Generation of continuous wavelength-tunable optical short pulses with two Fabry–Pérot laser diodes in an external injection-seeding scheme

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We have developed an external-injection seeding system to generate continuous wavelength-tunable optical short pulses with a side-mode suppression ratio of more than 28 dB over a wavelength-tuning range of 21.2 nm. The system consists of two Fabry–Pérot laser diodes, one of which is gain switched and another that is dc biased; two tunable optical filters; an erbium-doped optical-fiber amplifier; and a circulator. The system is simple, easy to operate, and robust and may be used in wavelength-division-multiplexed optical-communication systems and in time-division multiplexing of spectroscopic gas sensors. © 2005 Optical Society of America

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1. INTRODUCTION

The development of wavelength-tunable optical-short-pulse sources is very important owing to its application in high-speed optical communications and optical measurements. The light source that can be used to generate optical short pulses includes fiber laser and semiconductor laser diodes.[1–4] The fiber laser supports a continuous wavelength tuning in a wide range and at a high repetition frequency. However, the stability of the fiber laser is prone to small environmental change, especially when a long laser cavity is involved. The distributed feedback (DFB) laser diode exhibits stable laser operation with continuous wavelength-tuning ability, but the tuning range is limited, typically less than 2 nm. Both the fiber laser and the DFB laser diode have a relatively high cost. On the contrary, the Fabry-Pérot (FP) laser diode is a low-cost light source with a larger wavelength-tuning range than that of the DFB laser diode and better operation stability than that of the fiber laser.[5,6] However, owing to the cavity structure of the FP laser diode, the tuning of the wavelength is usually implemented on a mode-to-mode basis, i.e., the smallest wavelength-tuning step is limited by the mode spacing of the laser diode, which essentially limits its application in optical-fiber communications, as the mode of the laser diode may not coincide with one of the International Telecommunication Union grid wavelengths. Although a smaller wavelength shift than the mode spacing may be achieved by use of thermal control, such an operation may be affected by mode hopping when a large wavelength-tuning range is required. There are several ways to produce optical short pulses, such as active mode locking, self-seeding, and external-injection seeding. Active mode locking is a widely used method for generation of optical short pulses at a relatively high repetition frequency. However, a specially designed laser structure is required or an antireflection coating is needed on the laser internal facet. Self-seeding is a relatively simple technique for optical-short-pulse generation. In self-seeding, the selected wavelength element from the gain-switched FP laser-diode output is fed back into the laser cavity during the next pulse build-up time. As the wavelength tuning is carried out through adjustment of the wavelength-selective device in the cavity together with the repetition frequency or the optical path length corresponding to the selected wavelength, the operation is not convenient, which may limit its application in optical-fiber communications and sensing. On the contrary, the wavelength tuning in external-injection seeding can be implemented at an arbitrary repetition frequency, and the optical path length does not need to be changed. The commonly used master source in external-injection seeding is the external-cavity laser, which is of high cost. Recently, the use of two FP laser diodes as the master and the slave sources was developed.[7–8] However, only mode-by-mode wavelength tuning is achieved with a small wavelength-tuning range of less than 10 nm.

In this paper, we present a simple external-injection seeding system for continuous wavelength-tunable optical-short-pulse generation. The system consists of two FP laser diodes, of which one is used as the master source and the other as the slave source; two tunable optical filters; an erbium-doped optical fiber amplifier (EDFA) and a circulator. The generated optical pulses exhibit a side-mode-suppression ratio (SMSR) of better than 28 dB across a wavelength region of 21.2 nm.

