Simple system for optical short-pulse generation in both active mode-locking and self-seeding schemes

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A simple system that simultaneously supports active mode-locking and self-seeding schemes for wavelength-tunable optical short-pulse generation is proposed. The system consists of a gain-switched Fabry–Perot laser diode, an erbium-doped fiber amplifier, a tunable optical filter, and two circulators. The mode-locked optical pulses exhibit good stability, a high side-mode suppression ratio of more than 31 dB over a wide wavelength tuning range of 42 nm, and a pulse width of around 35 ps at a repetition frequency of ~2.8 GHz. © 2006 Optical Society of America

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1. Introduction

Wavelength-tunable optical short-pulse generation is of great importance in high-speed and wavelength division multiplexed optical fiber communication systems, optical signal processing, and optical fiber sensor networks. Among the various techniques of optical short-pulse generation, the active mode locking of a semiconductor laser diode or an erbium-doped fiber ring laser is attractive because it produces narrow optical pulses and operates at a relatively high repetition frequency.[1–5] However, in the mode-locking scheme, a specially designed laser diode or antireflection coating on the laser internal facet is usually required, and the pulses generated by a fiber ring laser structure may exhibit low stability because of small environmental changes, especially in a relatively long laser cavity. Another simple and robust way for wavelength-tunable optical short-pulse generation is by the self-seeding of a gain-switched Fabry–Perot (FP) laser diode.[6–8] In a self-seeding system the multimode laser output from a gain-switched FP laser diode is wavelength selected and then reflected back into the laser cavity. As long as the feedback optical pulse arrives within a time window just before the new pulse emission, a single-wavelength optical short-pulse operation can be established. The tunability of the pulse wavelength is achieved by adjusting the wavelength-selective element in the cavity. Because the width of the time window is around a few tens of picoseconds,[6] the self-seeded optical pulse is less sensitive to the environmental perturbation and thus supports a relatively stable optical short-pulse operation.

In this paper we present a system that can generate stable wavelength-tunable optical short pulses by using a commercial FP laser diode in a combined active mode-locking and self-seeding scheme to increase operation stability. In our system the feedback loop of the gain-switched FP laser diode consists of an erbium-doped fiber amplifier (EDFA), a tunable optical FP filter, and two circulators, which effectively support a self-seeding operation. Such a loop also forms a fiber ring laser structure in which the gain-switched FP laser diode plays the role of the mode locker. When the system operates in a self-seeding regime, further tuning of the frequency of the rf signal to the multiple of the fundamental frequency of the fiber ring laser leads to a combined operation of self-seeding and active mode locking of the fiber ring laser. The optical short pulses obtained exhibit a good side-mode suppression ratio (SMSR), greater than 31 dB across a wide wavelength tuning region of more than 42.4 nm. The pulse width is around 35 ps at a repetition frequency close to 2.8 GHz. The system is simple and easy to operate and exhibits good stability.

2. Injection-Locking Condition

When single-mode semiconductor lasers are used in an external injection-locking regime, both the fre-

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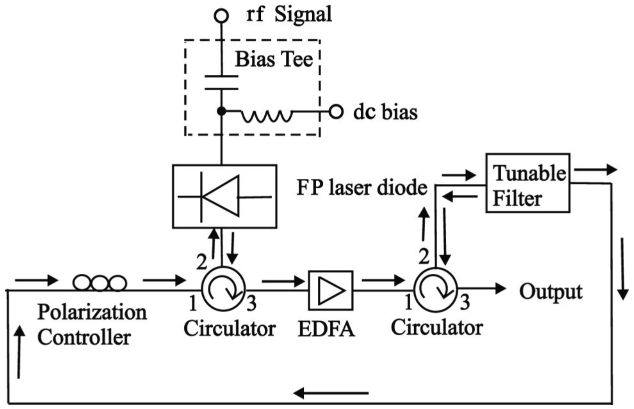

Fig. 1. Experimental arrangement for the combined self-seeding and active mode-locking system.

