Wavelength-tunable optical short pulses with high sidemode suppression ratio generated by use of Bi-EDFA

Xia Fang and D. N. Wang*

Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

**Corresponding author: eednwang@polyu.edu.hk*

Received August 8, 2008; accepted September 15, 2008;
posted September 23, 2008 (Doc. ID 99878); published October 31, 2008

A bidirectional erbium-doped fiber amplifier (Bi-EDFA) has been used in a self-seeding scheme for wavelength-tunable optical short pulse generation. The pulse wavelength is selected and purified by use of two tunable Fabry–Perot (FP) optical filters with bandwidth of 0.11 nm and 99 pm respectively, while a constant repetition frequency of 1.045 GHz is maintained. The sidemode suppression ratio (SMSR) of the output pulses achieved is better than 40 dB over the wavelength tuning range of 33 nm. The system is simple and efficient, and a continuous wavelength tuning can be readily achieved. © 2008 Optical Society of America

OCIS codes: 320.0320, 320.7090, 320.5550.

1. INTRODUCTION

An optical short pulse with a high sidemode suppression ratio (SMSR) is of critical importance for high-bit-rate optical fiber communications owing to group velocity dispersion and material dispersion in optical fibers. The generation of optical short pulses can be achieved by Q-switching, i.e., switching the resonator quality or losses of the laser diode (LD). However, Q-switching is normally involved with specially designed laser structures, as different sections being worked on gain medium and absorbers, respectively, that are required in the laser cavity. Gain switching of the LD provides an easy and convenient way for optical short-pulse generation by directly driving the LD with ultrashort pulses [1] or sinusoidal electrical currents [2,3]. Moreover, to generate tunable single-wavelength optical short pulses by gain-switching, an injection locking scheme is usually employed, which can be achieved externally by the injection of a cw light beam [4], the optical pulses generated in another LD [5,6], or internally by the feedback optical pulses, i.e., self-seeding [7–9]. Self-seeding is a relatively simple method, as only one commercially available LD is used. To enable a high SMSR by the self-seeding method, an erbium-doped fiber amplifier (EDFA) is usually employed to enhance the pulse intensity injected back into the LD [10–12]. However, in the systems reported so far, an EDFA performs only single-directional amplification, and a considerable amount of pump energy is wasted. To achieve a large gain in one-way signal amplification, the pump power must be sufficiently high to enhance the signal power. This in turn leads to an increase of the amplified spontaneous emission (ASE) noise of the system and a decrease of the lifetime of the LD used owing to strong feedback injection power.

In this paper, a self-seeding system with a bidirectional EDFA (Bi-EDFA) configuration is presented, which efficiently increases the pump power efficiency while suppressing the ASE noise in the system, and as a result, wavelength-tunable optical short pulses with a high SMSR of larger than 40 dB over a wavelength range of 33 nm have been achieved. The tuning range can be extended to 35.6 nm with a corresponding SMSR of larger than 38 dB.

2. EXPERIMENT

Our experimental setup is shown in Fig. 1. One commercially available Fabry–Perot laser diode (FPLD) with a central wavelength of 1549 nm was biased by a dc current of 10 mA, slightly below its threshold value of 11 mA, and gain-switched by rf electrical signals at 1.045 GHz. The output from the FPLD was firstly sent to the input port of the Bi-EDFA via a circulator, and the intensified light pulses were then directed to a tunable optical FP filter (TF1; Micron Optics; TF00EY) with a bandwidth of 0.11 nm to select the operating wavelength. The single wavelength optical pulses were amplified again before leaving the output port of the Bi-EDFA and subsequently spectrally purified by another tunable optical FP filter (TF2; MICRON OPTICS; TF078E) with bandwidth of ~99 pm to reduce ASE noise and control the feedback power into the FPLD. A polarization controller was used after the TF2 to optimize the polarization state of the injected pulses, hence improving the SMSR and emission stability of the output pulses.

The self-seeded output pulses were extracted from the Bi-EDFA via a 3 dB coupler and then divided into two parts by the use of an 80:20 coupler. About 80% of the output power was further enhanced by another EDFA before being directed into a high-speed photodetector (New Focus 1410) connected to a digital-sampling oscilloscope (Trektronics CSA 8003C) to observe the pulse waveform.

