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Stable tunable single-longitudinal-mode semiconductor optical amplifier erbium-doped fiber ring lasers for 10 Gbps transmission over 50 km single-mode fiber

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We demonstrate a stable and tunable single-longitudinal-mode SOA-EDF ring laser for high-speed data transmission systems. The laser is constructed by incorporating an SOA into the EDF ring cavity. The SOA acts as a saturable absorption high-pass filter to suppress cavity mode partition noise at low frequencies. Such design ensures a stable and single-frequency operation for more than several hours. The ring laser has a 30 nm tuning range in the C band and a 0.8 nm wavelength spacing to match 100-GHz ITU-T grids. The variation in the maximum power is smaller than 0.02 dB and the optical signal-to-noise ratio is above 53 dB. By employing this fiber laser, a 10 Gbps non-return zero data transmission over a 50 km long single-mode fiber with a power penalty less than 2.4 dB is demonstrated.

Keywords: optical fiber transmission, tunable fiber ring lasers, erbium-doped fiber, semiconductor optical amplifier, single-longitudinal-mode, saturable absorber.

1. Introduction

Tunable single-frequency or single-longitudinal-mode (SLM) lasers are very important light sources for dense wavelength division multiplexing (DWDM) optical communication systems. They can be applied to dynamic wavelength assignment (DWA) networks to facilitate wavelength selectability, network reconfigurability, and traffic management. Such lasers can be built with semiconductors [1, 2] and rare-earth doped fibers [3–13]. In particular, erbium-doped fiber (EDF) laser is becoming more and more attractive because of its high output power, narrow linewidth, and potentially all-fiber construction features. Unfortunately, the EDF ring laser has the possibility of mode partition noise appearing in multimode operation because of its long cavity length and narrow longitudinal mode spacing. In order to realize wavelength tuning and stable SLM operation of the EDF ring laser, several approaches to suppress multimode oscillation have been reported, such as by employing a compound-ring resonator [4], a tunable ring resonator [5], a undirectional loop mirror [6], a fiber Fabry–Perot tunable filter (FFP-TF) [7, 8], an external light injection [8, 9], an acousto-optic tunable filter [10], three narrow-bandpass tunable filters [11], an unpumped EDF as a saturable absorber [9–13], *etc*. However, all of them have not been demonstrated on high-speed data transmission systems.

In this paper, a semiconductor optical amplifier (SOA) is incorporated into the EDF ring cavity to form a hybrid gain medium ring laser. In general, EDF is a gain medium exhibiting homogeneous line broadening at room temperature. In the opposite, SOA has a dominant feature of inhomogeneous line broadening. Using an SOA as a saturable absorber to stabilize the oscillating SLM, a stable and SLM laser operation for more than several hours at room temperature can be achieved. Our tunable SOA-EDF ring laser has been demonstrated for a 10 Gbps transmission over a 50 km long standard single-mode fiber (SMF).

2. Experimental setup

The experimental setup of the tunable SOA-EDF ring laser is shown in Fig. 1. It was composed of an EDF, an optical tunable filter (OTF), two optical isolators (OIs), a 10/90 coupler, an optical polarization controller (OPC), and an SOA. The total ring cavity length is about 17.4 m. The EDF is 0.9 m long and has a peak absorption of 12.4 dB/m at 979 nm. A WDM coupler was used to launch the 980 nm pump power into the EDF from a pumping laser diode (LD). A commercial OTF (Santec OTF-30M) with a 3-dB linewidth of 0.3 nm and a tuning range of 1535 nm to 1565 nm was inserted into the cavity as a wavelength-selective element. Two OIs ensured a unidirectional

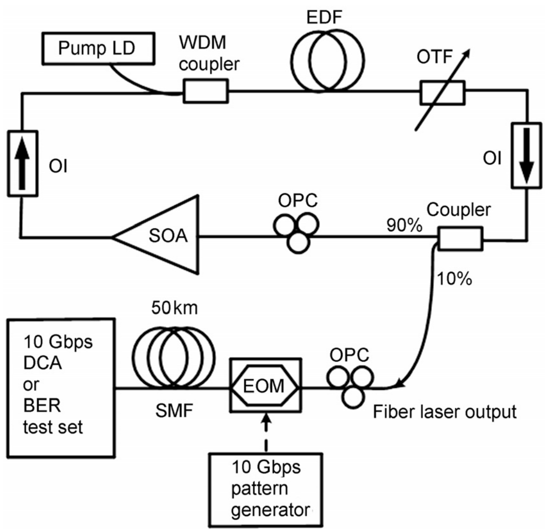

Fig. 1. Experimental setup of the tunable SOA-EDF ring laser for a 10 Gbps downstream data transmission.

operation of the ring laser. An OPC was placed in the ring to control the polarization state and optimize the laser operation. A commercial SOA (Inphenix IPS-AD1501) acts as a saturable absorber because of its fast carrier recovery rate and the gain saturation effect. A 10% coupler was employed to direct the output of the ring laser to an optical spectrum analyzer (OSA) of 0.05 nm resolution. A delayed self-homodyne interferometer technique was utilized for linewidth measurement. The SLM oscillation was also verified by detecting the laser light with a photodetector and radio frequency (RF) spectrum analyzer.