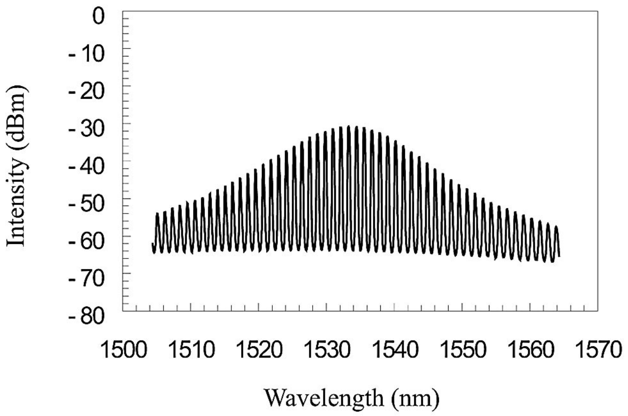

Fig. 2. Output pulse spectrum of the gain-switched FP laser diode (with a bias current of ~16 mA).

quency and the phase of the slave laser are locked. The frequency-locking range of the injection-seeded, gain-switched slave laser diode is given by detuning $|\Delta\omega| < \Delta\omega_L$:[9]

$$\Delta\omega_L = \frac{k_m E_m}{R_s}\,(1+\alpha^2)^{1/2}, \tag{1}$$

where $\Delta\omega = \omega_m - \omega_s$, 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 light intensity of the slave laser diode in the on state, and α is the linewidth enhancement factor, which is determined by the laser diode itself.

The locked phase is determined as a function of the frequency detuning $\Delta\omega$:

$$\phi_L = -\arcsin\left(\frac{\Delta\omega}{\Delta\omega_L}\right) - \arctan\alpha, \tag{2}$$

where $\phi_L \in [-\pi; \pi]$. From Eq. (2) we can observe that, when $\phi_L = 0$, the slave laser is locked at the same phase with the master laser. Equations (1) and (2) are also applicable in a self-seeding scheme.

3. Experiment

The experimental configuration of our combined self-seeding and active mode-locking system is shown in Fig. 1. The electrical signal from a radio frequency (rf) signal generator was power enhanced by an electrical amplifier to ~11 dBm. Approximately 90% of the amplifier output was sent to the FP laser diode through a bias-tee circuit to drive the laser diode into a gain-switching operation together with a dc driving current. The rest of the signal power was used as the trigger to the oscilloscope. The peak wavelength of the gain-switched FP laser diode was around 1534 nm with a mode spacing of 1.1 nm. The dc driving current was 16 mA, slightly below its threshold current of 17 mA.

In the self-seeding operation the multimode optical pulses from the gain-switched FP laser diode were amplified first by an EDFA with a gain of ~10 dB and then sent through a circulator to a tunable optical FP filter with a bandwidth of 2.4 GHz and a free spectral range of 8860 GHz. The transmitted single-wavelength element from the tunable filter was directed back into the gain-switched FP laser diode and stimulated the single-wavelength optical short-pulse emission as long as the selected wavelength pulses arrived within the time window just before the next pulse emission. The stimulated single-wavelength optical short pulses were further enhanced by the EDFA and then sent to the tunable optical filter via a circulator. The tunable filter reflected part of its input, which was subsequently branched out through the circulator as the system output.[8] A polarization controller was used in the optical loop to adjust the polarization states of the light injected into the laser diode to optimize the SMSR of the output pulses.

The self-seeding system mentioned above also forms a fiber ring laser loop that consists of an EDFA, a tunable optical filter, two circulators, and a gain-switched FP laser diode. The active mode-locking was achieved by using the gain-switched FP laser diode as the modulator, which was driven by rf electrical signals at a repetition frequency of 2.8 GHz. The fundamental frequency of the laser ring cavity was 4.5303 MHz, and the length of the feedback loop was estimated to be 45.17 m. The wavelength of the mode-locked optical pulses was selected from the FP laser output by a tunable optical filter. During the system operation the self-seeded single-wavelength optical short-pulse emission was easily achieved because of the tolerance in the pulse arriving time. The rf electrical signal used to drive the FP laser diode was close to the multiple of the fundamental frequency of the fiber ring laser. Further tuning of the driving frequency to the exact multiple of the fundamental frequency would lead to the longitudinal modes of the fiber ring laser actively mode locked (phase locked), and as a result the stable and phase-locked output pulses were generated. In addition a combined system of active mode locking and self-seeding should exhibit higher stability than mode