0740-3224/08/111926-5/$15.00

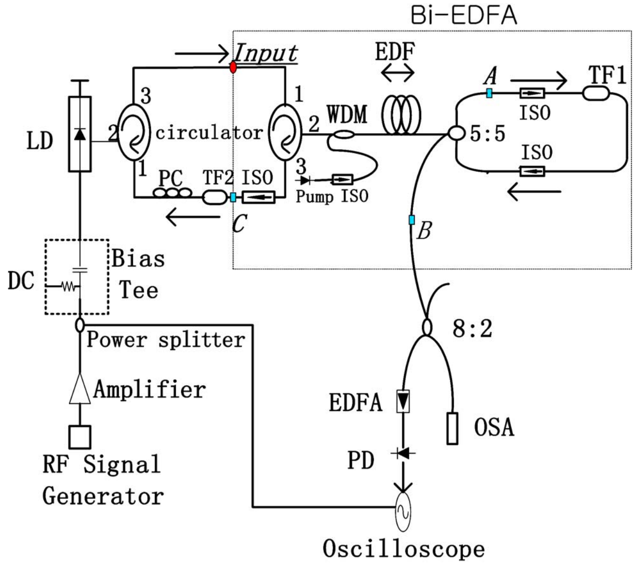

Fig. 1. (Color online) Experimental arrangement by use of Bi-EDFA.

The remaining of the 20% output power was sent to an optical spectrum analyzer (OSA) with a 0.01 nm resolution to monitor the pulse spectrum.

The Bi-EDFA shown in Fig. 1 consists of an erbium-doped fiber (EDF) with a length of 20 m, pumped by a 1440 nm LD (FITEL FOL1425RUX-617-1440) with a maximum output power of 360 mW, and a fiber loop. The absorption coefficient of the EDF is 4.6 dB/nm at 1530 nm. The fiber loop contains a tunable filter, a TF1, and two isolators. The TF1 can effectively reduce the ASE noise and select the pulse wavelength before the second amplification implemented by the EDF. Owing to the critical requirement of low reflectivity (less than −50 dB at 1535 nm [13]) in the Bi-EDFA, two isolators are used at both ends of the TF1 to suppress the reflected light. The isolator used before the pump laser can essentially minimize the instability of the pump caused by the reflection light. Special care should also to be taken to block the reflections from the connectors during system operation [14].

Since the ASE of the EDF is bidirectional, the spectrum of injection light contains both the ASE light and the operation wavelength elements, which makes the total injection power ~2–5 mW, whereas the maximum output power of the FPLD is only 1 mW. To avoid possible damage to the FPLD, the tunable filter TF2 is used to minimize the ASE feedback power while further enhancing the operation wavelength intensity, and as a result, the SMSR of the output pulses has been significantly improved.

Table 1. Output Signal Power Values at Point B (for One-Way EDFA) and Point C (for Bi-EDFA) of System Setup When the Feedback Loop is Disconnected at Point C and Operating Wavelength is 1552.18 nm

Pump Power at 1440 nm (dBm)	Signal Power at Point B (dBm)	Signal Power at Point C (dBm)
−10.35	−37.58	−22.75
−7.37	−30.74	−7.17
−6.58	−26.0	−2.79
−4.95	−24.34	−0.45

Table 2. Pump Currents Needed to Maintain the Same Output Power Level at Point B (Pump1) and Point C (Pump2), Respectively, When Feedback Loop is Disconnected at Point C and Operating Wavelength is 1552.18 nm

Signal Power (dBm)	Pump1 (mA)	Pump2 (mA)
−42.53	83.5	77.5
−37.58	91.0	81.5
−31.03	118.5	86.5
−29.58	129.0	88.0
−24.58	229.5	94.5

3. EXPERIMENTAL RESULTS AND DISCUSSION

To examine the pump efficiency improvement of the Bi-EDFA, a number of measurements were carried out when the feedback loop of the system was disconnected at point C, and the results obtained are summarized in Tables 1 and 2, respectively.

