Suppression of Supermode and Phase Noises in Mode-Locked Erbium-Doped Fiber Laser with a Semiconductor Optical Amplifier Based High-Pass Filter

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ABSTRACT

The variations and trade-off between single-sided-band (SSB) phase noise and supermode noise (SMN) suppression ratio of an actively mode-locked erbium-doped fiber laser (EDFL) with intra-cavity semiconductor optical amplifier (SOA) based high-pass filter are discussed. The insertion of an SOA increases the SMN suppression ratio of the EDFL from 26 dB to 41.4 dB, however, the SSB phase noise at 100 kHz offset frequency from carrier is concurrently degraded from -114 dBc/Hz to -96 dBc/Hz. Such an operation also causes a broadening in the EDFL pulsewidth from 36 ps to 130 ps. The insertion of an optical bandpass filter (OBPF) further reduces the SSB phase noise to -110 dBc/Hz and improves the SMN suppression ratio to 43 dB. Theoretical simulation interprets that the optimized operation of the SOA based high-pass filter at nearly transparent current condition is mandatory to achieve a better SMN suppression ratio and minimize the SSB phase noise of the mode-locked EDFL without sacrificing its output pulsewidth.

Keywords: Mode-locked lasers, supermode noise (SMN) suppression, single-sided-band (SSB) phase noise, semiconductor optical amplifier (SOA)

1. INTRODUCTION

Mode-beating induced supermode noise, environmental perturbations, thermal noise, phase noise, and fluctuations in pumping power are the principal noise sources of a mode-locked erbium-doped fiber laser (EDFL). Recently, low noise fiber ring lasers have been extensively studied to meet the demands of versatile applications. Various methods for partial noise reduction were proposed [1-3]. Sanders *et al.* reduced supermode noise (SMN) from an EDFL by intra-cavity spectral filtering [1] in contrast to the regeneratively mode-locking technology proposed by Gupta *et al.* [4]. Later experiments show that the SMN and intensity noise in pulses can be suppressed by adding an intracavity semiconductor optical amplifier (SOA). Maximum SMN suppression can be up to 33 dB [5]. Seo *et al.* used external injection-seeding to achieve SSB phase noise (or timing jitter) reduction [9]. Recently, Xu *et al.* have also used an SOA as a high-pass filter to suppress the SMN in an EDFL [7, 8]. However, the SSB phase noise characteristic of a SOA-filtered EDFL has never been studied. In this paper, we theoretically and experimentally analyze the SSB phase noise reduction of a mode-locked EDFL by changing the gain of the SOA based high-pass filter. Adding the SOA greatly suppresses the SMN at a cost of SSB phase noise but the SSB phase noise is reduced by increasing the driving current of the SOA. The optimum condition for a high SMN suppression ratio and the lowest SSB phase noise is demonstrated and the optimum operation of the driving current of the SOA can be obtained experimentally.

2. THEORY

Although the principle of the SSB phase noise in an actively mode-locked EDFL has been elucidated, the SSB phase noise characteristics of a mode-locked EDFL with an intra-cavity SOA filter were less addressed. It is known that the SSB phase noise in an SOA can be generated through the carrier density fluctuation, which results from both induced emission and spontaneous carrier recombination [10]. The SSB phase noise originated from the induced emission is correlated with the intensity noise, whereas that from spontaneous carrier recombination is independent. The spontaneous emission induced SSB phase noise is written as [11]:

$$S_{\phi 1}(f) = h\nu (G-1) n_{sp} / G P_{in}$$

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where h is Planck's constant, ν is optical frequency, G is amplifier gain, n_{sp} is the spontaneous emission factor, and P_{in} is input optical power. In comparison, the stimulated emission induced indirect SSB phase noise is given as [11]:

$$S_{\phi 2}(f) = \frac{C_2}{(2\pi f \tau_e)^2 + 1}$$

$$C_2 = \left(\frac{2\pi K \Gamma}{\lambda A}\right)^2 4G(G-1) n_{sp} \tau_e^2 P_{in} / h\nu$$

$$K = \Delta n_r(z,t) / \Delta n_e(z,t)$$

where Δn_r is real refractive index change, Δn_e is fluctuation of carrier density, Γ is optical confinement factor, λ is wavelength, A is amplifier cross section, and τ_e is carrier lifetime. The theoretical model thus predicts a minimum phase-noise operation of an SOA in the unitary gain regime, as shown in Fig. 10.

3. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. A commercial fiber-pigtailed SOA with small-signal gain of 25 dB is used as a SMN suppressor in EDFL. A $LiNbO_3$ Mach-Zehnder intensity modulator (MZM) biased at half-wave voltage ($V_\pi \approx 8$ V) is driven by a microwave synthesizer at 22 dBm and 977.64 MHz. A pair of polarization controllers (PCs) and Faraday optical isolators are employed to optimize the polarization orientation of the circulating pulses and ensure unidirectional propagation.

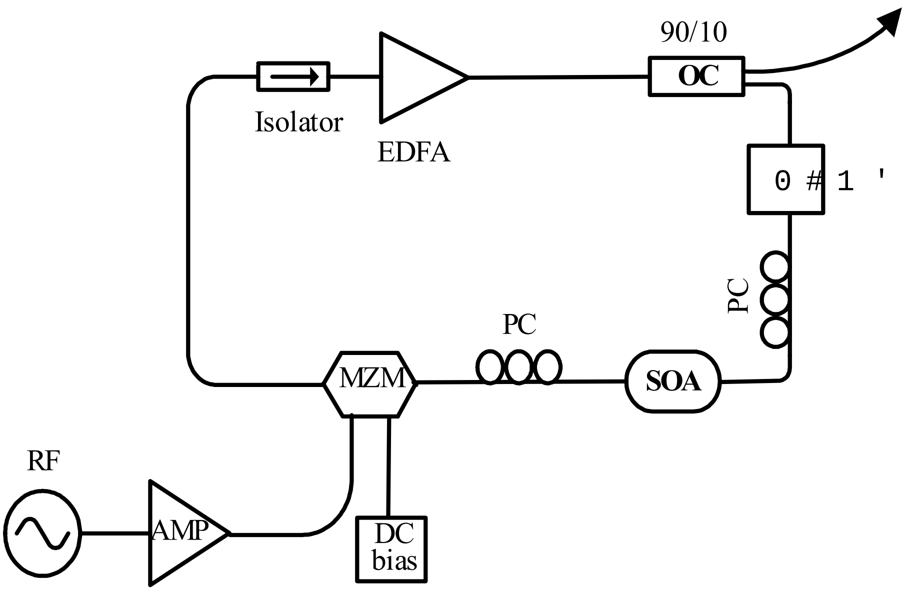

Fig. 1. The SOA-filtered mode-locked EDFL.

The output coupling ratio of the EDFL is 10%. The length of the EDFL ring cavity is 19.37 m, which gives rise to a longitudinal mode spacing of 10.32 MHz. In the mode-locked EDFL, the amplified spontaneous emission (ASE) of an erbium doped fiber amplifier (EDFA) is filtered through a commercially available optical band-pass filter (OBPF) and then is injected into the SOA. The bandwidth of the OBPF (JDS, TB 1500B) at 3dB decay is 1.38 nm. The OBPF inserted between the EDFA and SOA enhances the gain profile of the SOA at 1532 nm and reduces the ASE components over a wide wavelength range. The SMN and SSB phase noise are further suppressed by adding an OBPF in a mode-locked EDFL.

4. RESULT AND DISCUSSION

The pulsewidth and timing jitter are 36 ps and 0.59 ps for the free-running EDFL, as illustrated in Fig. 4. Without the SOA, the SMN is not suppressed with a ratio of only 26 dB in the EDFL, as shown in Fig. 2, and the optical spectrum is illustrated in Fig. 6. As the SOA and OBPF are inserted into the EDFL, the SMN suppression ratio increases up to 43 dB at a cost of pulse broadening (63.5 ps) and jitter degradation (0.98 ps), as shown in Figs. 3 and 5. The optical spectrum of the EDFL with the SOA and the OBPF is illustrated in Fig. 7.

