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Study of a mode-locked erbium-doped frequency-shifted-feedback fiber laser incorporating a broad bandpass filter: Experimental results

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ABSTRACT

We present rigorous experimental studies on the spectral and temporal behaviors of an erbium-doped frequency-shifted-feedback fiber laser (FSFL), with respect to various parameters of the laser cavity, including the direction of the frequency-shift mechanism, the quantity of frequency-shift, and the output coupling ratio (OCR) of the cavity. We show that if the filter bandwidth is much broader than the laser linewidth, the laser spectrum tends to split and form a secondary spectral band (SSB) on the shorter or longer wavelength side of the primary spectrum, depending on whether the direction of the frequency-shift mechanism is upward or downward, respectively. We found that the SSB forms a parasitic pulse with much lower peak power traveling on the leading or trailing edge of the primary pulse, which leads to a significant asymmetry in the whole pulse formation in the time domain.

1. Introduction

Since the first report in Ref. [1], frequency-shifted feedback (FSF) lasers (FSFLs) have generated a considerable amount of research interests as coherent light sources for applications, such as broadband continuous-wave (CW) lasers [2,3], optical sources for distance metrology [4,5], multi-wavelength lasers [6–9], and pulsed lasers [10–19]. In principle, FSFLs are formed via repetitive frequency shifts of the spectral components of the cavity modes, using a frequency-shifting element, e.g., an acousto-optic modulator (AOM), located inside the laser cavity. The operating regime of these lasers (broadband CW or pulsed) is determined by several cavity parameters, such as intracavity gain (which depends on pump power), filter bandwidth, frequency-shift quantity, Kerr nonlinearity, frequency/polarization-dependent losses, etc. [6,10,19,20].

To date, there have been a series of research attempts to investigate various FSFL regimes both experimentally and theoretically because of their unique and distinctive characteristics which are significantly alternated depending on the operating regime. In fact, mode-locked FSFLs have been demonstrated with various gain media, e.g., in erbium (Er) [11–13], ytterbium (Yb) [14,15] and Er/Yb fibers [16,17], and in various cavity configurations, e.g., in linear [15], ring [12,13] and hybrid [14,16] laser cavities. While pulse durations obtained with FSFLs are, in general, in the order of tens of picoseconds, they can also be reduced to the order of a few picoseconds to hundreds of femtoseconds once they are combined with other mode-locking techniques, e.g., nonlinear polarization rotation (NPR) [12,14]. So far, most experimental investigations carried out with mode-locked FSFLs have mainly focused on achieving short pulses through modifying cavity configurations [12–14,16,18]. In comparison, little attention has been paid to the interplay among the various parameters of the laser cavity, such as filter bandwidth, frequency-shift quantity, output coupling ratios (OCRs), etc., and their impact on the resultant pulse formation in terms of spectral and temporal behaviors. For example, the spectral asymmetry generally observed with FSFLs is among the various distinctive features that have not been well analyzed and explained, although this has roughly been described as the consequence of the quadratic frequency chirp imposed by the frequency shifter [19] in conjunction with the filter dispersion in the cavity [20]. In addition, while there have been a handful of experimental and numerical studies dealing with the subjects on how key laser cavity parameters, such as filter bandwidth and frequency-shift quantity, affects the pulsewidth and spectral linewidth [10], a rigorous study on the spectral and temporal behaviors and their inherent correlations has yet to be conducted. We would like to emphasize that such a rigorous and systematic study will make a useful stepping stone for making further advances in FSFL technology, considering their unique features and on-going research activities in recent years [9,17,18]. Here we carry out an experimental investigation on FSFLs, paying particular attention to the spectral and temporal behaviors of the FSFL pulses and their inherent correlations when the cavity incorporates a broad bandpass filter (BPF).

In the following sections, we present experimental results based on a mode-locked Er-doped FSF fiber laser (EDF-FSFL) in a ring cavity configuration, with which we carry out three sets of experiments to identify the consequence of the key cavity

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parameters, including the direction of the frequency-shift mechanism, the quantity of the frequency-shift, and the OCR of the laser cavity, to the spectral and temporal responses of the output pulses.

2. Experimental arrangement

The schematic of the EDF-FSFL is shown in Fig. 1. It consists of 2 m of an EDF (Fibercore) that has a small-signal absorption rate of 37 dB/m at 1530 nm. The EDF is pumped through a wavelength-division-multiplexed (WDM) coupler (1480/1550 nm) by two laser diodes (LDs) at 1480 nm that are combined through a polarization beam combiner (PBC) and can deliver a total power of 250 mW. A second WDM coupler spliced at the other end of the EDF is for removing the unabsorbed pump light from the cavity. The combination of two sets of polarization controllers (PCs, PC1 and PC2) and a fiberized polarization beam splitter (PBS) are utilized to introduce a polarization rotation in the ring cavity and to adjust the OCR of the cavity. The output ports of the PBS are pigtailed by polarization-maintaining fibers (PMFs). PC1 and PC2 consist of three wave plates (a quarter-wave plate, a half-wave plate, and a quarter-wave plate) and two wave plates (a quarter-wave plate and a half-wave plate), respectively. A tap coupler having a split ratio of 95:5 after PC2 is for monitoring the intracavity signal. The frequency-shifting mechanism inside the cavity is obtained through an AOM. For this, we investigate four different fiber-coupled AOMs (Gooch & Housego) driven by a radio-frequency (RF) signal generator. Three of the AOMs operate in a downshifting-frequency mode at 80, 110 and 200 MHz, and the fourth AOM in an upshift-frequency mode at 110 MHz. All the AOMs exhibit similar characteristics except for the 200-MHz AOM, which has a slightly higher insertion loss (~7 dB) than the other three (~3 dB). In addition, the cavity incorporate a fiberized optical tunable filter (Santec) with a spectral bandwidth ($\Delta\lambda_F$) of 1.3 nm measured at full-width half maximum (FWHM). (It is noteworthy that the use of this BPF was essential to stabilize the mode-locked pulse generation while we could manage to generate mode-locked pulses without incorporating a BPF, which will be discussed in detail in Section 4.) Finally, the unidirectional operation of the ring cavity is ensured via a fiberized isolator. In consequence, the total cavity length becomes approximately 14.5 m with an average GVD parameter of $\beta_2 = -0.2175$ ps^2 at ~1550 nm.