Table 1 shows that, for the same pump power level, the output signal power values obtained at points B and C of the system setup correspond to the one-way EDFA and Bi-EDFA, respectively. It is clear from Table 1 that the Bi-EDFA provides a much higher gain of more than 23 dB than that of the one-way EDFA at a relatively large pump power level. To maintain the same signal power level at points B and C, respectively, a substantially smaller pump current (Pump2) is needed for the Bi-EDFA than that of the one-way EDFA system (Pump1) as demonstrated in Table 2. The difference of pump currents is 135 mA for the signal power of −24.58 dBm.

The multimode output pulse spectrum of the gain-switched FPLD is shown in Fig. 2 where the mode spacing

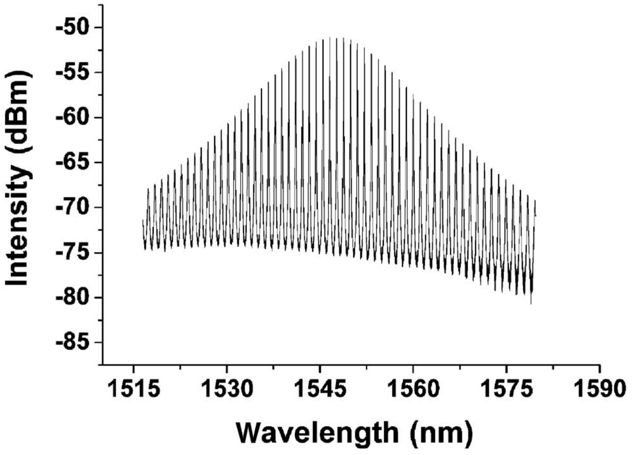

Fig. 2. Gain-switched FPLD output pulse spectrum at 1.045 GHz.

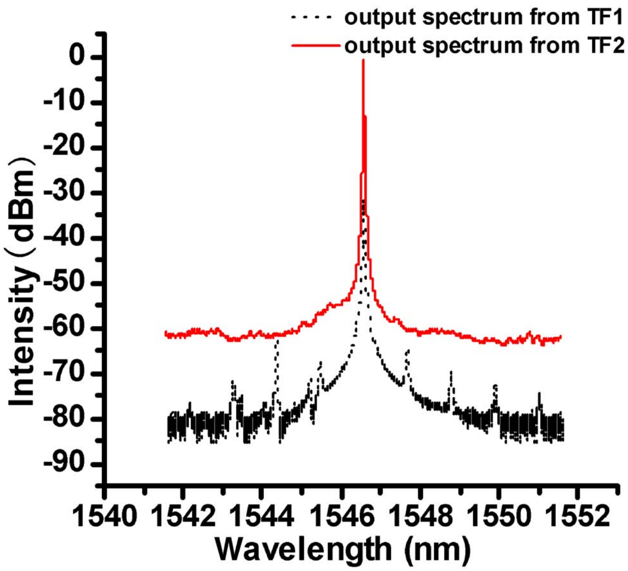

Fig. 3. (Color online) Optical pulse spectra at TF1 and TF2 outputs.

is ~1.1 nm. The FPLD is modulated by a rf signal with the power of ~−13 dB. After passing through the EDF, the gain-switched optical pulses are enhanced by ~25.56 dB at a wavelength of around 1546.57 nm, and the selected single wavelength output from the TF1 is further intensified to 52.71 dB by the second amplification of the Bi-EDFA pumped by 1440 nm laser power. Figure 3 shows the output spectra of the TF1 and the TF2, respectively. When compared with the multimode pulse spectrum shown in Fig. 2, the side modes are reduced by the TF1 and significantly suppressed by the TF2, and a SMSR improvement of as large as ~23.13 dB is achieved by the TF2.

The output pulse spectrum and the corresponding waveform of the system are shown in Fig. 4. The optical pulse is operated at the central wavelength of the FPLD, 1536.78 nm, and the modulation frequency is 1.045 GHz.

