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

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We present a comprehensive numerical study on the spectral and temporal behaviors of a mode-locked erbium-doped frequency-shifted-feedback fiber laser as a function of the frequency shift and optical bandwidth of the laser cavity. For this we develop a numerical model which is based on the rate equation and nonlinear Schrödinger equation for the fiber-based active cavity. We numerically verify that if the ratio of the filter bandwidth to the frequency-shift value is higher than ~400 times, the spectral broadening of the laser output tends to break up and form a secondary spectral band (SSB) on the wavelength side of the spectrum where the spectral components of the cavity modes are constantly shifted by the intracavity frequency shifter. We also verify that the SSB forms a satellite pulse in the time domain, traveling on either the trailing edge or leading edge of the main pulse, depending on whether the SSB is formed on the shorter or longer wavelength side of the pulse spectrum. We emphasize that these numerical results are also in good agreement with the experimental results discussed in our previous report [25].

1. Introduction

Frequency-shifted feedback (FSF) lasers have been widely studied since their first report in the literature by Streifer et al. [1]. The distinctive performance of FSF lasers, capable of operating in either broadband continuous-wave (CW) or pulsed regimes, makes them attractive as light sources for applications ranging from broadband CW lasers [2,3], multi-wavelength lasers [4–6], distance metrology [7,8], and various types of pulsed sources [9–26] FSF lasers are formed by constantly shifting the spectral components of the cavity modes through a frequency-shifting device, e.g., an acousto-optic modulator (AOM) located inside the laser cavity. The operating regime of these lasers is primarily determined by several cavity parameters, such as intracavity gain (which depends on pump power), optical filter bandwidth, frequency shift, Kerr nonlinearity, and frequency/polarization-dependent loss [9,18–26].

In particular, theoretical investigations of FSF lasers have yielded many different theoretical/numerical models in order to describe the output characteristics of such lasers that significantly vary with the type of the operating regime [9,19–23]. For example, in a regime of low pump power, where FSF lasers normally present broadband CW outputs, the rate-equation models by Bonnet et al. [19] and Stellpflug et al. [20], offer good descriptions on the dynamics of these lasers. However, these models lack the phase information of the optical fields and are not capable of describing mode-locked regimes of FSF lasers. The models by Nakamura et al. (the moving comb model) [21] and Yatsenko et al. (the discrete-frequency model) [22] consider the phase information of the optical fields, so that they are capable of showing steady-state pulse formations for specific conditions. However, both models still do not take into account the phase fluctuations generated by the nonlinear elements of the laser cavity. A different approach to analyze the behavior of FSF lasers in mode-locked regimes was carried out by Kodama et al. [23], whose model compares the formation of pulses in FSF lasers to that of periodically amplified soliton systems with sliding-frequency filters [24]. However, this model can only cover soliton-type pulse formations [10]. In addition, Martijn de Sterke et al. has reported that pulse formation in mode-locked FSF lasers can also be described without taking into account the role of dispersion in the cavity [18]. Sabert et al. have discussed the attribution of Kerr nonlinearity, i.e., self-phase modulation (SPM), as a key element to generate stable pulses in mode-locked regimes [9]. They analyzed the behavior of the output signal in terms of its bandwidth and pulsewidth for different parameters of the laser cavity. However, the behaviors of the output signal in terms of its spectral and temporal shapes

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and its evolution were not discussed in detail, even though the spectral and temporal behaviors of FSF lasers are significantly influenced by the optical filter bandwidth and the amount of frequency shift, as have been experimentally observed in our previous reports [25,26].

In particular, pulses generated by FSF lasers can yield slightly asymmetric characteristics both in the spectral domain and in the time domain. While these distinctive characteristics are thought to be the consequence of inclusion of frequency shifters together with dispersive optical bandpass filters (BPF) in the cavity [24], there have been few reports which thoroughly analyze them via a comprehensive theoretical or numerical model linked with experimental results for various cavity parameters [9,12,19]. It is noteworthy that in our previous reports, we have experimentally observed the spectral asymmetries of two typical FSF lasers incorporating optical BPFs of 0.45 nm (relatively narrowband) and 1.3 nm (relatively broadband) [25,26]. In fact, we observed that the spectral shape of the output signal in the mode-locked regime presents quite distinctive asymmetries depending on the filter bandwidth as well as the amount of frequency shift of the AOM. For example, for cavities with a broadband BPF, a secondary spectral band (SSB) is developed on the wavelength side where the frequency components are constantly shifted by the AOM [25]. However, such an SSB does not appear from cavities with a narrowband BPF [26].

Here, to have a better understanding of the dynamics of FSF lasers, we carry out comprehensive numerical studies of an FSF erbium (Er)-doped fiber (EDF) laser in a ring cavity configuration, paying attention to the influence of the frequency shifter and optical filter bandwidth on the evolution of the spectral shape of the output pulse and its correlation with the resultant temporal shape of the output pulse. We develop a numerical model based on the rate equation and nonlinear Schrödinger equation for the fiber-based active cavity. We highlight that our numerical results are in line with the previous results carried out in Refs. [9,10,18] and agree well with the experimental results presented in [25], which will offer a route forward to better understanding and new insights on pulse formation dynamics of FSF lasers in continuation of our previous experimental report [25].