2. EXPERIMENT

The experimental configuration is shown in Fig. 1. A commercial FP laser diode with a central wavelength of 1537 nm and a threshold current of 15 mA was gain

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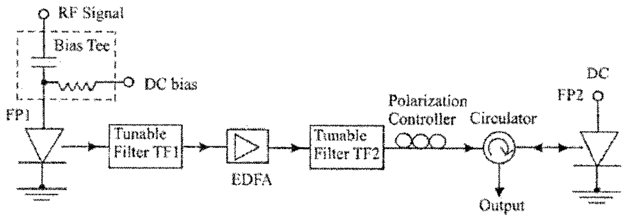

Fig. 1. Experimental configuration of the external-injection seeding system for continuous wavelength-tunable optical short pulse generation.

switched by use of rf electrical signal in conjunction with a dc bias current of ~14 mA via a bias-tee circuit. The electrical signal power used to modulate the laser diode was approximately 12 dBm, and the dc driving current was ~15 mA. The output from the master source, a gain-switched FP laser diode, FP1, was first sent to a tunable optical bandpass filter (TF1; TB 1570, JDS Fitel), with a bandwidth of ~1 nm, before being power amplified by use of an EDFA with the gain of 25 dB. The function of TF1 was to perform rough wavelength selection and to reduce the dc level of the output signal. The enhanced wavelength elements from the EDFA were directed to a tunable optical FP filter with a bandwidth of 2.4 GHz and a free spectral range of 8860 GHz to implement a fine-wavelength selection and then were launched to the slave source, a dc-biased FP laser diode (FP2) via a circulator. The external-injection-seeded output pulses were extracted from one of the circulator output ports. The central wavelength and the threshold current of FP2 were 1534 nm and 17 mA, respectively, and the dc driving current used in the experiment was ~15 mA. A polarization controller was included in the system for optimization of the polarization states of the pulses and improvement of the SMSR. The output pulse trains were sent to an optical spectrum analyzer (OSA) with 0.1-nm resolution for spectrum characterization and also to a photodetector connected to a digital sampling oscilloscope for observation of the pulse waveform.

3. RESULTS AND DISCUSSION

The optical pulse spectrum from the gain-switched FP1 is shown in Fig. 2(a), and the spectrum from the dc biased FP2 is displayed in Fig. 2(b). Both spectra exhibit a multimode nature with mode spacing of approximately 1.05 and 1.15 nm. After passing through the tunable optical filter TF1, the output spectrum of FP1 becomes sharpened and centered at the selected wavelength, as demonstrated in Fig. 3. The spectra of the wavelength-tunable optical-short-pulse trains are displayed in Fig. 4, where the wavelengths are situated at 1528.8, 1537.8, and 1545.8 nm, approximately coincident with the corresponding mode wavelengths of FP2. The FWHM of the spectral width is measured to be ~0.1 nm, limited by the resolution of the OSA used. The wavelength tuning is implemented by adjustment of TF2 and a slight tuning of TF1 for SMSR enhancement. The SMSR of the pulses achieved in Fig. 4 is larger than 28 dB. If the selected wavelength is located close to the middle point of the two adjacent modes of FP2, the SMSR of greater than 30 dB can be observed, as shown in Fig. 5, where the wavelengths are situated at 1529.1, 1537.3, and 1545.3 nm and the spectral width measured is also ~0.1 nm owing to the limited resolution of the OSA used. The relatively small SMSR obtained at the FP2 mode wavelengths is due to the fact that the adjacent side modes of the selected wavelength in the two FP laser diodes are well overlapped because of their similar wavelength spacing, which results in an increased side-mode intensity in the output pulse

