Comparison on the noise and jitter characteristics of harmonic injection-locked and mode-locked erbium-doped fiber lasers

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ABSTRACT

We compare the noise characteristics of optical pulses generated from an actively mode-locked (AML) erbium-doped fiber laser (EDFL) with a semiconductor optical amplifier and an injection-locked EDFL with a gain-switched Fabry-Perot laser diode (FPLD). The mode-locked EDFL pulse exhibits a phase noise of -110.1 dBc/Hz (at 1 MHz offset frequencies from the carrier), the timing jitter of 1.16 ps, and a supermode noise suppression ratio of 47.5 dB. The injection-locked EDFL pulse exhibits a phase noise of -121.1 dBc/Hz (at 1 MHz offset frequencies from the carrier), a timing jitter of 0.31 ps, and a supermode noise suppression ratio of 51 dB. It is demonstrated that the injection-locked EDFL with a gain-switched FPLD has lower noise characteristics than the AML-EDFL.

Keywords: Pulsewidth, Phase noise, Timing jitter, Supermode noise.

1. INTRODUCTION

Pulses can be generated from erbium-doped fiber lasers (EDFL's) either by mode-locking technique with a Mach-Zehnder intensity modulator or by injection-locking technique with a gain-switched laser diode [1]. Actively mode-locked EDFL's have been emerged to generate short and high repetition-rate optical pulse trains [2-4] for application in high-speed optical time division multiplexed (OTDM) transmission system [5] and electro-optical sampling [6]. However, EDFL's are sensitive to environmental perturbation such as temperature fluctuations and mechanical vibration due to their relatively long cavity length and a large number of cavity modes are associated with the main longitudinal modes. Thus, the optical pulses generated from an actively mode-locked erbium-doped fiber laser (AML-EDFL) suffer from both pulse supermode and phase (timing jitter) noises. Previously, Gupta *et al.* used a regeneratively mode-locked fiber laser technique to suppress supermode noise and phase noise (or timing jitter) [7]. On the other hand, gain-switched laser diodes (GSLD's) also have been extensively used to generate the picosecond optical pulses needed by high-bit-rate transmission system [8-10], all-optical demultiplexers [11], optical sampling systems [12], and so on. GSLD's do not require specially fabricated devices or external cavity configuration to generate the repetition-rate-variable pulse. In most applications, the pulse-to-pulse timing jitter seriously degrades the bit error rate (BER) performance [13] or temporal resolution. The latter aspects are particularly essential for application in electro-optic probing or sampling instrumentations. Wang reported that timing jitter reduction of GSLD's with external pulse injection [14]. Lin *et al.* used mutually injection-locked Fabry-Perot laser diode and erbium-doped fiber amplifier (EDFA) link to achieve supermode-noise suppression [15]. In this paper, we compare the output characteristics of a mode-locked EDFL [with a conventional loss modulator and a semiconductor optical amplifier (SOA)] with an injection-locked EDFL (with a GSLD). The latter is based on injection of a gain-switched Fabry-Perot laser pulse into a ring cavity with an erbium-doped fiber amplifier inside. The characteristics of pulse such as the supermode noise, the phase noise, and the timing jitter are measured and compared.

2. EXPERIMENT SETUP

Two types of pulsed EDFL's are constructed; one is an AML-EDFL and the other is an injection-locked EDFL with a GSLD.

