Generation of continuously wavelength-tunable optical short pulses by use of two self-seeded Fabry–Perot laser diodes and an optical switch

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Generation of wavelength-tunable optical short pulses by use of two self-seeded Fabry–Perot laser diodes in a parallel configuration is described. The system supports continuous wavelength tuning in a relatively wide range of 42 nm. The side-mode suppression ratio achieved is 35 dB across the entire wavelength tuning range. The system is convenient for continuous wavelength tuning. © 2005 Optical Society of America

OCIS codes: 140.5960, 140.3520, 140.3600.

1. Introduction

Wavelength-tunable optical short pulses are useful for various applications such as optical communications, optical fiber sensors, and optical signal processing. One of the simple and stable methods for generation of optical short pulses is the use of an injection seeded, gain-switched semiconductor laser such as a Fabry–Perot (FP) laser diode, which has better tunability than a distributed-feedback laser and lower cost than an external-cavity laser.[1–4] However, the intensity of light injected into the laser diode is usually small, which leads to a relatively low side-mode suppression ratio (SMSR) of the output pulses.[5,6] Another problem of weak intensity light injection is the limited injection-locking range; i.e., injection locking can happen only within a small range centered on each laser's longitudinal mode,[7,8] with the results that wavelength tuning of a FP laser diode can be implemented only in a discrete manner and that the smallest wavelength-tuning step depends on the mode spacing of the laser diode used. As the laser emission mode wavelengths may not coincide with the International Telecommunication Union grid wavelengths, the applications of FP laser diodes in optical fiber communications may be limited.

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Received 14 March 2005; revised manuscript received 25 May 2005; accepted 30 May 2005.

0003-6935/05/306444-05$15.00/0

The wavelength-tuning range is another important criterion with which to evaluate system performance and is usually limited by the gain bandwidth of the laser diode. Recently an integrated dual-FP laser diode source was used in a self-seeding scheme to extend the wavelength-tuning range to almost 50 nm with a high SMSR.[9] However, two sets of optical pulses are generated at the region of overlap of the two FP laser diode spectra, and this creates a difficulty for time-division multiplexing applications at these wavelengths. Furthermore, wavelength tuning of the output pulses is performed on a mode-by-mode basis.

In this paper we describe a self-seeding system for generation of continuously wavelength tunable optical short pulses. In our system, two FP laser diodes with different central wavelengths are connected in parallel in an external cavity through an optical switch. Such an arrangement can extend the wavelength-tuning range without generating two sets of spectrally overlapped optical pulses. An erbium-doped fiber amplifier (EDFA) is used to enhance the light's intensity over a number of round trips of the traveling optical pulses and to improve the SMSR. The EDFA can also be used as the injection light source to induce optical pulses at the wavelengths near the center of the two adjacent laser modes, thus increasing the injection-locking range. An optical delay line is used to change the length of the external cavity and to control the arrival time of the feedback pulse to the laser diode. The output pulses have a relatively high SMSR of greater than 35 dB across a wide wavelength range of 42 nm. The system can be operated at a constant repetition

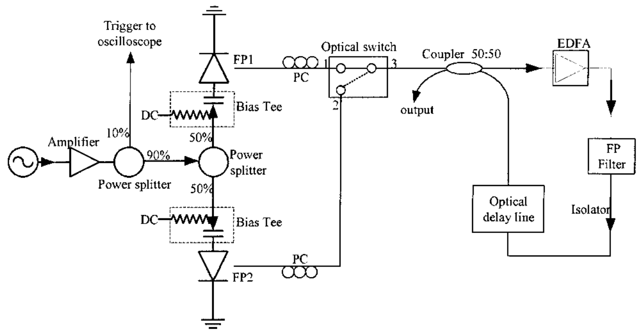

Fig. 1. Experimental setup for the generation of continuously wavelength-tunable optical short pulses. PCs, polarization controllers.

frequency and therefore is convenient for wavelength tuning.