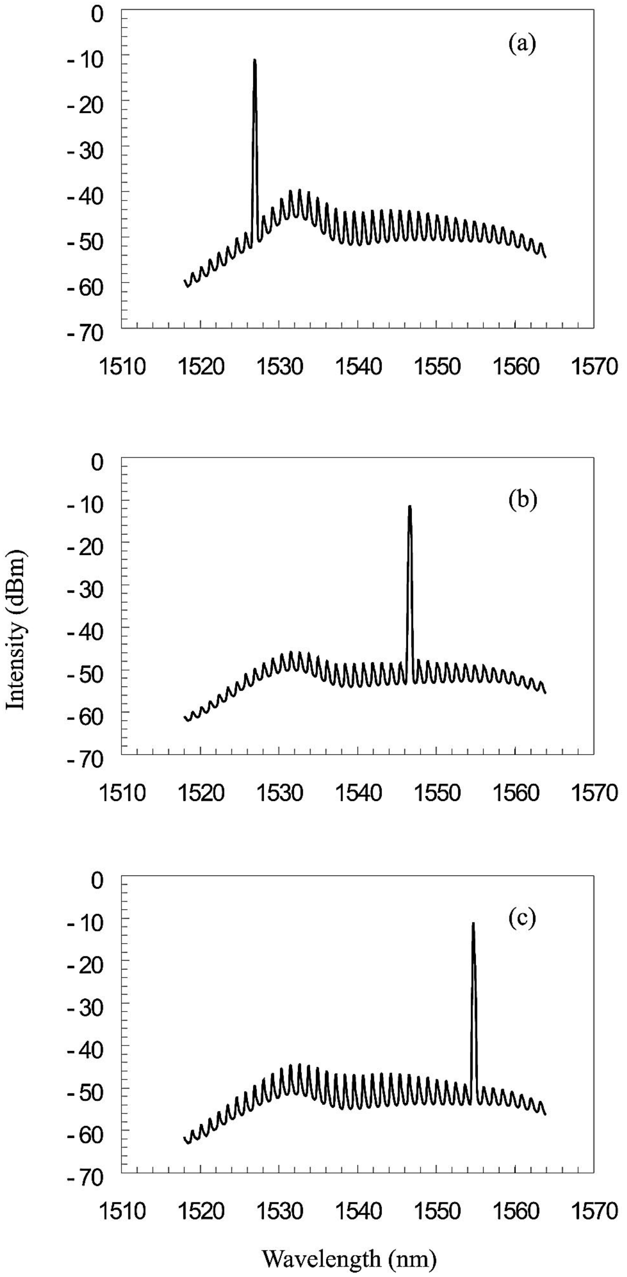

Fig. 3. Wavelength-tunable active mode-locked output optical short-pulse spectrum: at (a) 1526.9, (b) 1546.6, and (c) 1554.7 nm.

locking alone because of the small time window for the feedback pulses allowed in a self-seeding scheme. Thus a small variation in temperature will not essentially affect stability as long as the feedback pulses arrive at the laser diode within the allowed time window.

4. Results and Discussion

The multimode output pulse spectrum from the gain-switched laser diode is recorded by an optical spectrum analyzer with a resolution of 0.08 nm, as demonstrated in Fig. 2.

The spectra of the actively mode-locked optical pulses are shown in Fig. 3. The repetition frequency is 2804.273 MHz, corresponding to the 619th harmonic of the fundamental frequency (4.5303 MHz). The wavelength tuning is achieved by adjusting the driving voltage on the tunable optical filter. In Fig. 3(a) the peak wavelength is situated at 1526.9 nm. By adjusting the tunable filter, the wavelength can be shifted to 1546.6 nm. In Fig. 3(c) the wavelength is further shifted to 1554.7 nm. The optical pulse trains corresponding to the wavelengths displayed in Fig. 3 are shown in Fig. 4. The FWHM value of the pulse width is approximately 35 ps. The time jitter value of the output pulses is ~1 ps, which is lower than that of an active mode-locked fiber ring laser (~3 ps in Refs. 10 and 11) and higher than that of a self-seeded, gain-switched FP laser diode (~0.2 ps in Ref. 12) for a similar pulse-width value.