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2.1 AML-EDFL

Figure 1 is an AML-EDFL by using a using a Mach-Zehnder intensity modulator (MZM) as a mode-locker, and a semiconductor optical amplifier (SOA) as an intra-cavity filter. It consists of an erbium-doped fiber amplifier (EDFA), a pair of Faraday optical isolators, an optical band-pass filter (OBPF), a pair of polarization controllers, an SOA, a $LiNbO_3$ MZM and an optical coupler (OC) of 90:10 coupling ratio. An MZM is biased at its half-wave voltage (1/2 V_π) of 8 V and driven by a microwave synthesizer with power of 22 dBm at frequencies of 980.16 MHz. As the frequency is detuned to coincide with one harmonic of the ring cavity, the perfect mode-locking can be achieved. A commercial fiber-pigtailed SOA, which has a typical small signal gain of 25 dB, is employed as an intra-cavity supermode-noise suppressor. Since the SOA and $LiNbO_3$ MZM are both sensitive to the polarization orientation, a pair of polarization controllers (PC's) optimizes the polarization orientation of the circulating pulses and a pair of Faraday optical isolators ensures the unidirectional cavity. The output optical power is coupled out from the cavity by using a 10% OC and feedback power ratio is 90%. In the AML-EDFL, the filtered amplified spontaneous emission (ASE) of EDFA feedback-injects into the SOA after passing through a commercially available optical band-pass filter (OBPF). The OBPF inserted between the EDFA and the SOA is used to avoid other unwanted cavity modes being amplified and reduces the amplification of the ASE components over a wide gain spectrum. The bandwidth of the OBPF (JDS, TB 1500B) at 3-dB decay is 1.38 nm, which is measured by using a gain-clamped EDFA based broadband ASE source. A stable pulse train can be obtained when the modulation frequency is detuned to coincide with one harmonic of the ring cavity and PC's are properly adjusted. The length of the EDFL ring cavity is 25 m, which gives rise to a longitudinal mode spacing of 8 MHz (calculated by c/nL). Moreover, the spectral output of an AML-EDFL is monitored by electrical spectrum analyzer (ESA, Agilent HP8565E) in connection with a photodetector (PD, New Focus 1014) to measure the supermode noise suppression ratio, the phase noise, and timing jitter.

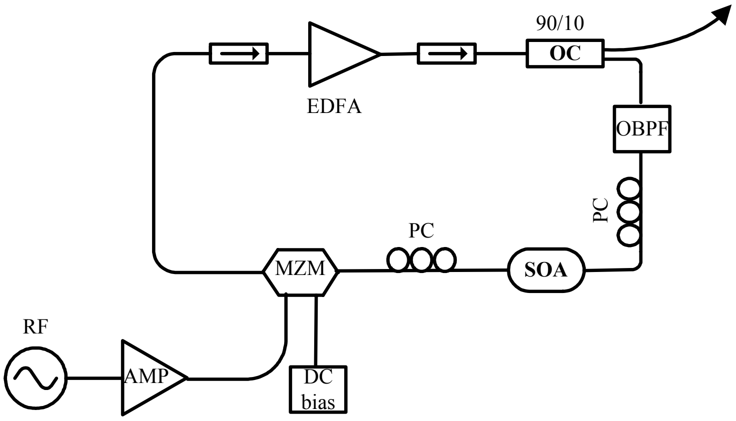

Fig. 1 The schematic diagram of the AML-EDFL. The V_{bias} is set at 8 V for linear operation. PC: polarization controller; OC: optical coupler; OBPF: optical band-pass filter; EDFA: erbium-doped fiber amplifier; SOA: semiconductor optical amplifier; and MZM: Mach-Zehnder intensity modulator.

2.2 GSLD-EDFA

Figure 2 is the injection-locked EDFL with a GSLD. It consists of a comb generator, an EDFA, an optical circulator, a pair of Faraday optical isolators, an OBPF, and an OC of 90:10 coupling ratio. An electrical pulse generator is employed to provide electrical pulse train at repetition rate of around 1 GHz for gain-switching the Fabry-Perot laser diode, which is dc-baised at 3.4 mA below threshold. The wavelength, threshold current, and longitudinal mode spacing of the free-running FPLD at 25 ^oC are about 1550 nm, 8 mA and 1.2 nm, respectively. The light travels in one direction due to the isolators inside the ring cavity. The filtered ASE of EDFA feedback-injects into the FPLD after passing through OBPF in the GSLD-EDFA link. Then, the FPLD is controlled at below threshold condition, and the center wavelength of the OBPF is adjusted to match that of the SOA (at 1550nm). After passing the OBPF, the amplified EDFL pulse is feedback injected into the FPLD to reduce the effect of spontaneous emission noise. This leads to a significant reduction in rms timing jitter, the stimulated emission reduces relative fluctuation in the photon density. The feedback from EDFA is also used to facilitate single longitudinal mode lasing with improved side mode

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suppression ratio (SMSR) lasing in FPLD. On the other hand, the feedback wavelength of gain-switched pulses must match the wavelength of center longitudinal mode of the FPLD at 1550 nm for getting the lowest phase noise (or timing jitter) and highest SMSR.