2. Continuous Wavelength Tuning of an Injection-Seeded Fabry–Perot Laser Diode

In external injection locking, when a single-mode semiconductor laser is considered, the locking range of an injection-seeded, gain-switched slave laser diode is given by detunings $|\Delta\omega| < \Delta\omega_L$,[7] where

$$\Delta\omega = \omega_m - \omega_s, \tag{1}$$

$$\Delta\omega_L = \frac{k_m E_m}{R_s}\sqrt{1+\alpha^2}. \tag{2}$$

ω_m is the angular frequency of the master laser, ω_s is the angular frequency of the slave laser, k_m is the injection strength, E_m is the injected field, R_s is the intensity of light of the slave laser diode in the on state, and α is a linewidth enhancement factor that is determined by the laser diode. Equation (2) is also favorable for a self-seeding scheme. From Eq. (2) it was found that the ratio E_m: R_s should be high enough to produce a large locking range, from which we can deduce that, in a self-seeding scheme, the higher the intensity of feedback than that of the laser diode emission, the larger the locking range that can be obtained. In our experiment a multimode FP laser

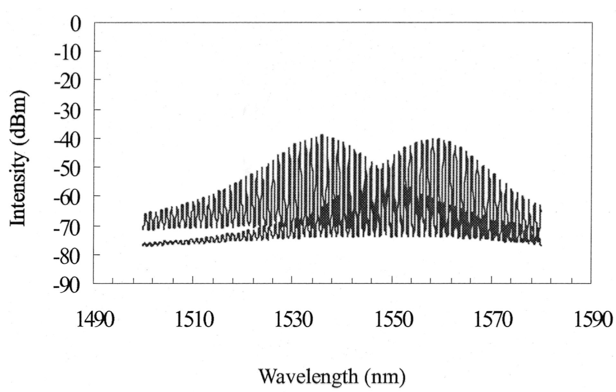

Fig. 2. Spectra of output from two gain-switched FP laser diodes.

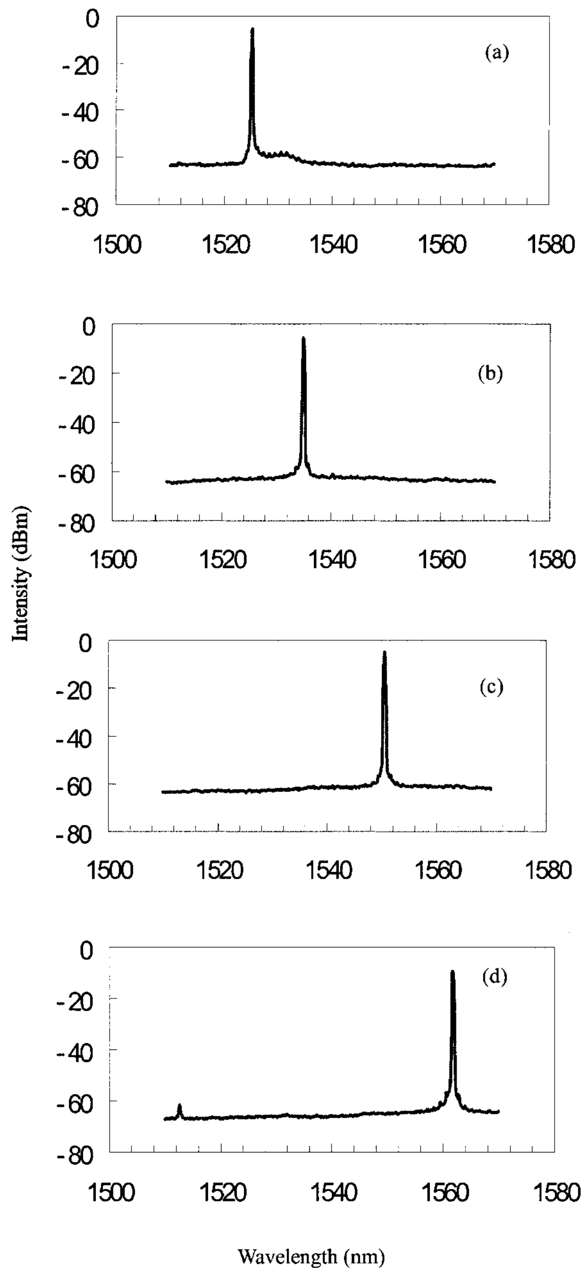

Fig. 3. Spectra of output pulses for the wavelengths at the laser modes: wavelengths (a) 1525.08 nm, (b) 1535.05 nm, (c) 1550.50 nm, and (d) 1561.75 nm.

diode is used instead of a single-mode laser diode to produce a wide wavelength-tunable range.