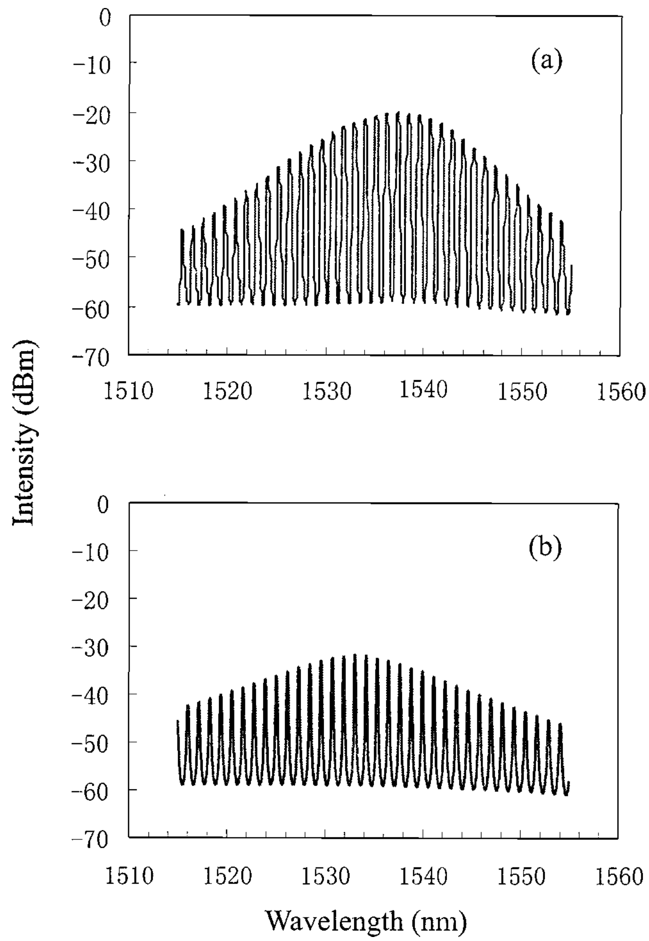

Fig. 2. FP laser diode spectra. (a) Gain-switched FP1 output, (b) dc-biased FP2 output.

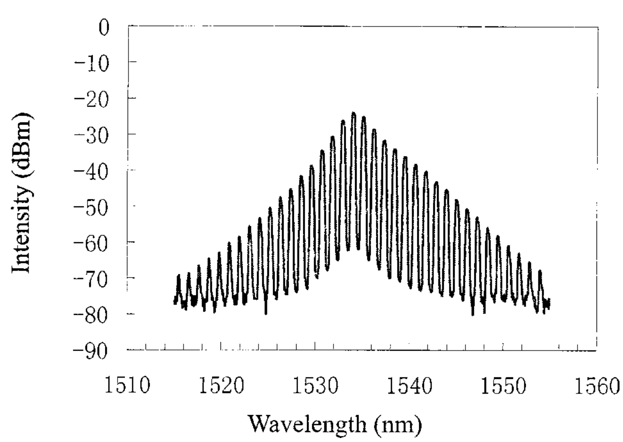

Fig. 3. Optical spectrum obtained at the tunable optical filter TF1 output.

