40-GHz wavelength tunable mode-locked SOA-based fiber laser with 40-nm tuning range

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A 40-GHz wavelength tunable mode-locked fiber ring laser based on cross-gain modulation in a semiconductor optical amplifier (SOA) is presented. Pulse trains with a pulse width of 10.5 ps at 40-GHz repetition frequency are obtained. The laser operates with almost 40-nm tuning range. The relationship between the key laser parameters and the output pulse characteristics is analyzed experimentally.

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Optical pulse sources that generate stable picosecond pulses are being developed for a variety of applications, such as ultra-high-bit-rate optical communication systems, all optical signal processing, all optical logic circuits, as well as test and measurement systems[1−4]. Actively mode-locked lasers are promising candidates to generate picosecond pulses around 1550 nm at a high repetition rate, especially when synchronization between optical and electrical signals is required. Several technologies have been proposed to generate actively mode-locked pulse trains with high repetition rate based on mode-locking in monolithic laser diodes[5], and on active and hybrid mode locking of external semiconductor lasers[6]. Another promising technology to generate high repetition pulse train is based on mode-locking fiber ring laser with an active medium in the ring cavity, such as photonic crystal fiber[7], electro-absorption modulators (EAMs)[8], lithium niobate modulators[9], and semiconductor optical amplifiers (SOAs)[10−12], or combining two of them as a mode-locking element[13−15]. The mode-locking fiber ring laser can generate high quality pulse with picosecond and subpicosecond duration, and have a wide wavelength tunable span over several tens nanometers with commercial available and low cost devices, which is really important for engineering consideration. Since SOA can provide both gain over a broad wavelength range and modulation due to its fast gain and refractive index dynamics, it attracts great attention from researchers to use it in active mode-locking fiber ring laser cavity. The SOAs serve as a modulator in the cavity of the fiber ring laser based on cross-gain modulation or cross-phase modulation from an external optical signal. In order to use cross-phase modulation in fiber ring laser, additional complex devices, such as Mach-Zehnder interferometer integrated with SOAs is needed to realize phase modulation to amplitude modulation[16], which adds the complexity of the system and limits the application field of this scheme. So in most cases, the SOA-based modulator in fiber ring cavity is designed based on the cross-gain modulation phenomenon in SOAs. To generate high repetition rate, rational harmonic mode-mocking technology is often used. However, this kind of technology will introduce the difference in amplitude among pulses, and the stability of the pulse train from the fiber laser still needs to be improved for practical use[9].

In this paper, we present a 40-GHz mode-locked fiber ring laser with a nearly 40-nm tuning range, which uses external pulse to modulate the gain of SOA based on cross gain modulation. The central wavelength of the mode-locked laser can be tuned over the entire C-band from 1530 to 1570 nm, which is limited by the tunable span of the optical bandpass filter used in experiments. The pulse train with 12-ps pulse width, low timing jitter less than 150 fs, and up to 8.4 dBm of average output power is generated at 40 GHz. We generate external pulse train with high repetition frequency by multiplexing pulse train with low repetition frequency. By using the external pulse to modulate the gain medium of SOAs, the output pulses train is synchronized to the external pulse and it will be avoided to use expensive optic-electronic modulator and driving electronics with wide electronic bandwidth in the fiber ring cavity. We also analyze the relationship between various laser parameters and the output pulse characteristics. The experimental configuration is easy to setup with commercially available standard fiber pigtailed components.

Figure 1 shows the experimental configuration of the actively mode-locked fiber ring laser based on SOA. The

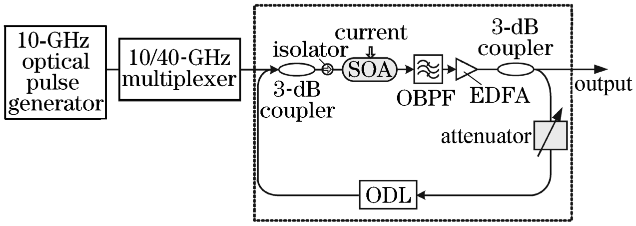

Fig. 1. Experimental setup of the actively mode-locked fiber ring laser based on cross-gain modulation in SOA.

gain is provided by the erbium-doped fiber amplifier (EDFA) with a saturation output power of 15 dBm. The EDFA used in our experiment is a commercial product with standard bench-top packet, which makes the fiber ring laser easy to setup. However, it also introduces some problems, such as unable to customize the gain and manage the dispersion in the cavity, which affects the output pulse quality. The SOA (CIP Company, UK) has a typical small signal gain of 32 dB at 200-mA current bias with an associated saturation output power of 10.4 dBm and a typical gain difference of 0.5 dB between TE and TM modes. In the setup, the SOA is used as an optically controlled mode-locker with 100-mA current bias. By the fiber-based 10/40-GHz multiplexer, 40-GHz optical pulse train is obtained by a 10-GHz optical pulse train. A 3-dB coupler, embodied in the cavity, couples the external pulse train into the fiber ring cavity. The tunable optical bandpass filter (OBPF) with a 3-dB bandwidth of about 1.5 nm and a 40-nm tunable span is employed to perform wavelength selection and tune the central wavelength of output pulse. The isolator in the fiber ring cavity is used to block the unidirectional operation of the laser. An attenuator is added in the cavity to change the net loss of the cavity and analyze the laser performance. An optical delay line (ODL) which can give a maximum tuning range of 300 ps is deployed in the cavity to adjust the cavity length to get high quality pulse output. It is also used to adjust the cavity length slightly to keep it constant during the process of tuning the central wavelength of filter. Another 3-dB coupler is used in the cavity to export the output pulses. At the output port, a 70-GHz sampling oscilloscope with a 50-GHz photodetector and an optical spectrum analyzer are used to measure the output pulse train.