In the experiment of data transmissions, the tunable SOA-EDF ring laser was externally modulated by an electro-optical modulator (EOM) with a 10 Gbps non-return zero (NRZ) (2^{31}-1) pseudo-random binary sequence (PRBS) from a pattern generator. Modulated outputs were transmitted downstream through a 50 km long SMF and were characterized by a digital communication analyzer (DCA) and a bit error rate (BER) tester.

3. Results and discussion

As shown in Fig. 2, the SOA-EDF ring laser has a 30 nm tuning range from 1535 nm to 1565 nm and a 0.8 nm wavelength spacing to conform with 100-GHz ITU-T grids in the C band. The average output power is about –6.5 dBm with the pump power of 55 mW and the SOA injection current of 145 mA. The variation in the maximum power is smaller than 0.02 dB and the optical signal-to-noise ratio (SNR) is above 53 dB. The emission linewidth, as measured by a delayed self-homodyne interferometer technique, fitting a Lorentzian curve is less than 150 kHz. That is the resolution limit of the measuring instrument.

Figure 3 shows the RF spectra of the laser output without and with SOA for lasing wavelength at 1545 nm. In case of the SOA not being included in the ring cavity of Fig. 1, the strong cavity mode partition noise (spot line) of EDF ring laser appeared in

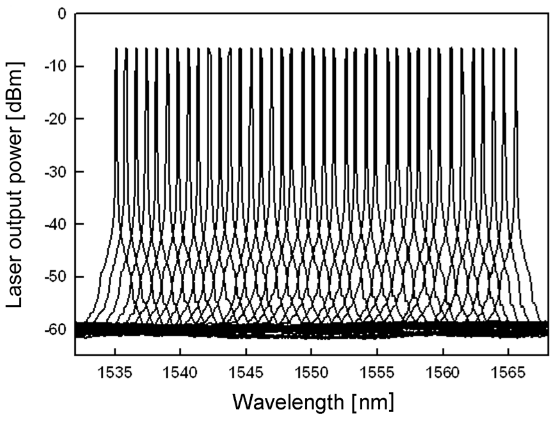

Fig. 2. The overlapped SOA-EDF lasing optical spectra between 1535 and 1565 nm with 100-GHz ITU-T grids.

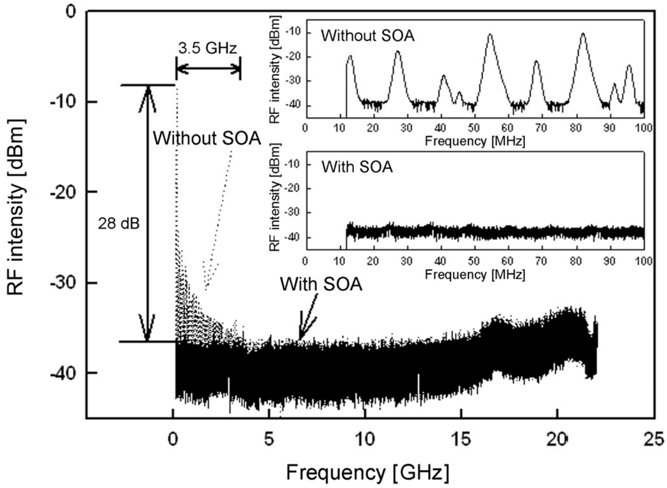

Fig. 3. RF spectra of the laser output without (spot line) and with (solid line) SOA. Insets indicate the laser is under a single-frequency oscillation.

the low-frequency region. When the EDF ring laser was incorporated with SOA as a high-pass filter, we observed that the cavity mode partition noise was dramatically improved (solid line) as observed by an RF spectrum analyzer. The cavity mode partition noise below 3.5 GHz frequency (with strength up to 28 dB) was radically suppressed. The insets show RF spectra of 100 MHz span without and with SOA for the SLM laser. This indicates that the SOA-EDF ring laser is under a stable single--frequency oscillation. This confirms that a laser, which operated in SLM with the help of an SOA, can be maintained without cavity mode partition noise at low frequencies for more than several hours. Thus this fiber laser is suitable for high-speed data transmissions.