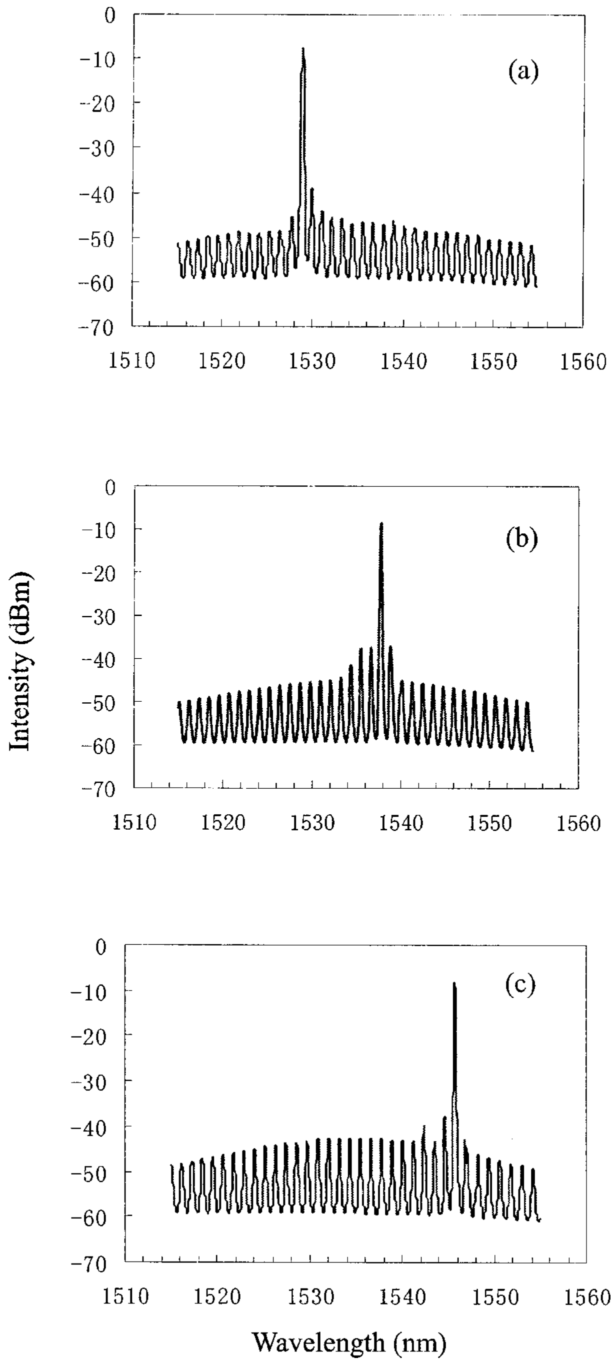

Fig. 4. Output pulse spectra for the wavelengths of (a) 1528.8, (b) 1537.8, and (c) 1545.8 nm situated at the laser modes of FP1.

spectrum and hence the reduced SMSR. In the developed external-injection-seeding system, the master laser source can provide a relatively larger power than the slave source. The spectral power at 1537.8 nm is approximately −19.9 dBm and approximately −38.6 dBm in the FP1 output and the FP2 output, respectively, and becomes approximately −8.5 dBm in the final system output, demonstrating the good efficiency of our external-injection-seeding system.

The waveforms of the optical pulse train corresponding to the spectrum demonstrated in Figs. 4(b) and 5(b), respectively, are shown in Fig. 6. The FWHM of the pulse width is around 100 ps in Fig. 6(a) and 50 ps in Fig. 6(b). A relatively narrow pulsewidth can be achieved for the wavelength at the middle point of the two adjacent modes of FP2, corresponding to a relatively high SMSR.

The continuous wavelength tuning is mainly carried out by a tuning of TF2 and a slight adjustment of the temperature controller of FP1 in the system. The tuning of TF2 allows a large power concentration on the selected wavelength, which is subsequently sent to FP2 to stimulate a laser operation. As the temperature controller needs to be adjusted only slightly to shift the wavelength up to half-mode spacing, and the driving current on FP2 remains constant during the system operation, the con-