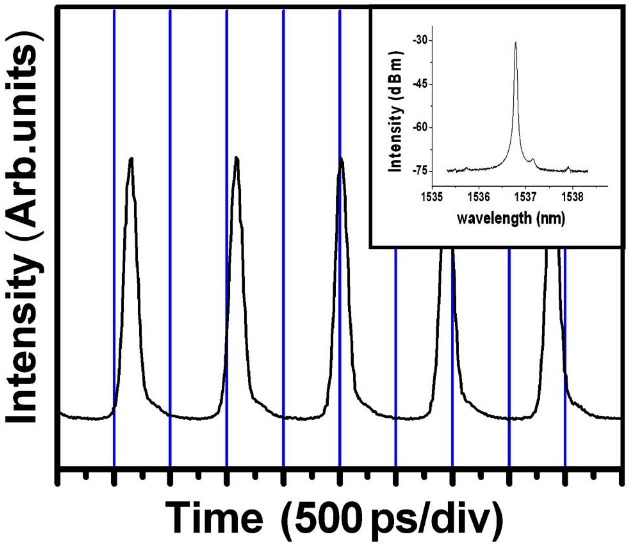

Fig. 4. (Color online) Output optical pulse waveform and spectrum at wavelength 1536.78 nm.

The spectral bandwidth of the pulse is 0.03 nm and the corresponding full-width at half maximum (FWHM) value of the pulse width is approximately 134.1 ps.

By adjusting the two tunable filters, the wavelength of the output pulses can be shifted from 1530.28 nm to 1565.86 nm, which gives a wavelength tuning range of ~35.6 nm as shown in Fig. 5, corresponding to the SMSR of higher than 38 dB. The modulation frequency of the rf signal that supports self-seeding operation depends on both the system cavity length and the parameters of the LD. The frequency and power of the rf signal should not be too low or too high ($I/I_{th} \gg 1$) to avoid multiple optical pulse generation within one period of the modulation current [15].

The values of the SMSR of the output pulses obtained at different wavelengths and the corresponding average power are demonstrated in Fig. 6. In the wavelength tuning range of 33 nm, a SMSR of higher than 40 dB can be observed, and the largest SMSR of more than 48 dB appears at ~1556 nm. When compared with the results reported in [10,11], where one tunable optical filter and single-directional EDFA were used, more than a 10 dB improvement in the SMSR was obtained over a slightly extended wavelength tuning range.

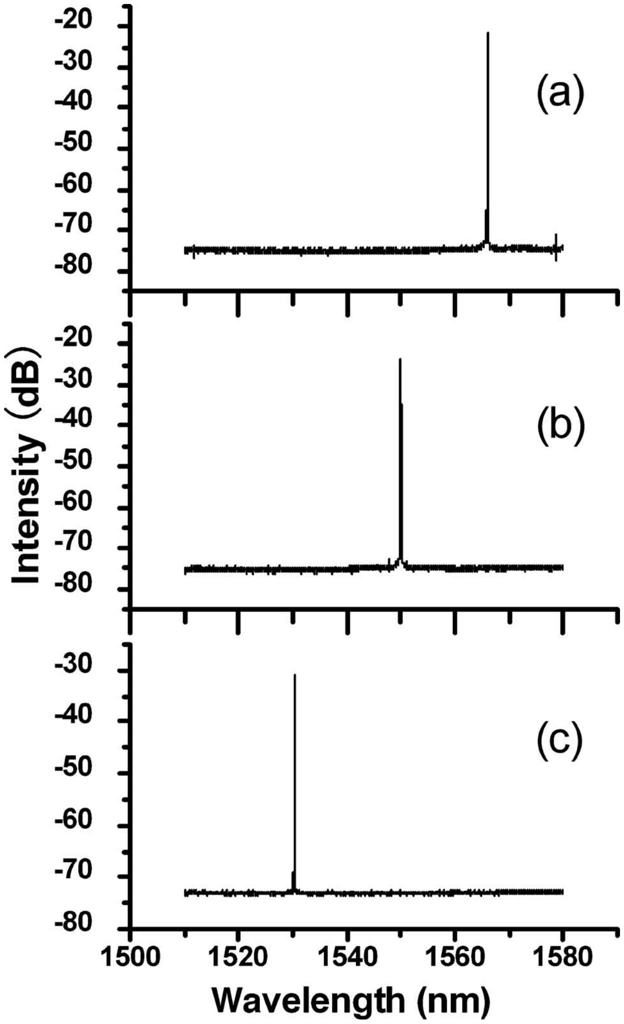

Fig. 5. Output spectra of the wavelength-tunable pulses at wavelengths (a) 1565.86 nm, (b) 1550.03 nm, and (c) 1530.23 nm.