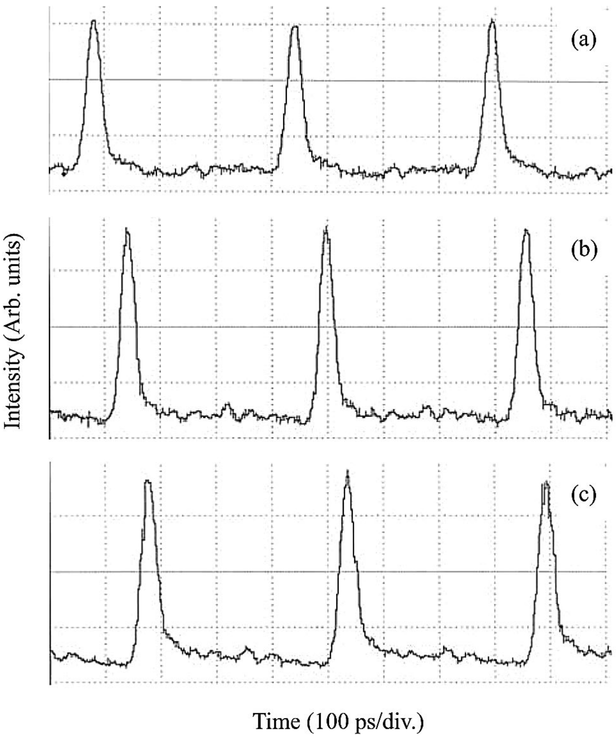

Fig. 4. Active mode-locked optical pulse trains at a wavelength of (a) 1526.9, (b) 1546.6, and (c) 1554.7 nm.

Figure 5 shows a variation in the optical pulse trains when the modulating frequency is detuned from the harmonics while the operating wavelength remains at 1539.2 nm. In Fig. 5(a) the modulating frequency is at 2804.273 MHz and the pulse width is approximately 35 ps, which corresponds to the combined effect of self-seeding in the FP laser diode and the active mode locking of the fiber ring laser. When the modulating frequency is set at 2804.223 MHz, the pulse width is increased to ~40 ps as shown in Fig. 5(b). A further increase in pulse width to ~65 ps is demonstrated in Fig. 5(c) when the modulating frequency is changed to 2804.173 MHz, where only the self-seeding operation takes effect. The pulse width can be compressed by a dispersion compensation fiber of 1706 m with a dispersion of

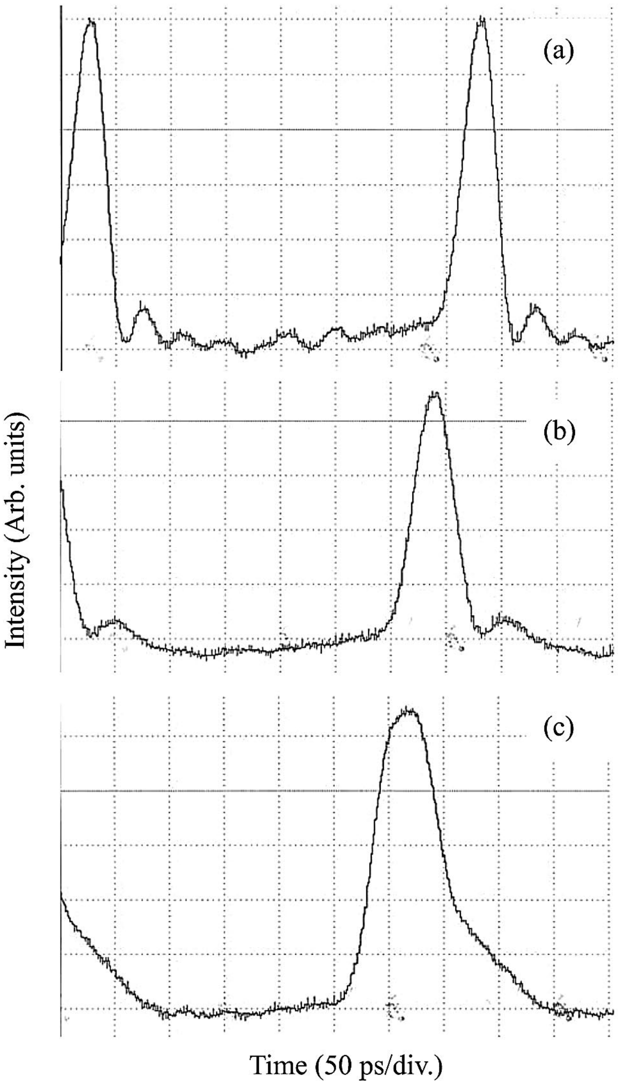

Fig. 5. Optical pulse trains at different modulating frequencies at (a) 2804.273, (b) 2804.223, and (c) 2804.173 MHz.

