# A Stable Smoothly Wavelength-Tunable Picosecond Pulse Generator

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***Abstract*—Smooth wavelength tuning over 10 nm has been realized in a dispersion-tuned harmonically mode-locked fiber ring laser. Supermode noise is suppressed by 13 dB by adding a semiconductor optical amplifier (SOA) into the cavity and the suppression improves as the SOA gain increases. 5.3-ps pulses are obtained at a repetition rate of 10 GHz. A simple numerical model demonstrates the effects of the intracavity dispersion and the SOA on the pulse characteristics.**

***Index Terms*—Mode-locked lasers, noise, optical fiber dispersion, optical fiber lasers, semiconductor optical amplifiers, wavelength tuning.**

## I. INTRODUCTION

WAVELENGTH-TUNABLE high-speed optical pulse generation is of great importance for testing and characterizing optical communication systems and components. Harmonically mode-locked fiber ring lasers (HMLFRLs) have proven to be able to generate widely wavelength-tunable picosecond pulses [1]–[4]. The most common way to achieve wavelength tuning in HMLFRLs is to change the center wavelength of a tunable filter inside the ring cavity [1], [2]. However, the modulation frequency has to be adjusted simultaneously in order to maintain stable pulsing due to intracavity dispersion [1]. This multiparameter tuning process is very complicated and thus not suitable for many applications.

Dispersion tuning has been proposed as an alternative way to realize tunable sources [3], [4]. The most remarkable feature of this technique is that it allows "smooth" wavelength tuning, which means that the oscillating wavelength can be continuously tuned by changing either the modulation frequency or the cavity length without interrupting the stable pulsing state. Although several dispersion-tuned HMLFRLs have been reported, little work has been done to address the important problem of supermode noise (SMN) in this type of mode-locked lasers [3]. This is partly because most SMN suppression techniques that have been widely used, such as soliton formation [5] and intracavity Fabry–Pérot filter [6], impose additional spectral restrictions, which conflict with dispersion tuning.

It has been pointed out that the fast gain saturation of semiconductor devices can be used to suppress SMN [7], [8]. In this letter, we report a dispersion-tuned HMLFRL incorporating a SOA as a SMN suppressor. We show that SMN suppression improves when the gain of the SOA increases. Single-parameter smooth wavelength tuning is achieved over a 10-nm range with little variations in the pulse temporal and spectral widths. The combined effects of the SOA and the intracavity dispersion on pulse characteristics are studied both experimentally and numerically.

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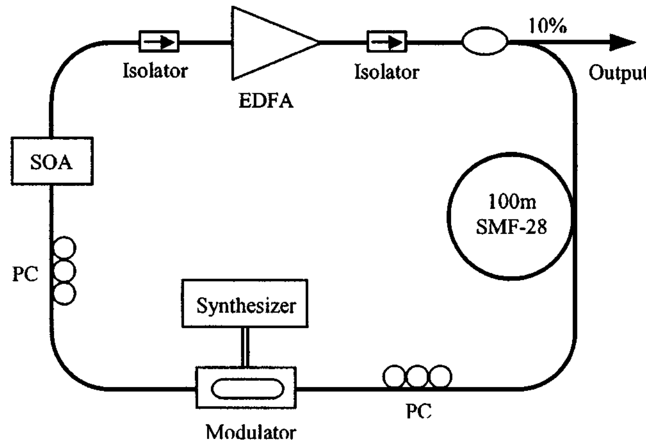


Fig. 1. The experimental setup.

## II. EXPERIMENT AND RESULTS

A schematic of the experimental setup is shown in Fig. 1. A commercial fiber-pigtailed SOA (Alcatel 1901), which has a typical small signal gain of 25 dB, a maximum bias current of 250 mA, and a measured transparency current of 24 mA, is used as a SMN suppressor. It is biased in its low-gain regime (60 mA) to prevent excessive nonlinear chirp. The majority of the total gain is provided by an erbium-doped fiber amplifier (EDFA). Its pump power is selected such that the average optical power inside the cavity is kept at a moderate value of 8.5 mW (measured right after the EDFA). A $LiNbO_3$ Mach–Zehnder intensity modulator is biased at its half-wave voltage (10.5 V) and driven by a synthesized microwave generator with 15-dBm RF power at 10 GHz. Intracavity group velocity dispersion is introduced by 100-m SMF-28 fiber, which has an anomalous dispersion parameter of 17.7 ps/(km·nm) at 1560 nm. Two Faraday optical isolators ensure the unidirectional cavity and a pair of polarization controllers (PCs) optimize the polarization orientation of the circulating pulses. Optical power is coupled out of the cavity by a 10% coupler. The total length of the cavity is about 150 m, giving a 1.38-MHz longitudinal mode spacing. Dispersion compensating fiber (DCF), which has a dispersion parameter of −88 ps/(km·nm), is used to compress the chirped output