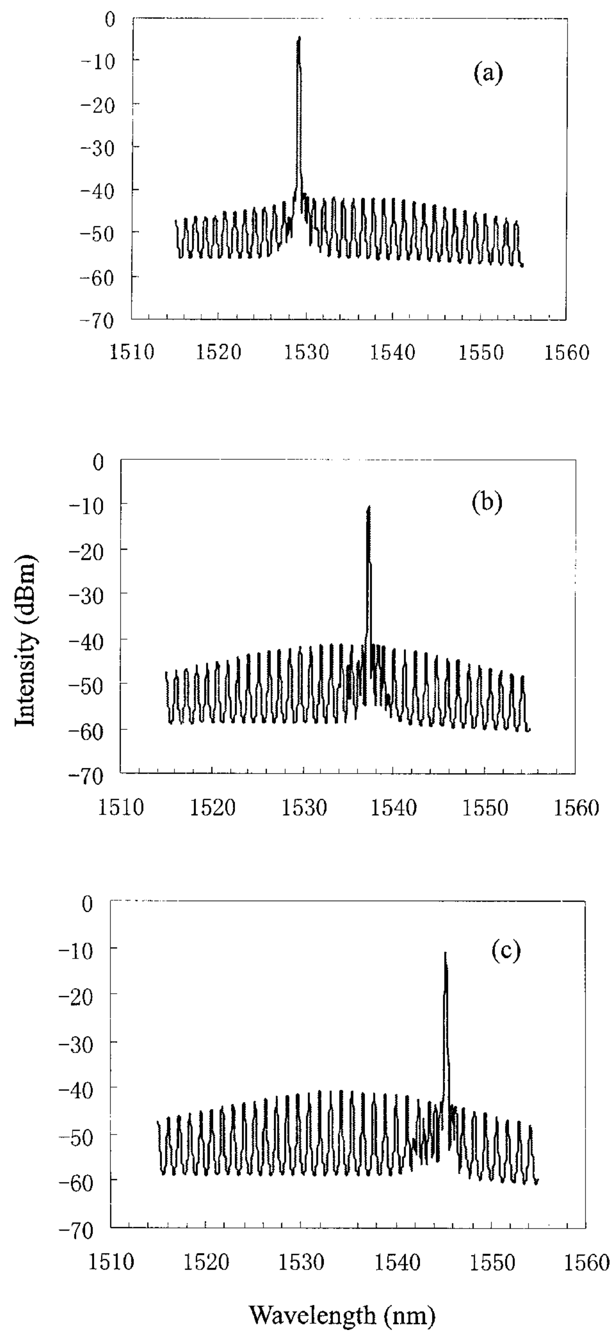

Fig. 5. Output pulse spectra for the wavelengths of (a) 1529.1, (b) 1537.3, and (c) 1545.3 nm at the center of the two adjacent modes of FP1.

tinuous wavelength tuning can be implemented smoothly and without any mode hopping. It is also expected that the continuous wavelength tuning can be achieved without the use of thermal control as long as another EDFA is placed after TF2 in the system to provide a high power concentration at the selected wavelength. In our experiment, the wavelength-tuning step of close to or less than 0.1 nm (limited by the resolution of the OSA) is used in the wavelength region between 1533.3 and 1534.4 nm, and the obtained optical spectra are shown in Fig. 7. It can be observed from this figure that within a small wavelength region of 1.1 nm, 10 consecutive tuning steps are adopted with an average step length of 0.11 nm, verifying the continuous wavelength-tuning capability of the system.

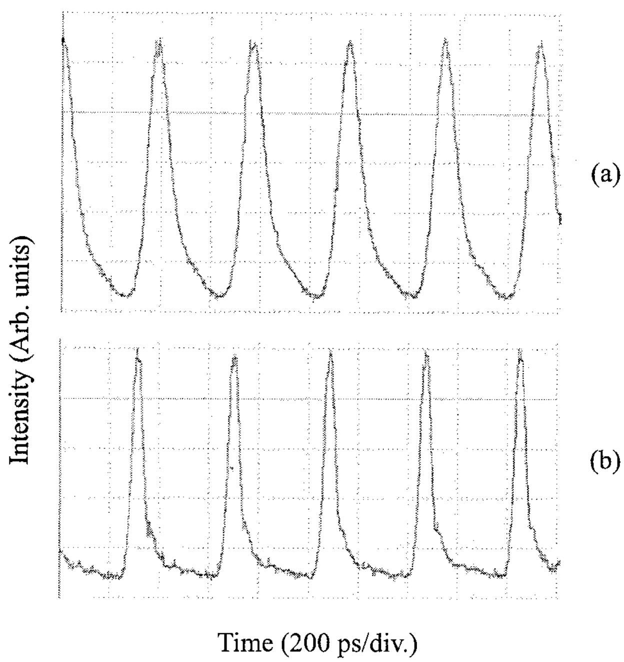

Fig. 6. Waveforms of the output optical pulse trains at wavelengths of (a) 1537.8 and (b) 1537.3 nm.