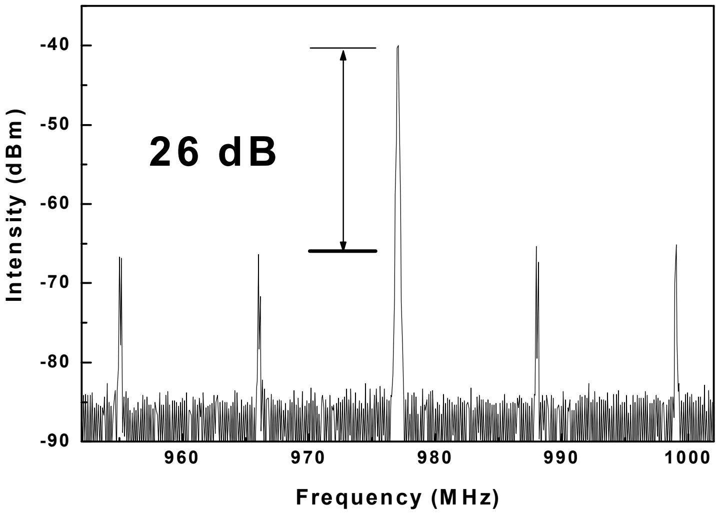

Fig. 2. The SMN suppression ratio in mode-locked EDFL without the SOA

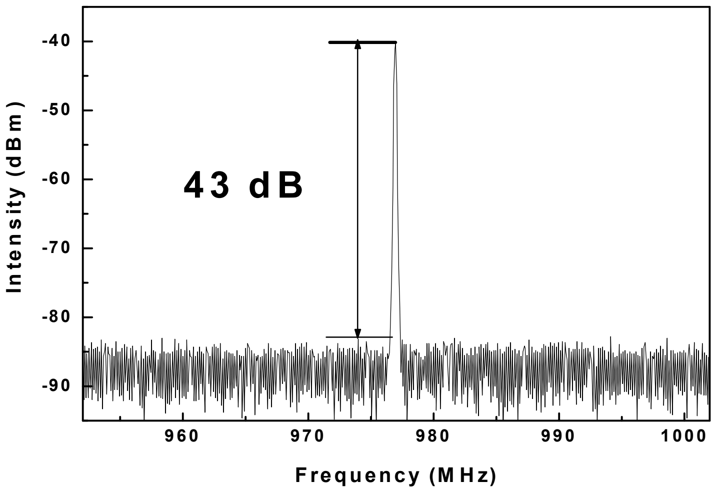

Fig. 3. The SMN suppression ratio in mode-locked EDFL with the SOA

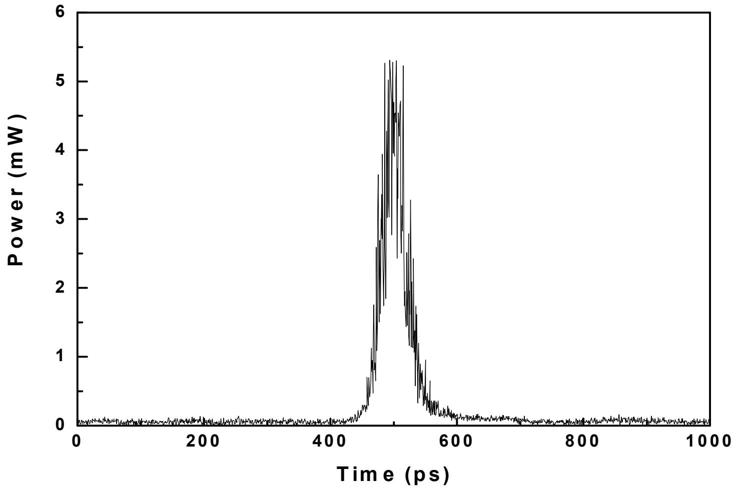

Fig. 4. The pulsewidth in mode-locked EDFL without the SOA

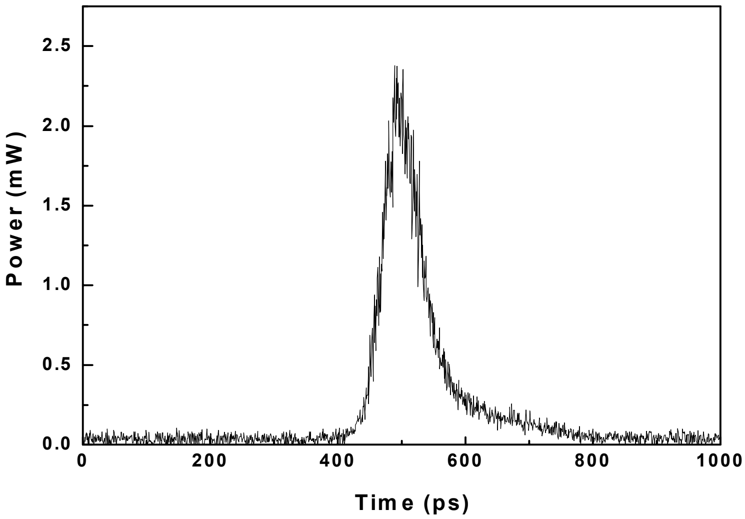

Fig. 5. The pulsewidth in mode-locked EDFL with the SOA

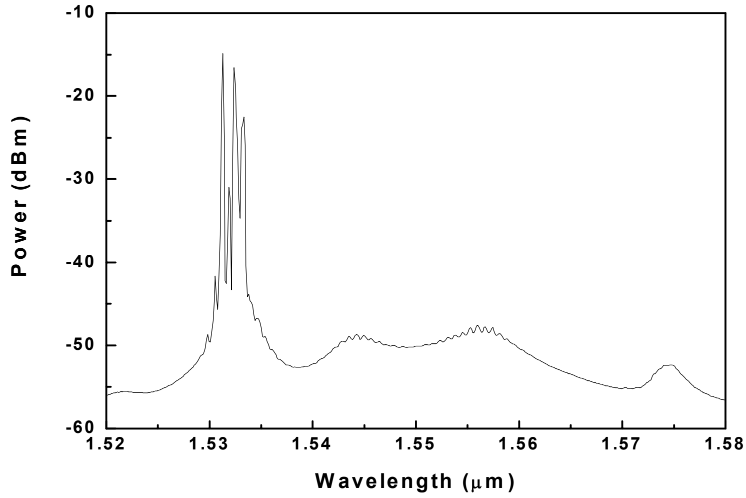

Fig. 6. The optical spectrum in mode-locked EDFL without the SOA

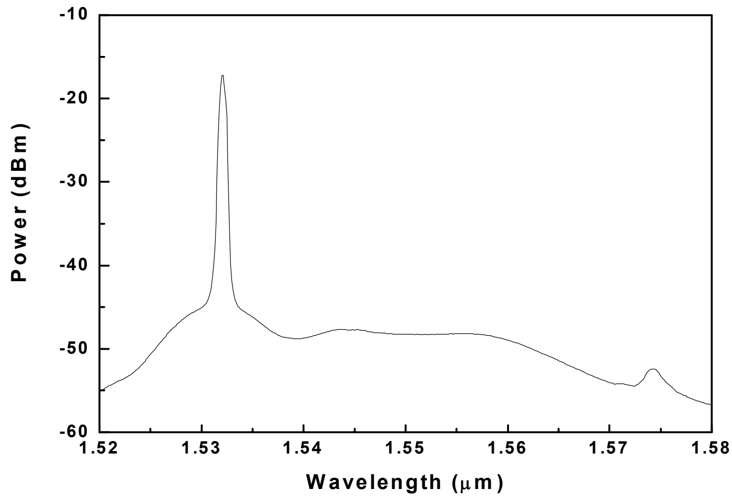

Fig. 7. The optical spectrum in mode-locked EDFL with the SOA

A maximum SMN suppression ratio of 43 dB is measured from the EDFL with the SOA, which is larger than from the EDFL without the SOA by about 17 dB. The SOA acts as a high-pass filter due to its relatively fast carrier recovery rate (several hundred picoseconds to a couple nanoseconds) and gain saturation effect [8]. Since the frequency of the SMN is primarily in the low frequency region, it can be suppressed by the high-pass SOA filter in the EDFL. Although the SOA greatly enhances the SMN suppression ratio, the SSB phase noise performance is sacrificed simultaneously due to both the stimulated and spontaneous emissions generated from the SOA. By increasing the driving current of the SOA from 45 to 76 mA, the SSB phase noise is changed from -96 to -100 dBc/Hz (at 100 kHz offset frequency from carrier) and the SMN suppression ratio is increased from 41.4 to 42.2 dBm. The minimum SSB phase noise is -104.2 dBc/Hz at 1.15 times the SOA's transparent current, as shown in Fig.8.