Under three different SOA current conditions, the Q factor (real square), extinction ratio (ER) (real diamond), and SOA gain (hollow circle) of the modulated laser as a function of SOA injection current is shown in Fig. 4. We observed that the Q factor and ER are bad when the SOA current is below 70 mA in region I. The inset shows eye diagram for a 10 Gbps back-to-back (B-B) testing transmission. It is not open because of strong cavity mode partition noise at low frequencies. When the SOA current is between 70–90 mA in region II, the inset shows that eye diagram is blurred. Due to the weak absorption, the fiber laser might operate in multimode in weak saturation region, and hence, the cavity mode partition noise was not completely suppressed. This means that the laser output intensity is unstable and is not suitable for high-speed data transmissions. When the SOA current is higher than 100 mA (the SOA gain is a turning point) in region III, good signal qualities (both Q factor and ER above 10) are obtained. The eye diagram is open and clear. The SOA acts as

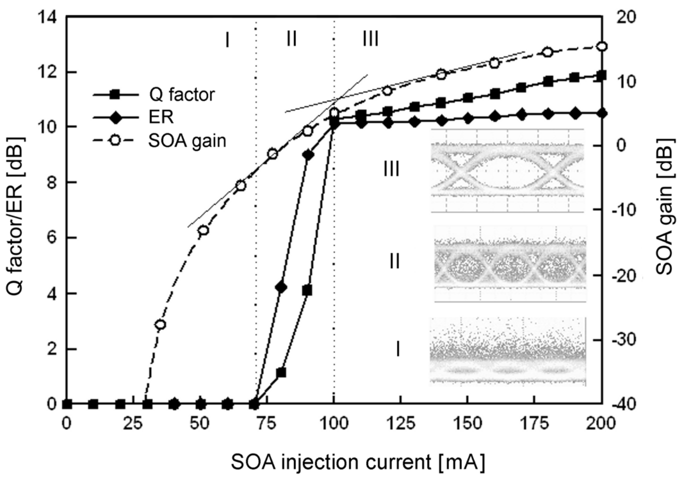

Fig. 4. *Q* factor, extinction ratio (ER), and SOA gain as a function of SOA injection current. Insets indicate three typical eye patterns at different SOA currents.

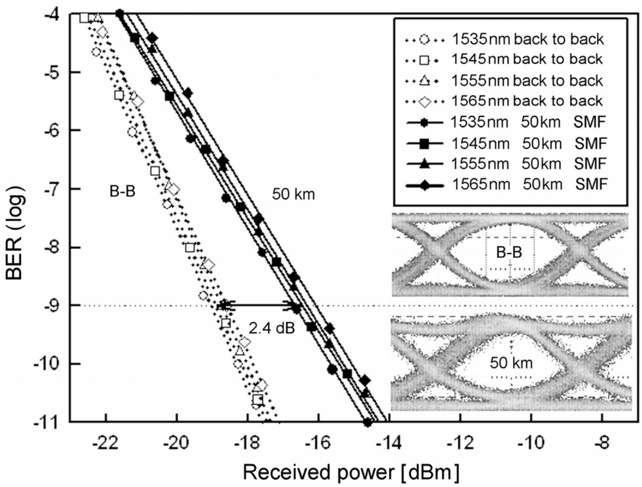

Fig. 5. BERs for back-to-back (B-B) and 50 km SMF transmissions when 10 Gbps downstream signals are transmitted. Insets show typical eye diagrams.

a saturable absorber so that the fiber ring laser is suitable for high-speed optical communication systems.

Figure 5 shows BERs versus received optical powers for 10 Gbps NRZ downstream data transmitted through a 50 km long SMF at wavelengths of 1535 nm, 1545 nm, 1555 nm, and 1565 nm. Good results and high transmission qualities are obtained at different tuning wavelengths. The power penalties at a BER of 10^{-9} are less than 2.4 dB for all four testing wavelengths. The insets show typical eye diagrams for 1555 nm operating lasing wavelength. The ERs are 9.6 dB and 7.4 dB for B-B and 50 km SMF transmissions, respectively. Hence, our tunable SOA-EDF ring laser is well suited for high-speed optical transmission systems.

4. Conclusions

We have proposed a wavelength-tunable SLM hybrid SOA-EDF ring laser for 10 Gbps NRZ optical transmissions. Using an SOA as a high-pass filter to suppress cavity mode partition noise at low frequencies, a stable and SLM laser operation for more than several hours at room temperature can be achieved. The modulated laser has both high ER and Q factor when the SOA (acts as a saturable absorber) is operated at injection current above 100 mA. For a 10 Gbps transmission over a 50 km long SMF, the power penalties are less than 2.4 dB for different operating wavelengths. This laser can also be used as a backup source for DWDM systems. Practical applications for our tunable SOA-EDF ring laser will no doubt be found in high-speed optical communications field and DWA networks.

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