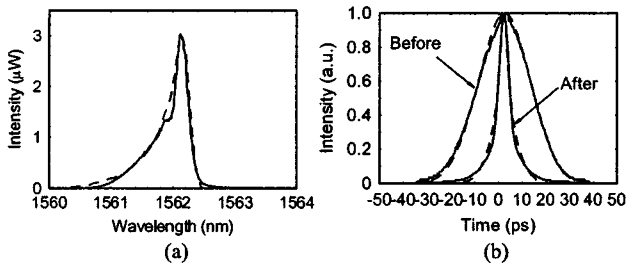


Fig. 2. Optical characteristics of the output pulses: (a) spectrum, (b) autocorrelation trace before and after pulse compression. The solid lines are experimental results and the dashed lines are simulation results.

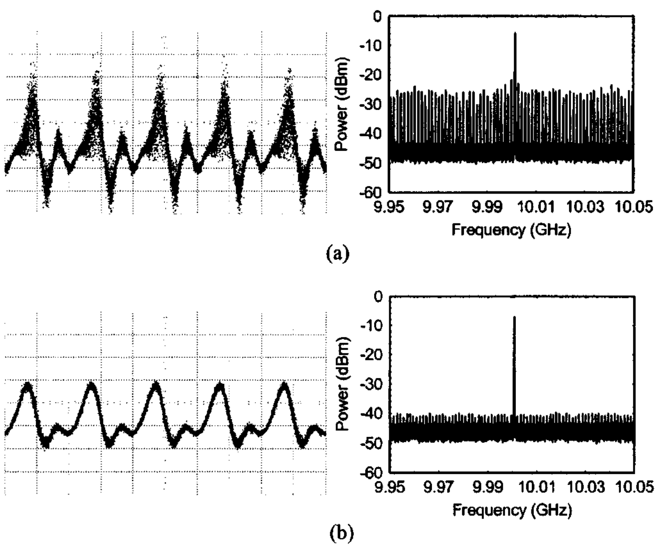


Fig. 3. Pulse intensity fluctuation and supermode noise. (a) Without the SOA. (b) With the SOA.

pulses. Note that there is no optical filter in the cavity because the intracavity dispersion functions as a self-tuned filter. The characteristics of the output pulses are monitored by a sampling oscilloscope, an optical spectrum analyzer and a RF spectrum analyzer. The pulse duration is measured by an autocorrelator.

A stable pulse train was obtained when the modulation frequency and the PCs were properly adjusted. Fig. 2 shows optical spectrum and the autocorrelation traces of the output pulses. A full-width at half-maximum (FWHM) pulsewidth of 26.4 ps and a 3-dB spectral width of 0.27 nm were measured at 1562 nm, giving a time bandwidth of 0.88. With 225-m DCF, the output pulses were compressed to 5.3 ps and the time-bandwidth product became 0.18, indicating that more power distributed on the spectral wings than Sech$^2$ pulses. The spectral shape results from the combination of the SOA and the anomalous dispersion. Its formation is demonstrated numerically in the next section.

To demonstrate the SMN suppression of the SOA, mode locking without the SOA was tested. The average optical power inside the cavity was kept at 8.5 mW by adjusting the pump power of the EDFA to eliminate the possible involvement of power-dependent fiber nonlinearities. The comparison of the sampling oscilloscope traces and the RF spectra with and without the SOA is shown in Fig. 3. It is clear that the SOA dramatically reduces the intensity fluctuation of the pulses. A

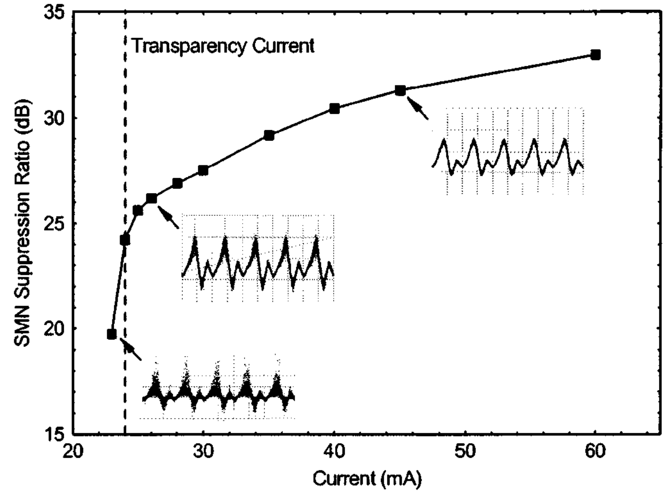


Fig. 4. SMN suppression ratios at different driving currents of the SOA (insets show the oscilloscope traces at 23, 26, and 45 mA).