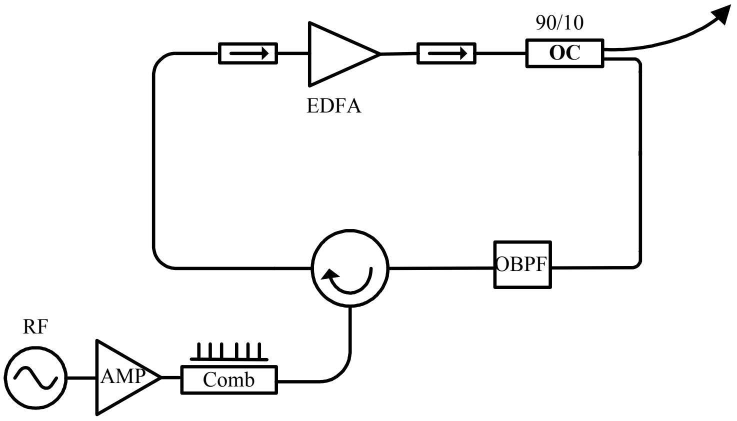

Fig. 2 The schematic diagram of the injection-locked EDFL with a gain-switched Fabry-Perot laser diode (GSLD). Comb: Electrical pulse generator; EDFA: Erbium-doped fiber amplifier; OC: Optical coupler; OBPF: Optical band-pass filter; FPLD: Fabry-Perot laser diode.

3. RESULTS AND DISCUSSION

As a result, we compare the evolution of peak power, pulsewidth, absolute single side band (SSB) phase noise spectra, timing jitter, and supermode noise. Figure 3 shows the pulsewidths without and with SOA in the AML-EDFL. The pulsewidths are 36.7 ps without SOA and 66.2 ps with SOA operated at 42.4 mA, respectively. The output peak powers are 1.7 mW and 2.3mW, respectively. When GSLD is without feedback injection, the pulsewidth is 29.4 ps and output peak power is 10.9 mW (see Fig. 4). When the gain-switched FPLD is injection-locked by an amplified pulse, the shorter pulsewidth of 25.7 ps and larger output peak power of 12.9 mW are obtained as compared with GSLD without feedback (see Fig. 4). The output peak power of the AML-EDFL with an intra-cavity SOA is larger, however, its pulsewidth is slightly broadened due to the adding of SOA.

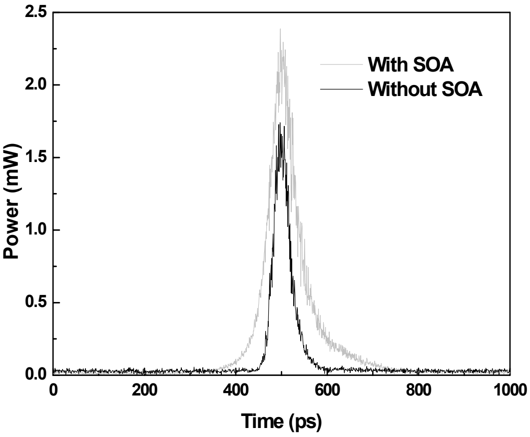

Fig. 3 The variations of pulsewidth as the AML-EDFL with and without SOA.

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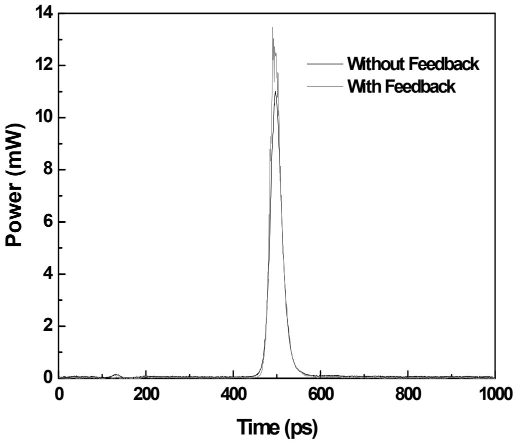

Fig. 4 The variations of pulsewidth as the GSLD with and without feedback.

The analysis of phase noise (or timing jitter) is extensively used in versatile lasers [16-20]. The phase noise of optical pulses generated from AML-EDFL and GSLD-EDFA link are also characterized. It is clearly found that the absolute SSB phase noise density of GSLD-EDFA link (see Fig. 8) is lower than that of AML-EDFL (see Figs. 5 and 6) with and without SOA at offset frequencies ranged from 10 Hz to 10 MHz. The phase noises in the AML-EDFL with and without SOA at offset frequencies of 1 MHz are -110.1 dBc/Hz and -114.4 dBc/Hz, respectively. This interprets that the phase noise is degraded as adding SOA into the ring cavity of AML-EDFL. The phase noise of GSLD without feedback injection is -113.7 dBc/Hz at offset frequencies of 1 MHz. However, the GSLD-EDFA link has a lower phase noise (-121.2 dBc/Hz at offset frequencies of 1 MHz from the carrier) than ever reported in the AML-EDFL.