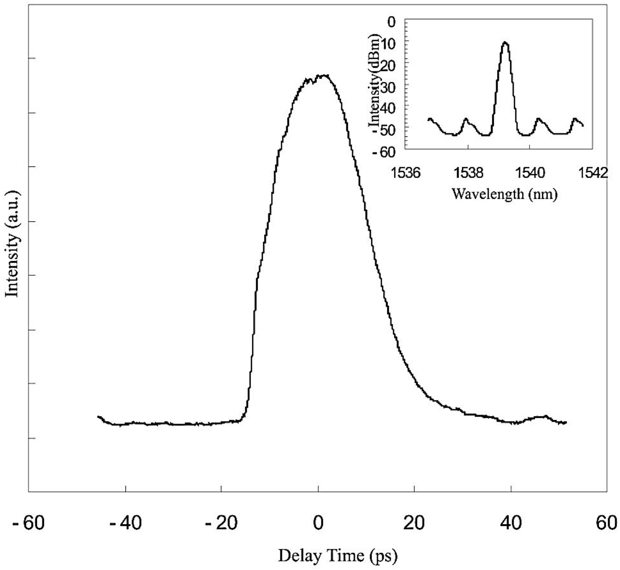

Fig. 6. Autocorrelation trace of active mode-locked pulses and the corresponding spectrum (inset) at 2804.273 MHz.

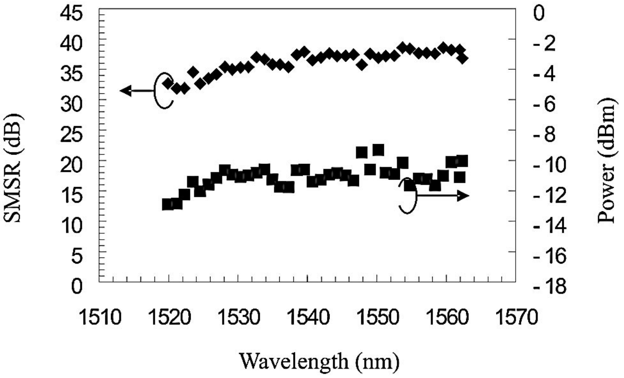

Fig. 7. Measured SMSR and the average power of the output pulses at different wavelengths.

−164 ps/nm at 1545 nm. The second-harmonic autocorrelation trace and the corresponding optical spectrum (inset) of the compressed active mode-locked pulse at a modulating frequency of 2804.273 MHz are displayed in Fig. 6. The FWHM value of the output pulse width becomes approximately 21.9 ps, and the corresponding spectral bandwidth is ~0.21 nm, which gives a time–bandwidth product of 0.57. The observed pulses exhibit a frequency chirp because the system output is a combined result of the active mode lock of the fiber ring laser and self-seeding operation of a FP laser diode. Such a chirp can be reduced, and a transform-limited pulse can be expected by using a more appropriate pulse compression scheme such as use of the exact calculated length of the dispersion-compensating fiber. The asymmetry of the pulse observed in Fig. 6 is due to the pulse width measured being on the edge of an autocorrelator resolution of 20 ps.

The SMSR and the average power of the output pulses obtained at different wavelengths are shown in Fig. 7. It can be observed from Fig. 7 that with an SMSR greater than 31 dB a wavelength-tuning range of more than 42.4 nm can be obtained, corresponding to the two wavelengths located at 1519.9 and 1562.3 nm. For an SMSR higher than 35 dB the wavelength-tuning range achieved is 34.2 nm, between 1528.1 and 1562.3 nm. The maximum wavelength-tuning range depends on the spectrum of the FP laser diode used and the EDFA gain at the selected wavelength. The wavelengths of the output pulses are also step tunable between the longitudinal modes of the FP laser diode. The value of the SMSR depends on the gain width of the laser diodes, the polarization states of the pulse trains, and the value of the EDFA gain.

5. Conclusion

Active mode-locking in combination with a self-seeding scheme has been demonstrated to produce wavelength-tunable optical short pulses. The mode-locked optical pulses exhibit a pulse width of 35 ps and can be compressed to 21.9 ps at a repetition frequency of close to 2.8 GHz. The wavelength-tuning range that can be achieved is 42.4 nm, corresponding to a SMSR of better than 31 dB. The system is simple and robust, and a stable active mode-locking optical short-pulse operation can be obtained.

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