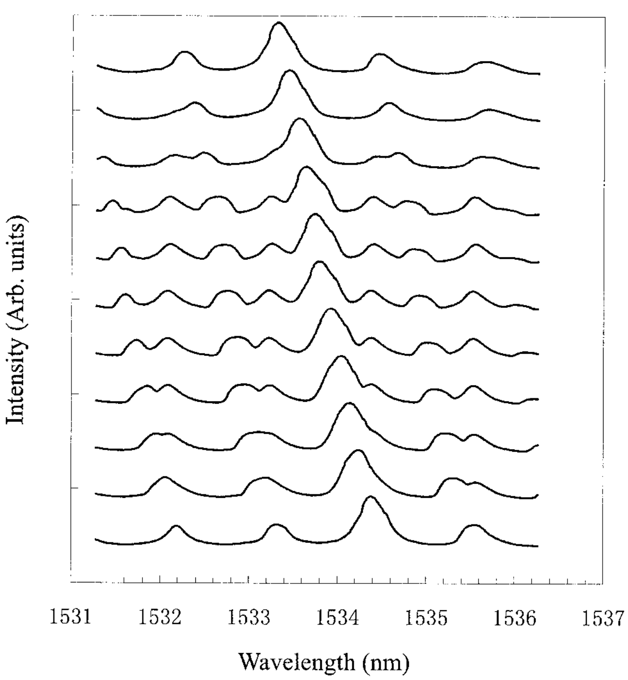

Fig. 7. Output spectra showing a continuous wavelength-tuning in a small region between 1533.3 and 1534.4 nm.

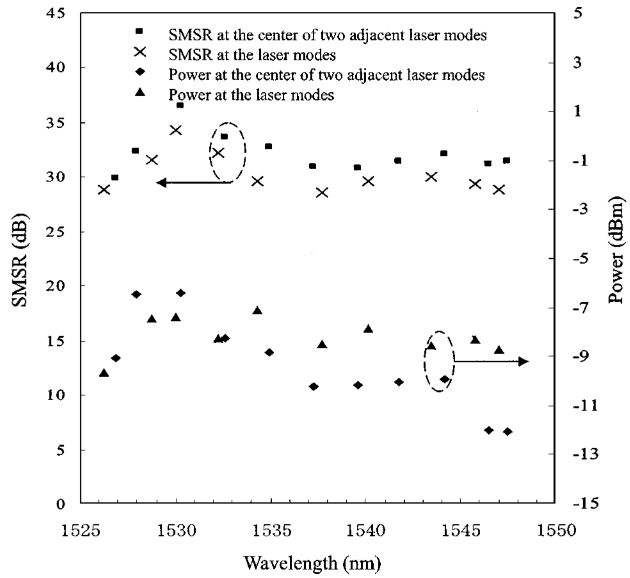

Fig. 8. Measured SMSR and average output power of the optical pulses.

The SMSR and the average power of the output pulses in the wavelength region between 1526.3 and 1547.5 nm are shown in Fig. 8. Across the whole wavelength-tuning region of 21.2 nm, the obtained SMSR is higher than 28 dB. At the middle point of the two adjacent laser modes of FP2, the SMSR is slightly larger than that at the mode wavelengths. The average power of the output pulses is close to or better than −10 dBm in most of the wavelength-tuning range. The system output pulses exhibit a good stability; the estimated accuracy of measurement for SMSR is ≤0.5 dB, and that for average power is less than 0.5 dBm.

The SMSR of better than 28 dB that was achieved in our system is still lower than that obtained in the reported self-seeding system, which is greater than 40 dB,[9,10] because of the repeat wavelength power intensification during the self-seeding process before the single-wavelength pulse emission.

When compared with our previous work reported in Ref. 8, a slightly larger SMSR and a continuous wavelength tuning are achieved in an increased wavelength range. The greater SMSR is produced by use of an additional filter for better spectral purification. The continuous wavelength tuning is enabled by the high power concentration on the selected wavelength to be sent to the slave laser diode, and the increase of the wavelength-tuning range is due to the broadband spectra of the laser diodes used and the capability of obtaining a high spectral power in a wide wavelength region.

4. CONCLUSION

We have demonstrated a simple system to produce continuously wavelength-tunable optical short pulses in an external-injection-seeding scheme based on two commercial FP laser diodes. The system is economic and easy to operate and exhibits a good SMSR of better than 28 dB and a relatively large wavelength-tuning range of 21.2 nm. The system has the potential to be used in spectroscopic gas sensor networks based on time-division multiplexing.

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