33-dB SMN suppression ratio was measured with the SOA, about 13 dB larger than the ratio without the SOA. No pulse dropout was observed on the oscilloscope using color-grade measurement. Note that the distorted pulse shape on the oscilloscope results from the insufficient bandwidth of the photodetector (30 GHz).

The relation of SMN suppression and the SOA gain was investigated by changing the driving current of the SOA while keeping the average optical power inside the cavity the same. Fig. 4 shows the SMN suppression ratios at different SOA currents. The current was varied from 23 mA, which is slightly below transparency, to 60 mA. The sampling scope traces at 23, 26, and 45 mA are shown in the insets. It is evident that SMN suppression improves as the gain increases, especially when the SOA switches from absorption to gain regime. The SMN suppression ratio exceeds 30 dB at 40 mA, where the estimated small signal gain across the diode is 17 dB and the small signal gain of the EDFA is 23 dB.

Smooth wavelength tuning was realized by varying *only* the RF modulation frequency. When the frequency was increased, the spectral peak blue shifted, indicting an intracavity anomalous dispersion, and the oscilloscope trace remained still, indicating stable pulsing during the tuning process. The relation of the oscillating wavelength versus the modulation frequency is linear, with a measured slope of $-4.36 \times 10^{-5}$ nm/Hz, which is determined by the amount of dispersion inside the cavity. Based on this value, the total intracavity dispersion is 1.76 ps/nm, which includes the dispersion from the 100-m SMF-28, the pigtail fibers and the EDFA. The pulsing remained stable within a 10-nm (1559.4–1569.4 nm) span. This range is limited by the competition of the continuous-wave modes and the locked modes [4] and can be extended by allowing PC adjustment during the tuning process. In fact, with PC adjustment, a much broader wavelength tuning range was obtained (1556–1585 nm). The temporal and spectral widths of the output pulses were also found stable during tuning, as shown in Fig. 5.

The ability to self-tune the wavelength also ensures the long-term stability of the laser [3]. Stable pulsing was observed

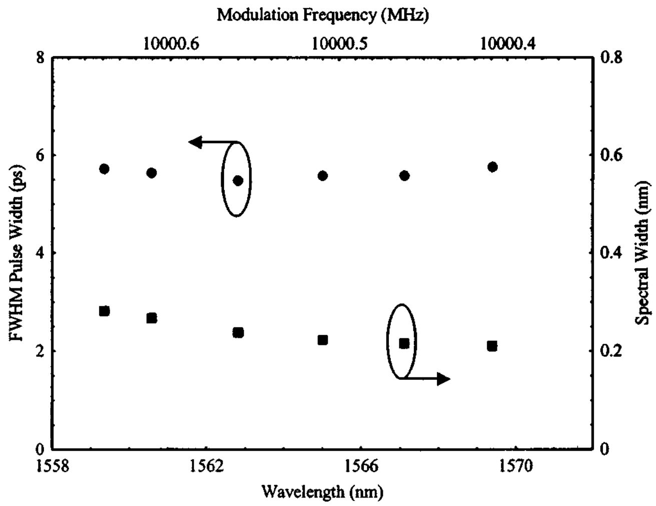


Fig. 5. Temporal and spectral widths versus the oscillating wavelength and the modulation frequency during wavelength tuning.

over a 5-h period. Only the PCs were adjusted occasionally to keep the locking state optimized. This is because of polarization fluctuation and can be prevented by using polarization-maintaining components [9] or a polarization insensitive modulator.

