality consists of many oscillating modes. It is interesting to observe that while the peak wavelength of the lower resolution spectra is approximately 1546.8 nm, analysis by the higher resolution OSA reveals that the oscillating modes from 1546.78 to 1546.82 nm in fact form the peak oscillating modes, at powers of approximately −8.20 to −16.97 dB m.

Fig. 5 enlarges the output spectrum obtained from the high resolution OSA, focusing onto the region of the oscillating modes after

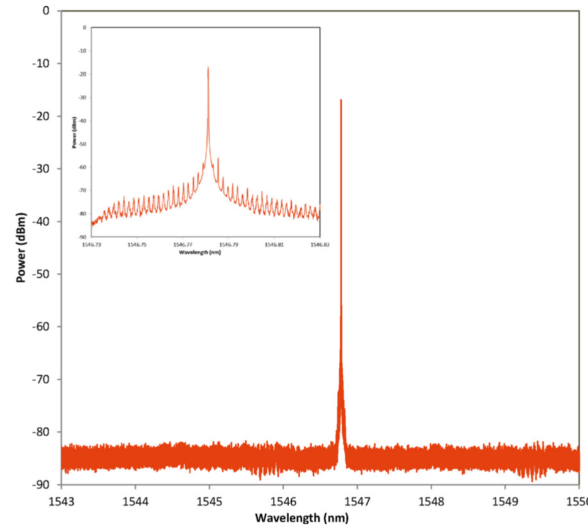

Fig. 6. Single mode output spectrum as taken from high resolution OSA (0.16 pm resolution) whereby the inset shows the spectrum with 0.10 nm span.

inserting the tunable filter. It is here that the role of the tunable optical filter becomes apparent – by inserting the filter into the cavity, a single oscillating mode can be extracted, in this case the mode at 1546.78 nm. Further adjustment of the filter provides a tunability in selectivity of mode within the wavelength range of 1546.78 to 1546.82 nm. It must be noted that the mode-tunable here arises solely from the tunable filter, with the wavelength filtered by the FBG being kept constant by ensuring that the FBG does not experience any strain or compression. This is accomplished by conducting the experiment in a controlled environment, with the temperature kept constant at 25 °C. The power of the selected mode drops from −14 dB m to −17 dB m, this being attributed to the losses induced by the filter.

Fig. 6 shows the obtained SLM output as seen from the high resolution OSA. The inset of Fig. 6 shows an enlarged view of the SLM as well as its side-modes, thus providing a clearer image of the SLM output. It can be seen that although an SLM output is obtained, there are still many oscillating side-modes at substantially lower powers present as well. These side-modes are attributed to the high power of the SLM wavelength [16], and can be removed by adding an unpumped EDF into the cavity as demonstrated by Refs. [17–19]. Even though these side modes are seen in high resolution OSA, the image of them is not visualized in regular OSA.

Verification of SLM operation in the laser cavity is carried out by analysis using an Anritsu MS2667C radio frequency spectrum analyser (RFSA) together with a high speed Agilent 83440C photodetector. The RFSA and photodiode replace the OSA in the setup of Fig. 3. The measured signal by the RFSA is shown in Fig. 7(a), where the frequency beats in the RF spectrum indicate a noisy and unstable output signal as a result of multi-mode oscillations, which arises due to the absence of the optical filter. Once the optical filter is integrated into the setup, a clean spectrum is observed, with no frequency beating as shown in Fig. 7(b). This verifies the fact that the system is now generating an SLM output. Furthermore, the RFSA output also indicates that the minor side-modes, as observed in Fig. 6, and its inset do not affect the generation of the SLM output, as the power of these side-modes is very low and not sufficient enough to result in frequency beating.

Further verification of SLM operation is carried out by the delayed self-heterodyne method, which also allows for the linewidth of the SLM to be measured. For this measurement, a setup as shown in Fig. 8 is used.