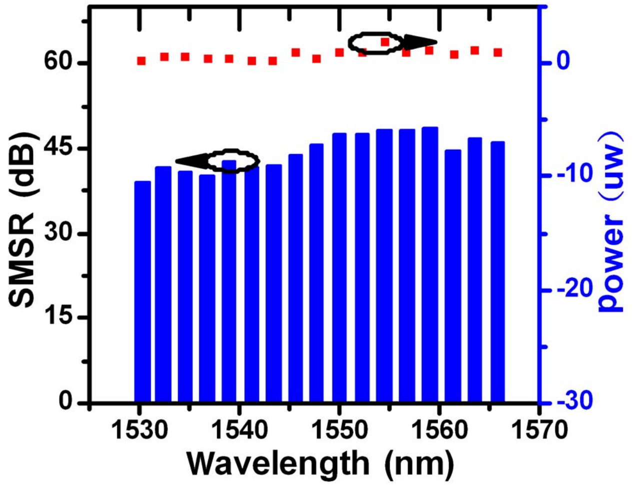

Fig. 6. (Color online) Measured SMSR and average power of the output pulses.

Continuous wavelength tuning of the optical pulses can be achieved by first calibrating the two filters at the same output wavelength close to one of the FPLD modes and slightly adjusting the temperature controller of the FPLD, followed by optimizing the SMSR by tuning the pump power. If the selected wavelength is far away from the mode peak, the optical pulse train is hard to observe in the oscilloscope. This is due to the fact that the light intensity in the middle of the two FPLD modes is very low, and the ASE noise becomes dominant at the Bi-EDFA output; thus, the low coherence TF2 output cannot excite the pulse operation in the FPLD. Although there is power competition between the LD mode and the injection light, a continuous tuning of the wavelength can still be carried out by adjusting the temperature controller to smoothly shift the LD mode to the injection wavelength, as shown in Fig. 7.

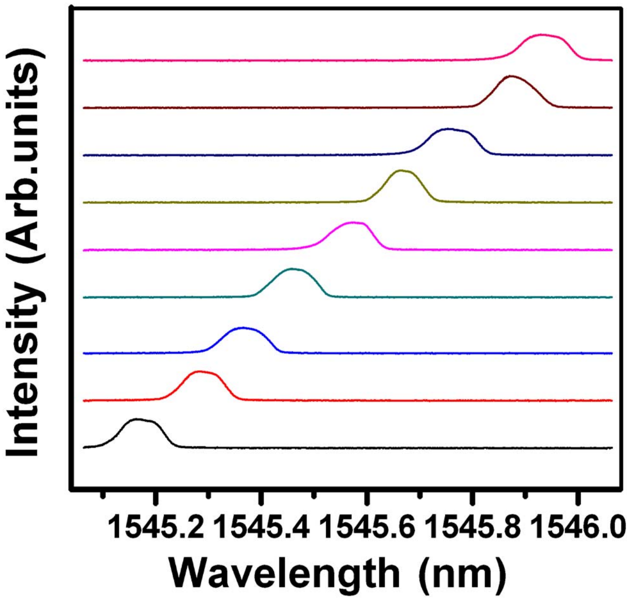

Fig. 7. (Color online) Continuous wavelength-tunable output pulse spectrum in a small region between 1545.16 nm and 1545.93 nm.

In the system operation, the seed power should be carefully selected. According to the injection-locking condition, the seed power must be high enough to enable LD oscillation, which can be achieved by increasing the pump power at 1440 nm. However, when the pump power becomes too high, the ASE noise of the Bi-EDFA increases, which causes instability of the self-seeded output pulses.