The structure of this manuscript is as follows: In Section 2, we describe and explain our numerical model constructed for this specific study, including a summary of the values given to the relevant cavity parameters. In Section 3, we present our numerical results: The first part focuses on the pulsewidth and spectral bandwidth of the output signal as functions of the frequency shift of the AOM and the bandwidth of the optical BPF. These results are mainly carried out to compare the trend of our numerical results with previous works [9]. The second part discusses the asymmetric characteristics of the spectral and temporal shapes of the output signal for various cavity parameters. We compare the numerical results specifically with the experimental results obtained from our previous report for broadband filters [25]. In addition, a brief discussion on the influence of the frequency shift of the AOM and the bandwidth of the optical BPF follows in Section 4. Finally we give the conclusions in Section 5.

2. Numerical model

Our numerical model is based on the iterative, sequential numerical simulations of the elements of an FSF laser cavity similar to the schematic shown in Fig. 1. It is built by hybridizing an in-house-coded numerical program in Matlab and a commercial software program (VPI Transmission Maker). The former is used to simulate the frequency shifter (AOM) and the optical BPF. The latter is used to generate the optical signal and to simulate the

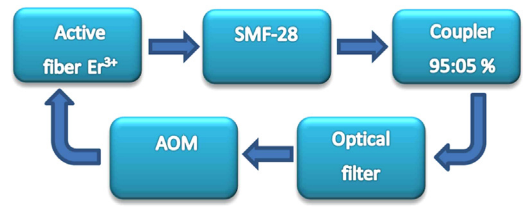

Fig. 1. Schematic of the FSF laser system used for the numerical simulations.

optical fiber amplifier in the cavity and the nonlinear pulse propagation in the passive cavity fiber sections. Indeed, this hybridized numerical model is capable of tracking the evolution of the optical field as it passes through every element in the cavity for various cavity conditions. The parameters of the numerical model correspond to a great extent to the experimental setup described in our previous report [25]. Yet, it should be noted that our numerical model only takes into account a single polarization component traveling in the ring cavity. Therefore, the saturable absorber effect introduced by the nonlinear polarization evolution (NLPE) is not considered in this model.

Numerical simulation starts from generating an initial, arbitrary optical field (e.g., a transformed limited sech^2 pulse or white noise). After a cavity round-trip, the resulting signal is then fed back as a refreshed input for the next round-trip calculation until the signal reaches a steady-state condition. The VPI Transmission Maker software uses an analytic signal approximation to represent optical processes [27]. This yields a complex optical field that is given by

$$E(t) = \sqrt{P(t)}\,\exp(-j2\pi\Delta_\nu t), \tag{1}$$

where Δ_ν is the offset between the emission frequency and the reference optical frequency ν_{ref} defined here as $\nu_{ref} = 193.1$ THz (1552.5 nm), and $P(t)$ is the optical power of the waveform. The optical field is normalized such that the modulus-square represents the corresponding optical power.

The description of each element shown in Fig. 1 is given as follows: The active fiber is formed of a piece of 2-m-long (L_{EDF}) EDF, which is analyzed by a stationary model based on a unidirectional propagation equation for signal and pump and a two-level rate equation for excited ion populations [28]. The emission and absorption spectra are specified in terms of the Giles parameters of the EDF used in the experiment described in [25]. The EDF module also accounts for the nonlinear effect of self-phase modulation (SPM) according to the following equation [29]:

$$\frac{\partial E(z,t)}{\partial z} = i\,\gamma_{EDF}\left|E(z,t)\right|^2 E(z,t) \tag{2}$$

where $E(z,t)$ is the slowly-varying complex-envelope of the optical field, and γ_{EDF} is the nonlinear coefficient of the active fiber at the carrier frequency. It should be noted that the EDF software module includes the influence of the spontaneous emission from active ions, assuming that the overlap integral between the optical mode and active ions is independent of signal power. (See Refs. [27,28] for more details). Although this software module does not consider the influence of the group velocity dispersion (GVD) parameter of the active fiber inclusively, we take it into account separately in the calculation for the passive fiber section by representing the total cavity dispersion with the average GVD coefficient, including both $\beta_{2,EDF}$ and $\beta_{2,SMF}$. Then, a passive fiber segment of SMF-28 follows the active fiber. Pulse propagation within this segment is governed by the nonlinear Schrödinger equation (NLSE) for linearly polarized optical waves, using the split-step Fourier method [29]. The NLSE model takes into account the average GVD coefficient β_2 of the cavity, the fiber loss α_{loss}, and the nonlinear parameter γ_{SMF} of the fiber at the carrier frequency ν_{ref}.