3. Experiment

Figure 1 shows our experimental setup for generation of continuously wavelength-tunable optical short pulses. Two commercial FP laser diodes, FP1 and FP2, with central wavelengths of 1535 and 1558 nm and threshold current 14 and 10 mA, respectively, and a mode spacing of ~1.1 nm are employed. The laser diodes are both gain switched to produce a multimode optical pulse output. A radio frequency electrical sinusoidal signal with power of ~12 dBm together with dc biased cur-

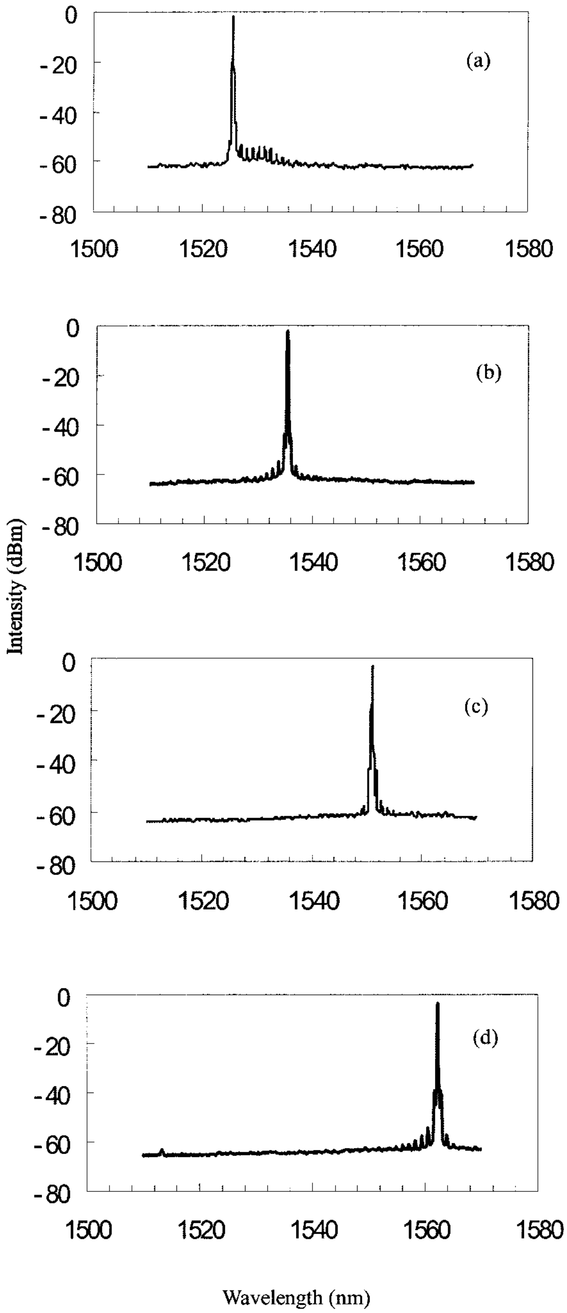

Fig. 4. Spectra of output pulses for the wavelengths between two adjacent laser modes wavelengths: (a) 1525.60 nm, (b) 1535.43 nm, (c) 1550.95 nm, and (d) 1562.28 nm.

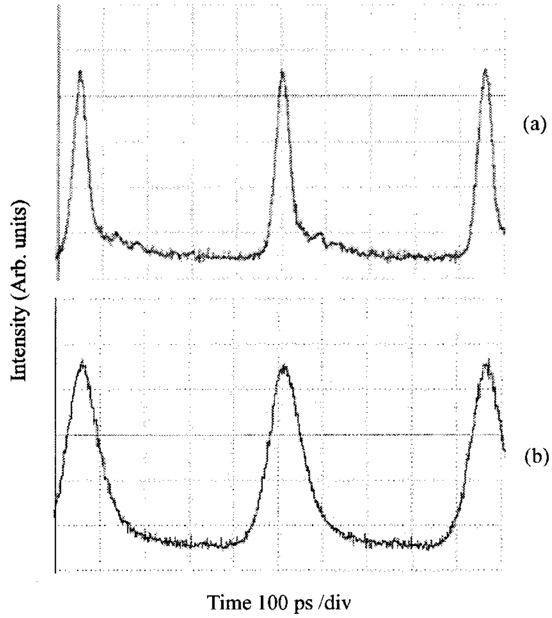

Fig. 5. Waveforms of the output optical pulse trains at wavelengths (a) 1535.05 and (b) 1535.43 nm.

rent of 14 mA (for FP1) and 11 mA (for FP2) is employed via two bias tee circuits. A constant repetition frequency of 2205.10 MHz is maintained during the system's operation.