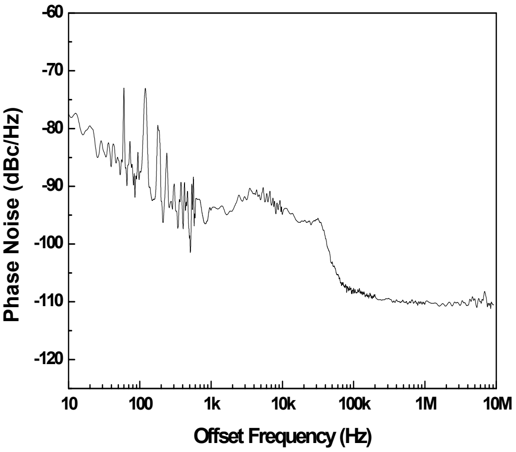

Fig. 5 The absolute single sideband phase noise density in the AML-EDFL with SOA.

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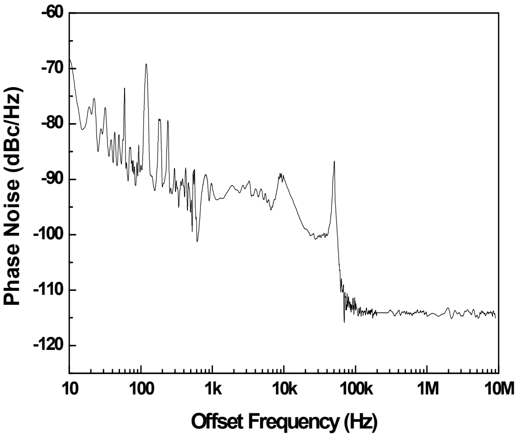

Fig. 6 The absolute single sideband phase noise density in the AML-EDFL without SOA.

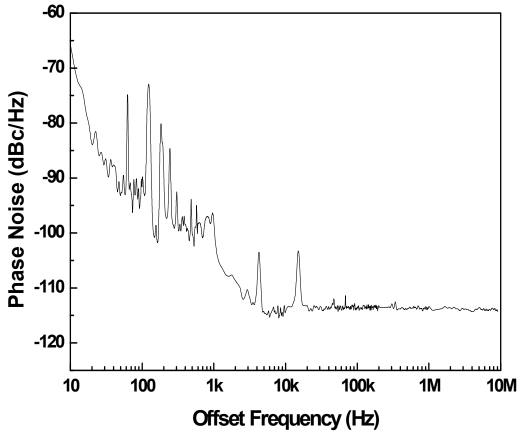

Fig. 7 The absolute single sideband phase noise density in the GSLD without feedback injection.

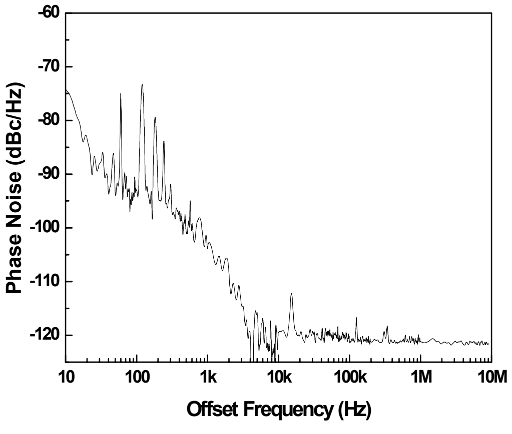

Fig. 8 The absolute single side band phase noise density in GSLD with feedback injection (*i.e*. GSLD-EDFA link).

To determine the timing jitter in the pulse train, the SSB phase noise density is calculated from phase noise spectra obtained by an RF spectrum analyzer. As shown in Figs. 9 and 10, the corresponding timing jitters of AML-EDFL with and without SOA at offset frequencies of 1MHz from the carrier are 1.16 ps and 1.12 ps, respectively. The timing

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jitter of 0.55 ps and 0.31 ps (at offset frequencies of 1 MHz from the carrier) in GSLD without and with feedback injection are also illustrated in Figs. 11 and 12, respectively.