## III. Numerical Model

Numerical simulation has been carried out to study the combined effects of the SOA and the intracavity dispersion. The simulation is based on the Kuizenga–Siegman model [10]. The pulse duration is assumed much shorter than the carrier lifetime of the SOA so that the rate equation solution can be expressed analytically [11]. Saturation-induced self-phase modulation is taken into account by introducing a constant linewidth enhancement factor ($\sim$3). The small signal power gain across the diode is taken to be 21 dB. The EDFA is treated as a constant gain to balance the loss. Electrical field is amplitude-modulated at 10 GHz with a modulation depth of 0.9. The fiber loop is 150 m long, with a total dispersion of 1.76 ps/nm. Linear pulse compression is provided by DCF with a dispersion parameter of $-88$ ps/(km·nm). An arbitrary seed pulse is injected into the loop and the solution after each round trip is calculated until it becomes stable. The stable pulse solution has a FWHM of 26.6 ps and a 3-dB spectral width of 0.33 nm. The output pulse can be compressed down to 5.5 ps with 220-m DCF. The calculated spectrum has a similar shape with the measured one, as shown in Fig. 1(a), although slightly wider. The autocorrelation function of the numerical solution also shows good agreement with the experimental result in Fig. 1(b).

## IV. Conclusion

A stable smoothly wavelength-tunable picosecond-pulse generator has been demonstrated using a dispersion-tuned HMLFRL. SMN suppression is significantly improved (13 dB) by introducing an SOA into the ring cavity and the suppression increases as the SOA gain increases. 5.3-ps pulses are obtained at 10 GHz with pulse compression. Single-parameter wavelength tuning over 10 nm is achieved by varying the modulation frequency within a span of 0.25 MHz. Stable pulsing, as well as the temporal and spectral widths of the pulses, are preserved during tuning. A simple numerical model of the system shows good agreement with the experiment. At the end, we want to point out that this system can be readily transformed to a wavelength-scanable pulse generator by adding an electrical control of the modulation frequency or the cavity length. It produces a stable pulse train with changing color and should be able to find many applications in photonic testing.

## References

[1] Th. Pfeiffer and G. Veith, "40 GHz pulse generation using a widely tunable all-polarization preserving erbium fiber ring laser," *Electron. Lett.*, vol. 29, pp. 1849–1850, 1993.
[2] J. Li, P. A. Andrekson, and B. Bakhshi, "Direct generation of subpicosecond chirp-free pulses at 10 GHz from a nonpolarization maintaining actively mode-locked fiber ring laser," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1150–1152, Sept. 2000.
[3] S. Li and K. T. Chan, "Electrical wavelength tunable and multiwavelength actively mode-locked fiber ring laser," *Appl. Phys. Lett.*, vol. 72, pp. 1954–1956, 1998.
[4] Y. Zhao, C. Shu, J. H. Chen, and F. S. Choa, "Wavelength tuning of 1/2-rational harmonically mode-locked pulses in a cavity-dispersive fiber laser," *Appl. Phys. Lett.*, vol. 73, pp. 3483–3485, 1998.
[5] A. D. Ellis, R. J. Manning, I. D. Phillips, and D. Nesset, "1.6 ps pulse generation at 40 GHz in phaselocked ring laser incorporating highly nonlinear fiber for application to 160 Gbit/s OTDM networks," *Electron. Lett.*, vol. 35, pp. 645–646, 1999.
[6] J. S. Wey, J. Goldhar, and G. L. Burdge, "Active harmonic modelocking of an erbium fiber laser with intracavity Fabry–Perot filters," *J. Lightwave Technol.*, vol. 15, pp. 1171–1180, July 1997.
[7] S. Li and K. T. Chan, "Wavelength-tunable actively mode-locked erbium-doped fiber laser using a distributed feedback semiconductor laser as mode locker and tunable filter," *Appl. Phys. Lett.*, vol. 75, pp. 313–315, 1999.
[8] C. Wu and N. K. Dutta, "High-repetition-rate optical pulse generation using a rational harmonic mode-locked fiber laser," *IEEE J. Quantum Electron.*, vol. 36, pp. 145–150, Feb. 2000.
[9] H. Takara, S. Kawanishi, M. Saruwatari, and K. Noguchi, "Generation of highly stable 20 GHz transform-limited optical pulses from actively mode-locked Er3+-doped fiber lasers with an all-polarization maintaining ring cavity," *Electron. Lett.*, vol. 28, pp. 2095–2096, 1992.
[10] D. J. Kuizenga and A. E. Siegman, "FM and AM mode locking of the homogeneous laser—Part I: Theory," *IEEE J. Quantum Electron.*, vol. QE-6, pp. 694–708, Nov. 1970.
[11] G. P. Agrawal and N. K. Dutta, *Semiconductor Lasers*, 2nd ed. New York: Van Nostrand Reinhold, 1993, ch. 11.