3. Experimental results

The cavity shown in Fig. 1 was initially tested without incorporating an AOM. However, in the given condition it was not possible to obtain mode-locking at any pump power level up to 250 mW. This indicates that the saturable absorber effect induced by the NPR in combination with the PBS in the cavity was not strong enough to generate stabilized mode-locked pulses, thereby only forming unstable noisy pulses in the time domain (see, for example, the inset of Fig. 2). A typical optical spectrum of the laser operating without an AOM is shown in Fig. 2. The black dotted-line shown in the figure represents the transmission spectrum of the optical filter ($\Delta\lambda_F = 1.3$ nm) used in the cavity when measured with a white light source. The spectral linewidth of the output signal generated under this condition was ~0.045 nm and had a roughly symmetric spectral shape. On the contrary, stabilized mode-locked pulses were readily achieved when any of the AOMs described previously was incorporated in the cavity for pump powers (P_{pump}) in excess of 150 mW. In addition, it should be noted that all the FSFL experiments shown in this work were carried out in the non-resonant regime since mode-locking was achieved more easily and kept with higher stability compared to the resonant regime [17].

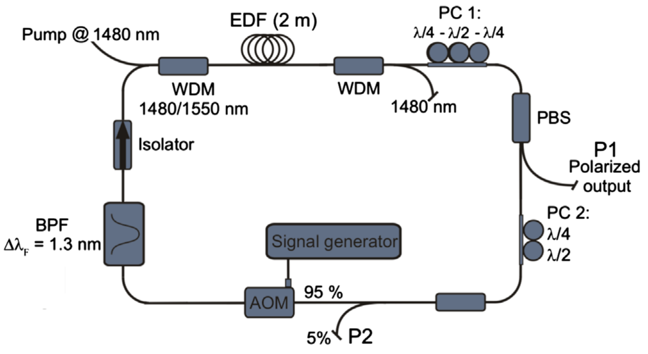

Fig. 1. Schematic of an EDF ring laser incorporating an AOM and a BPF ($\Delta\lambda_F = 1.3$ nm).

Fig. 3 shows the optical spectrum formed when the laser was operating in the mode-locked regime for different OCR conditions with the AOM of a 110-MHz downshift frequency spliced in the

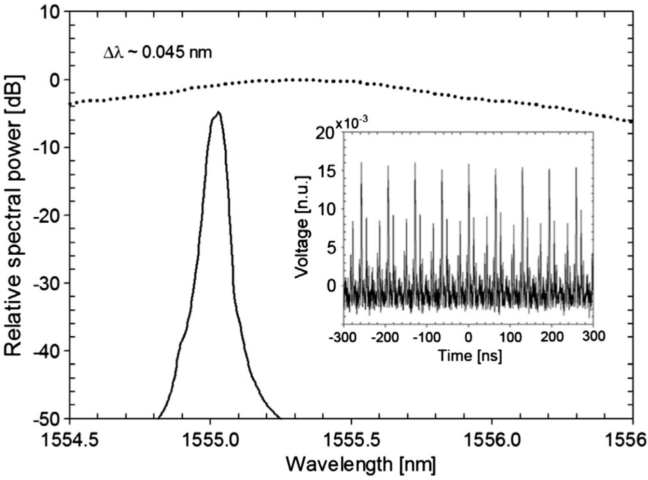

Fig. 2. Output spectrum of the EDF ring laser without incorporating an AOM. Inset: time trace of the signal output.

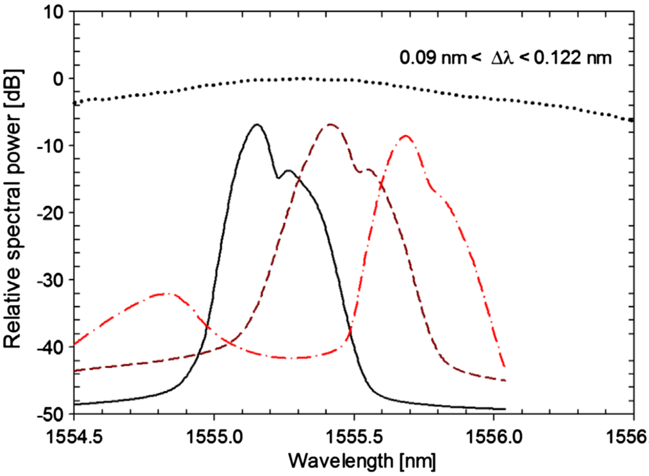

Fig. 3. Output spectra of the EDF-FSFL with a 110-MHz downshifting AOM for three different polarization states when operating in the mode-locked regime. The dotted line on top of the optical spectra represents the transmission spectrum of the 1.3-nm BPF centered at 1555.4 nm.