4. CONCLUSION

Continuous wavelength-tunable optical short pulses have been generated by use of a Bi-EDFA structure in a self-seeding scheme. Such a system can effectively improve pump power efficiency while suppressing ASE noise. The SMSR of greater than 40 dB has been obtained over a wavelength tuning range of 33 nm. It is expected that the wavelength tuning range of the pulses can be further increased by use of a LD with a broadband spectrum such as that of a quantum-well LD [16].

REFERENCES

1. C. Lin, P. L. Liu, T. C. Damen, D. J. Eilenberger, and R. L. Hartman, “Simple picosecond pulse generation scheme for injection lasers,” Electron. Lett. **16**, 600–602 (1980).
2. H. Ito, H. Yokoyama, S. Murata, and H. Inaba, “Picosecond optical pulse generation from an r.f. modulated AlGaAs d.h. diode laser,” Electron. Lett. **15**, 738–740 (1979).
3. J. Auyeung, “Picosecond optical pulse generation at gigahertz rates by direct modulation of a semiconductor laser,” Appl. Phys. Lett. **38**, 308–310 (1981).
4. T. Andersson, S. Lundqvist, and S. T. Eng, “Generation of single-mode picosecond pulses by injection locking of an AlGaAs semiconductor laser,” Appl. Phys. Lett. **41**, 14–16 (1982).
5. K. Chan and C. Shu, “Electrically wavelength-tunable pulse generated by synchronous two-way injection seeding,” IEEE Photon. Technol. Lett. **11**, 170–172 (1999).
6. M. Zhang, D. N. Wang, H. Li, W. Jin, and M. S. Demokan, “Tunable dual-wavelength picosecond pulse generation by the use of two Fabry–Perot laser diodes in an external injection seeding scheme,” IEEE Photon. Technol. Lett. **14**, 92–94 (2002).
7. K. Y. Lau, “Gain-switching of semiconductor injection lasers,” Appl. Phys. Lett. **52**, 257–259 (1988).
8. M. Schell, D. Huhse, A. G. Weber, G. Fischbeck, D. Bimberg, D. S. Tarasov, A. V. Gorbachov, and D. Z. Garbuzov, “20 nm wavelength tunable single mode picosecond pulse generation at 1.3 μm by self-seeded gain-switched semiconductor laser,” Electron. Lett. **28**, 2154–2155 (1992).
9. L. P. Barry, R. F. O’Dowd, J. Debau, and R. Boittin, “Tunable transform-limited pulse generation using self-injection locking of an FP laser,” IEEE Photon. Technol. Lett. **5**, 1132–1134 (1993).
10. J. Debeau, L. P. Barry, and R. Boittin, “Wavelength tunable pulse generation at 10 GHz by strong filtered feedback using a gain-switched Fabry–Perot laser,” Electron. Lett. **30**, 74–75 (1994).
11. K. Chan and C. Shu, “Performance improvements in high-frequency modulation of a laser diode under enhanced optical feedback,” IEEE Photon. Technol. Lett. **14**, 1650–1652 (2002).
12. J. W. Chen and D. N. Wang, “Wavelength tunable optical short pulse generation by self-seeding of a gain-switched Fabry–Perot laser diode with extended wavelength-tuning range,” Opt. Commun. **226**, 345–350 (2003).

13. S. Yamashita and T. Okoshi, "Performance degradation of erbium-doped fibre amplifier induced by terminal reflection," Electron. Lett. **28**, 1323–1324 (1992).
14. F. W. Willems, J. C. Van Der Plaats, and D. J. Digiovanni, "EDFA noise figure degradation caused by amplified signal double Rayleigh scattering in erbium-doped fibres," Electron. Lett. **30**, 645–646 (1994).
15. Peter Vasil'ev, *Ultrafast Diode Lasers: Fundamentals and Applications* (Artech House, 1995).
16. Y. P. Wang, D. N. Wang, W. Jin, and Xiao-hui Fang, "Continuously wavelength-tunable short pulse fiber ring laser employing a high output power MQW Fabry–Perot laser diode," IEEE J. Quantum Electron. **42**, 868–872 (2006).