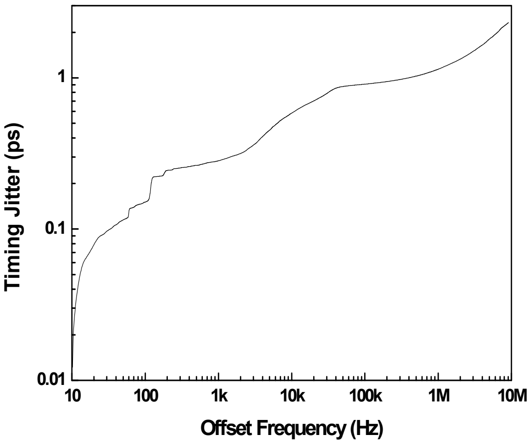

Fig. 9 The timing jitter in the AML-EDFL with SOA.

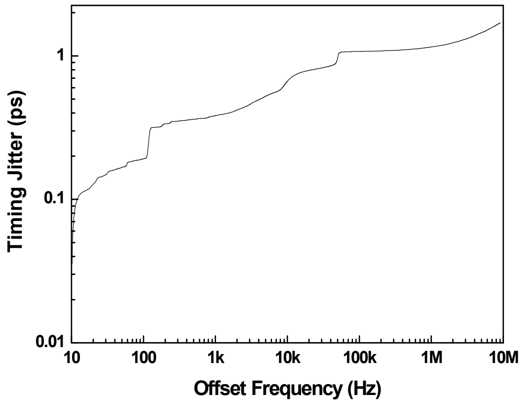

Fig. 10 The timing jitter in the AML-EDFL without SOA.

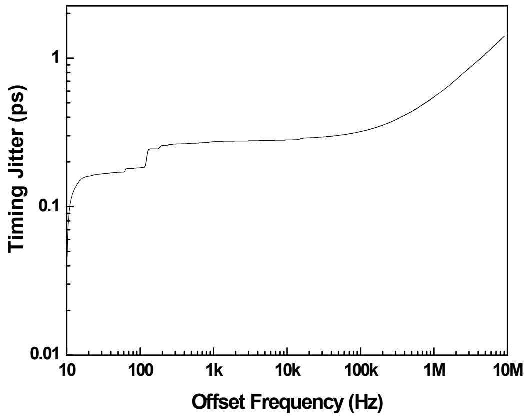

Fig. 11 The timing jitter in the GSLD without feedback injection.

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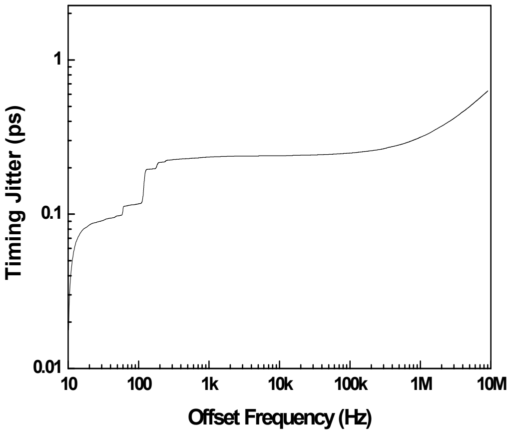

Fig. 12 The timing jitter in the GSLD with feedback injection (*i.e.* GSLD-EDFA link).

The AML-EDFL exhibits an improvement of the supermode noise suppression ratio due to the insertion of SOA. As shown in Figs 13 and 14, it is found that the supermode noise suppression ratios in the AML-EDFL without and with SOA are 42 dB and 47.5 dB, respectively. However, the supermode-noise suppression ratio is improved in the GSLD-EDFA link. Figure 15 shows a maximum supermode-noise suppression ratio of 51 dB over a frequency span of 50 MHz in the GSLD-EDFA link. The measurement confirms that supermode noise induced by cavity modes is greatly suppressed in the GSLD-EDFA link. According to all measured results, GSLD-EDFA link is more suitable than AML-EDFL for electro-optics sampling systems or high-speed TDM applications.