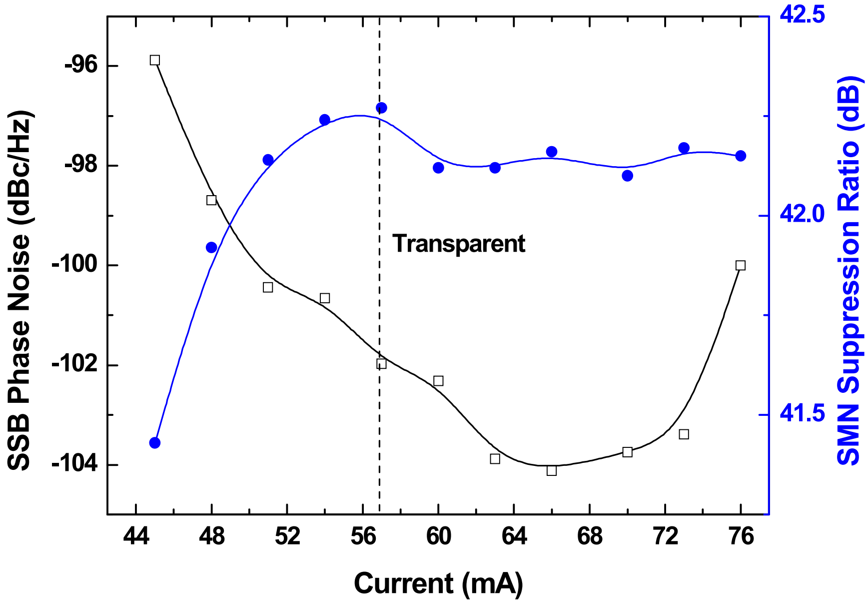

Fig. 8. The SMN suppression ratio and the SSB phase noise at different currents of the SOA in mode-locked EDFL.

It is evident that the SMN suppression ratio slightly improves as the SOA gain increases, especially when the SOA switches from absorption to gain regimes. However, the SSB phase noise degrades rapidly at higher driving of the SOA, whereas the SMN suppression ratio remains unchanged. These results are interpreted as meaning that the optimized driving current of the SOA based high-pass filter for the EDFL is about 1.15 times larger than its transparent current, and the SMN suppression ratio and SSB phase noise can be improved by 0.8 dB and 8.2 dB, respectively. Nonetheless, such an operation also causes a broadening in pulsewidth of the EDFL from 36 ps without the SOA to 130 ps with the SOA.

By further employing intra-cavity OBPF in the EDFL, the SSB phase noise can be decreased from -96 to -104.5 dBc/Hz as a result of the ASE reduction, and the pulsewidth can be shortened to 63.5 ps. The SMN suppression ratio is improved from 39.7 to 43 dBm and the SSB phase noise is changed from -104.5 to -109 dBc/Hz (at 100 kHz offset frequency from carrier) by increasing the driving current of the SOA from 37 mA to 55 mA, as shown in Fig. 9. The transparent current is 47 mA and the mode-locked pulse is also distorted at currents above 53 mA. The minimum SSB phase noise is -110 dBc/Hz at the transparent current of the SOA. Note that the transparent current is controlled at a different value because different input powers support the different transparent currents of the SOA. The optimized driving condition of the SOA for EDFL is its transparent current, while the SSB phase noise can be greatly suppressed without sacrificing the SMN suppression ratio of EDFL.

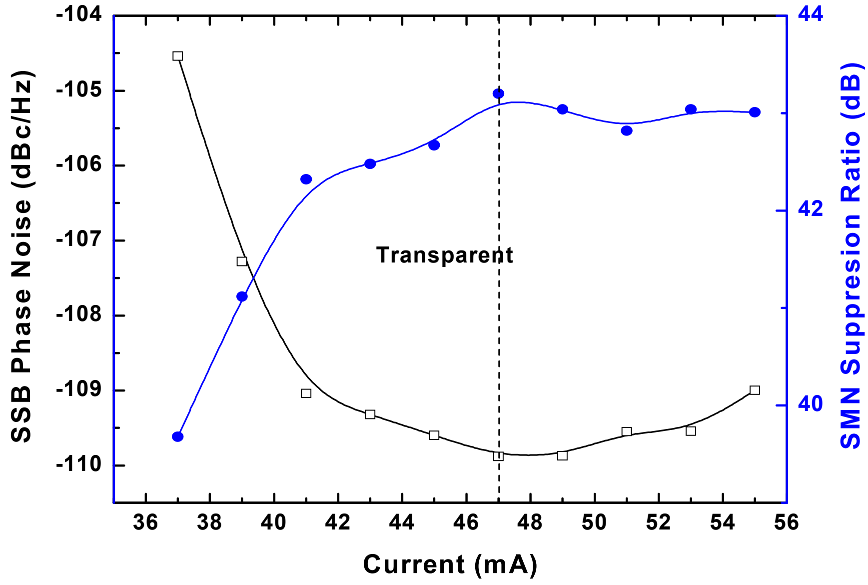

Fig. 9. The SMN suppression ratio and the SSB phase noise at different currents of the SOA by employing an intra-cavity optical band-pass filter in mode-locked EDFL.