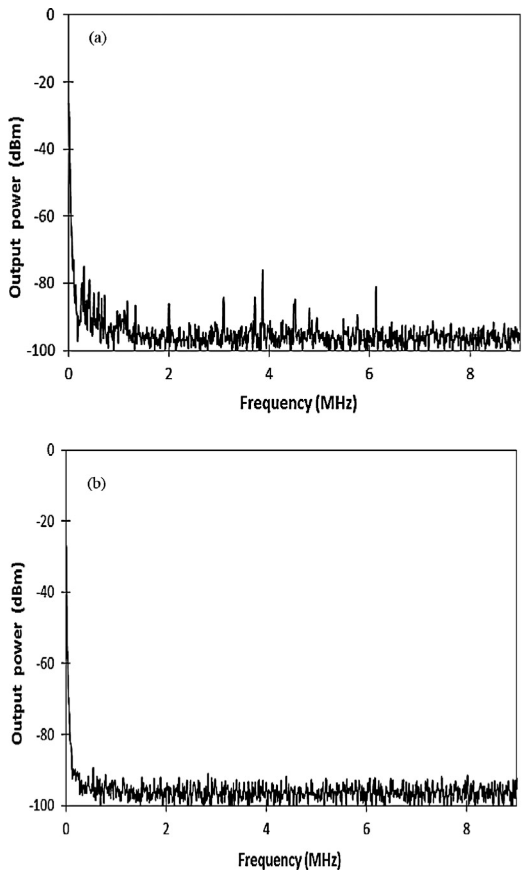

Fig. 7. RF spectrum of output laser (a) without optical filter, (b) with optical filter.

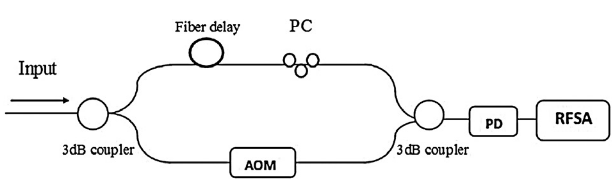

Fig. 8. Setup for delayed self-heterodyned method.

The setup consists of a 1 × 2 3 dB coupler with one port is connected to a single mode fiber (SMF) of 500 m long which functions as the delay line, and the other port is connected to an acousto-optic modulator (AOM) and both output signals are then recombined using another 2 × 1 3 dB coupler. The input coupler divides the signal from the fiber laser into two portions of the same power, with one portion propagating into the 500 m long SMF, while the other portion propagates into the AOM which operates at 80 MHz. Both equally split signals are then recombined at the output coupler to be observed in the RFSA via the photodetector.

The resulting RF beat spectrum obtained using this method is given in Fig. 9. The linewidth is measured using a Lorentzian FWHM calculation, which gives a linewidth value of 61.5 kHz, together with a signal-to-noise ratio (SNR) of approximately 23 dB.

Although this linewidth is not the narrowest as compared to the values reported in Refs. [13–15], the mechanism to realize this ultra-narrow linewidth SLM erbium-doped fiber laser is easy and reliable. It must be noted that in Ref. [13], an ultra-narrow linewidth of 109 Hz is obtained by adding an unmpumed EDF as a saturable absorber. However, optimization process of saturable absorber's parameters and a low output power obtained make it generally unsuitable for most real-world applications, as opposed to the system demonstrated in this work.

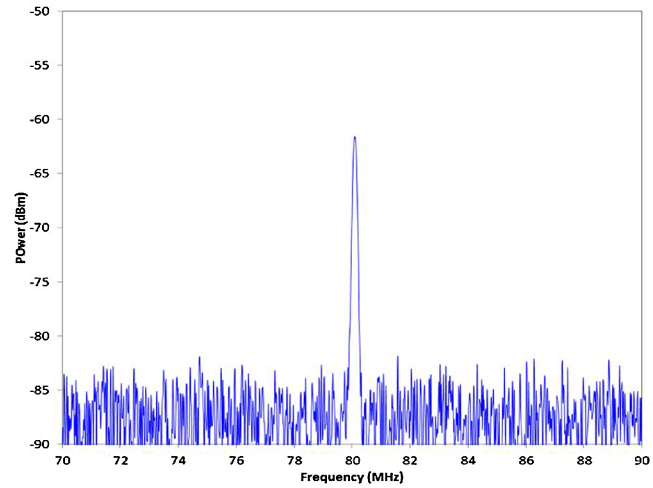

Fig. 9. RF beat spectrum using delayed self-heterodyne method.

5. Conclusion

An EDF-based SLM ring laser using an ultra-narrow bandwidth optical filter is demonstrated. The system uses a 2-m EDF with an absorption coefficient of 24 dB m^{-1} as the gain medium, while an ultra-narrow tunable filter is used for isolating an SLM output. The SLM output has been obtained at a wavelength of 1546.78 nm with an output power level of −17 dB m. Verification of the yielding an estimated laser linewidth of 61.5 kHz.

Acknowledgement

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