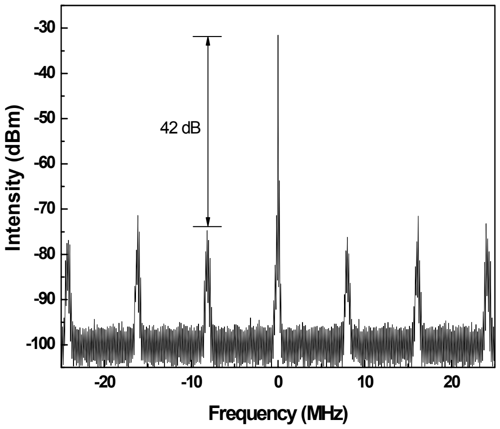

Fig. 13 The supermode noise in the AML-EDFL without SOA. (VBW=10 kHz; RBW=100 kHz; and SPAN=50 MHz)

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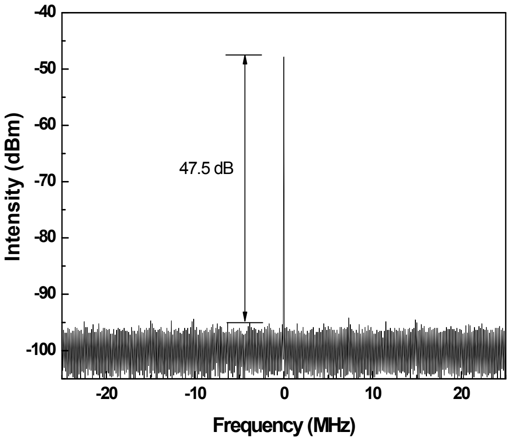

Fig. 14. The supermode noise in the AML-EDFL with SOA. (VBW=10 kHz; RBW=100 kHz; and SPAN=50 MHz)

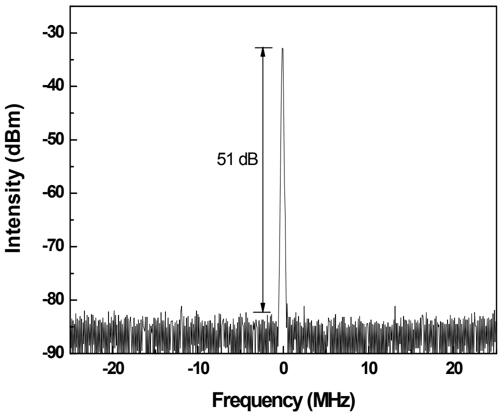

Fig. 15. The supermode noise in the GSLD-EDFA. (VBW=10 kHz; RBW=100 kHz; and SPAN=50 MHz)

4. CONCLUSION

An actively mode-locked erbium-doped fiber laser (AML-EDFL) and an injection-locked erbium-doped fiber laser with a gain-switched Fabry-Perot laser diode (GSLD-EDFA) are compared in this paper. The evolution of peak power, pulsewidth, absolute single side band (SSB) phase noise spectra, timing jitter, and supermode noise for two kinds of different system are compared. The results show that for electro-optic sampling application a GSLD-EDFA has better performance in the pulsewidth, the peak power, the phase noise, the timing jitter, and supermode noise. Without an SOA inside the cavity of AML-EDFL, the peak power of 1.7 mW, the pulsewidth of 36.7 ps, the phase noise of -114.4 dBc/Hz (at 1 MHz offset frequencies from the carrier), the timing jitter of 1.12 ps, and the supermode noise suppression ratio of 42 dB are measured. By adding an SOA into the cavity of an EDFL, the peak power of 2.3 mW, the pulsewidth of 66.2 ps, the phase noise of -110.1 dBc/Hz (at 1 MHz offset frequencies from the carrier), the timing jitter of 1.16 ps, and the supermode noise suppression ratio of 47.5 dB are also measured. By contrast, AML-EDFL with SOA has better performance than AML-EDFL without SOA in the peak power and the supermode noise suppression ratio but the pulsewidth, the phase noise, and the timing jitter are worse. Therefore, GSLD-EDFA link has higher peak power (12.9 mW), shorter pulsewidth (25.7 ps), and lower noise (phase noise of-121.1 dBc/Hz at offset frequencies of 1 MHz from the carrier, timing jitter of 0.31 ps, and supermode noise suppression ratio of 51 dB) than AML-EDFL (either with or without SOA). Therefore, the GSLD-EDFA link is most suitable for applications such as high-speed optical time division multiplexed (OTDM) transmission, electro-optical sampling, and so on.

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