The simulated SSB phase noise of the SOA can also be plotted as a function of the change in gain of the SOA, as shown in Fig. 10. According to the theory [11], the SSB phase noise generated from the SOA can originate from the carrier density fluctuation, which is caused by induced emission and spontaneous carrier recombination. The spontaneous emission of the SOA below transparent gain predominates the SSB phase noise performance of the EDFL, however, the SSB phase noise contributed by stimulated emission of the SOA above transparent gain is more pronounced.

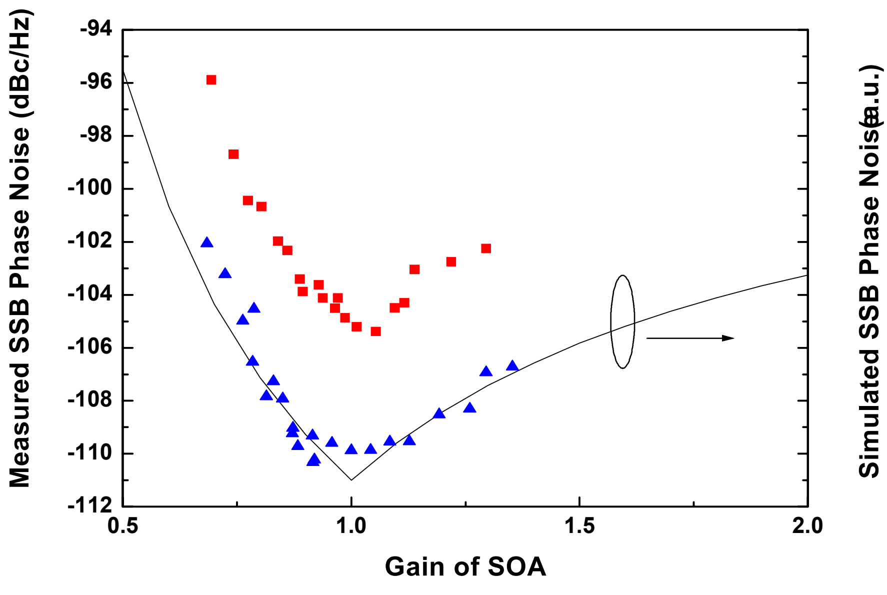

Fig. 10. The simulated SSB phase noise of the SOA as a function of the gain variation of the SOA and with measured values.

The solid curve in Fig. 10 is a theoretical SSB phase noise obtained by fitting (1) and (2) with measured values. When the OBPF is not inserted in the EDFL, the measured SSB phase noise is far beyond the simulated curve, which is decreased by increasing the gain of the SOA but degrades above the transparent gain condition. Adding an intra-cavity OBPF in the EDFL helps the reduction of the SSB phase noise and the trend of the SSB phase noise is also decreased by increasing the gain of the SOA and bent up at gain regime. We find that the measured SSB phase noise characteristics correlate well with the theoretical prediction.

4. CONCLUSSION

We demonstrate the SMN suppression and SSB phase noise reduction of the harmonic mode-locked EDFL by using an intra-cavity SOA and an OBPF. Without the SOA, the SMN suppression ratio is only 26 dB and the SSB phase noise is -114 dBc/Hz (at 100 kHz offset frequency from carrier). By adding an SOA into the EDFL, the SMN suppression ratio can be up to 42.2 dB, however, the SSB phase noise is reduced from -96 dBc/Hz to -100 dBc/Hz as the SOA current increases from 45 mA to 76 mA. The insertion of an OBPF in EDFL remains the SMN suppression ratio (43 dB) and further reduces the SSB phase noise from -104.5 to -110 dBc/Hz even at a lower SOA current of 53 mA. It is observed that the SOA with the OBPF in the EDFL exhibits a better SMN suppression ratio and lower SSB phase noise performance as compared to conventional mode-locked EDFL without SOA and OBPF. By driving the SOA at nearly transparent current and adding the OBPF, the SSB phase noise of mode-locked EDFL can be greatly suppressed without sacrificing the SMN suppression ratio.

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