Which of the two FP laser diodes is used in the self-seeding operation is determined by the optical switch. This setup provides a wider wavelength-tuning range than that with one FP laser diode without generating two sets of optical pulse trains with the same wavelengths but at different times.

The output of FP1 is amplified by the EDFA with a gain of approximately 15–20 dB via a coupler (50:50) and then sent to a tunable optical FP filter with bandwidth of 32 GHz. Adjusting the optical delay line causes the optical pulse that is fed back to the gain-switched FP1 to arrive when the next pulse is going to build up, thus producing a single-wavelength optical pulse emission. When the filter is set to the wavelength near the center of the two adjacent FP modes, the output of the filter is just an amplified spontaneous emission from the EDFA, which is directed to the FP laser diode to form a stable injection-seeded optical pulse train. To achieve a high SMSR at these wavelengths, a high EDFA gain ($\sim$25 dB) is needed. The stimulated single-wavelength optical pulses are further enhanced by the EDFA and then pass through the filter before being extracted via the coupler as the system's output.

The system also forms a fiber ring laser. When the repetition frequency is a multiple of the fundamental frequency of the ring laser, active mode locking occurs and the pulses become their narrowest. A polarization controller is used to improve the SMSR of the output pulses. The spectra and the waveform of the output pulses are displayed by use of an optical spectrum analyzer with 0.08 nm resolution and a high-speed optical sampling oscilloscope.

4. Results and Discussion

The multimode output spectra from the two gain-switched FP laser diodes are shown in Fig. 2. The central wavelengths are located at 1535.9 and 1558.2 nm. There is a spectral overlap between the two laser diodes. The spectra of the single-wavelength pulses that correspond to the injection on the FP laser mode are shown in Fig. 3, where Figs. 3(a) and 3(b) are arbitrarily selected injection-seeded outputs of FP1 and the wavelengths are located at 1525.08 and

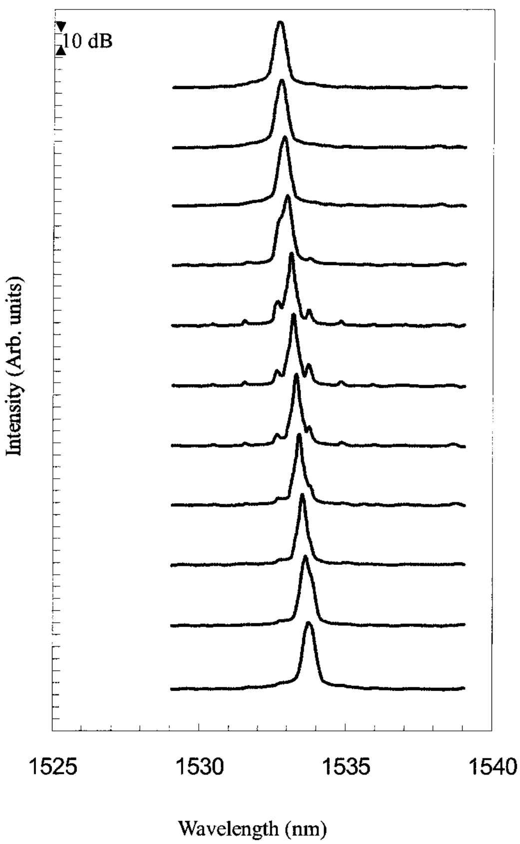

Fig. 6. Output spectra showing continuous wavelength tuning with 11 tuning steps in a small wavelength region of 1.1 nm from 1532.69 to 1533.75 nm.

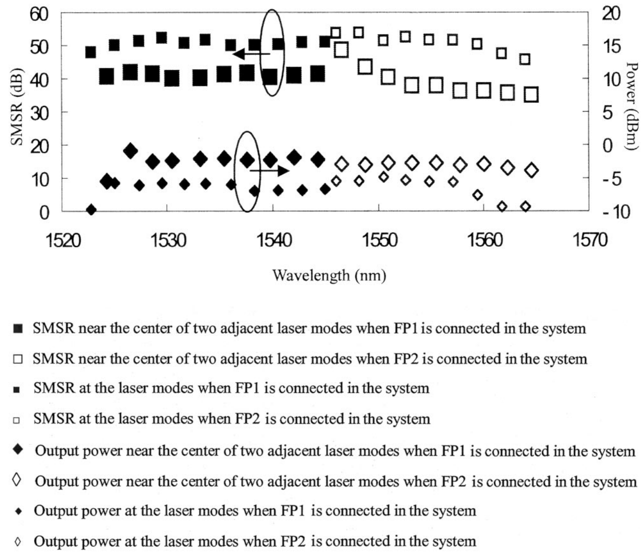

Fig. 7. SMSR and average power of optical pulses obtained at several wavelengths.

1535.05 nm. Figures 3(c) and 3(d) are the outputs of FP2 at 1550.50 and 1563.2 nm, respectively. The SMSRs achieved are ~50.1, 51.2, 51.5, and 47.4 dB respectively. When the operating wavelengths are near the center of the two adjacent FP modes situated at 1525.60, 1535.43, 1550.95, and 1562.28 nm, respective SMSRs of 42.0, 41.2, 40.4, and 35.7 dB can be observed (Fig. 4). Injection-seeded output originates mainly from the amplified spontaneous emission of the EDFA. The waveforms of the output pulse trains that correspond to the spectra shown in Figs. 3(b) and 4(b) are illustrated in Fig. 5. In Fig. 5(a) the FWHM value of the pulse width is ~32 ps, where the actively mode-locked fiber ring laser locks the phase of the injection-seeded FP mode.[8] In Fig. 5(b) a FWHM value of ~85 ps is obtained, mainly owing to the pulse that originated from the amplified spontaneous emission of the EDFA.

The continuous wavelength-tuning capability of the system is shown in Fig. 6. A wavelength-tuning step of less than or close to 0.1 nm (limited by the resolution of optical spectrum analyzer) is used in the two adjacent FP modes with a wavelength range of ~1.1 nm, between FP mode M at 1532.69 and FP mode $M + 1$ at 1533.75 nm. During tuning, it was found that the PC need not be changed when the injection-seeded pulse is close to the mode wavelength. When the wavelength is shifted away from the mode by 0.3–0.4 nm, the PC should be adjusted because the refractive index between the two adjacent FP modes is different from that at the FP modes. A SMSR of greater than 40 dB is shown in Fig. 6. As can be seen, a relatively wider spectral bandwidth is obtained at the wavelengths near the laser modes because active mode locking of the fiber ring laser modes occurs on these FP modes.

Figure 7 shows the SMSR and average power of output pulses obtained at several wavelengths. The SMSR and the average power of the output pulses obtained when FP1 is connected to the external cavity are within the wavelength range 1522.8–1545 nm, and those obtained when FP2 is connected into the external cavity are in the range 1546–1564.5 nm. It can be observed that, at the laser mode wavelengths, the SMSR is slightly higher, while the average power of the output pulses is slightly smaller, than those away from the laser modes, which is so because there is a stronger reflection from the FP laser cavity for wavelengths away from the modes than for those at the modes. (The cavity of the FP laser diode can also be considered a FP interferometer: When a light beam is injected into this laser diode, each free-running mode of the FP laser diode corresponds to a transmission peak of the FP interferometer, and the center of the two adjacent FP modes corresponds to a reflection peak of the FP interferometer.) A SMSR greater than 35 dB is achieved across a wavelength range of 42 nm at a constant repetition frequency of 2205.10 MHz. The wavelength tuning range is limited by the gain profile of the EDFA, which falls sharply outside the range 1520–1560 nm.

5. Conclusions

We have demonstrated a self-seeding system for generation of continuously wavelength-tunable optical short pulses. The system consists of two Fabry–Perot laser diodes connected in parallel with an optical switch to extend the wavelength-tuning range, an erbium-doped fiber amplifier, a tunable optical FP filter, an optical delay line, and a coupler. A side-mode suppression ratio of greater than 35 dB is achieved across a wavelength range of 42 nm at a constant repetition frequency of 2205.10 MHz. The system is convenient for continuous wavelength tuning.

The research was supported by the Hong Kong Polytechnic University through grant G-T614 and by the Hong Kong Special Administrative Region government through CERG Competitive Earmarked Research Grant PolyU5207/03E.

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