In the absence of the external pulse, the fiber ring laser source operates in continuous-wave (CW) mode and the central wavelength of output CW light is tuned from 1530 to 1570 nm with almost constant 9.4-dBm output power across its tuning span. When the external pulse train with the power of 0.17 dBm with the central wavelength at 1551 nm is coupled into the cavity, the cavity length is tuned precisely by adjusting the delay time of the ODL to make a harmonic of the fiber ring laser. When the oscillator frequency equals the external pulse repetition rate, the ring laser source will break into stable mode-locked operation with 8.4-dBm output power, which is slightly lower than that in CW mode. Figure 2(a) shows the 40-GHz pulse train measured by a 70-GHz wideband sampling oscilloscope (CSA8000, Tektronix, USA) with a 50-GHz photodetector (XPDV 1020R, U^2T, Germany). The laser operates at 1540 nm and has a 10.5-ps pulsewidth. Figure 2(b) shows the corresponding optical spectrum of the pulse train, and for easy comparison the CW output spectrum is also presented in Fig. 2(b). The central wavelength of the output laser is 1539.7 nm and the −20-dB spectral width is about 0.837 nm, indicating that the output pulse is not transform-limited but a chirped one. Tuning the ODL, we can get several operation points where the stable mode-locked output pulse is generated in the full tunable span of the ODL with 25-ps intervals. To address the pulse quality, a 42.98-GHz radio frequency (RF) spectrum analyzer (E4447A, Agilent, USA) was used to measure the phase noise of the output pulse. Figure 3 shows the phase noise test result, and the signal-to-noise ratio (SNR) is about 48 dB with 1-Hz noise bandwidth. We also compared the phase noises of the external pulse and the output pulse, and they showed almost the same phase noise characteristics.

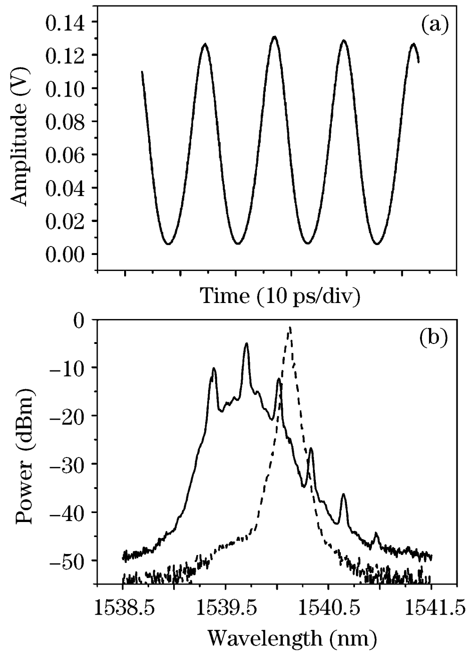

Fig. 2. (a) Output pulse train measured by a wideband sampling oscilloscope with a 50-GHz photodetector; (b) measured spectrum characteristics of the output 40-GHz pulse train of the actively mode-locked fiber ring laser (solid line) and the output spectrum when the laser operates in CW mode (dashed line).

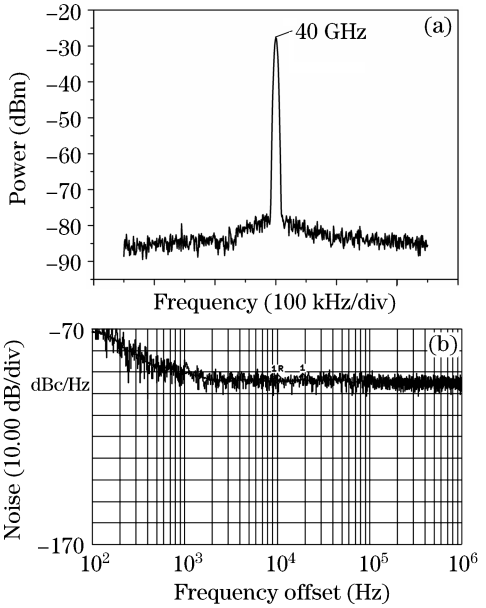

Fig. 3. (a) RF spectrum of the output pulse train after optical-electrical conversion by a 50-GHz photodetector; (b) phase noise of the output pulse train measured by a spectrum analyzer.

In order to test the fiber ring laser, we changed the cavity loss introduced by the optical attenuator deployed in the cavity, the input power of the external pulse sequence, and the central wavelength of the optical bandpass filter respectively. Figure 4 shows the change of the pulse shape with additional internal loss of cavity introduced by the attenuator. The laser works at 1540 nm and the input power of external pulse is 0.17 dBm. We can observe that the pulse shape keeps nearly constant with constant rise time, fall time, and pulsewidth, which means that the internal loss will not affect the pulse shape. Figure 5 shows the pulse shape changing with different input powers of external pulse. It is observed that by increasing the input power of the external pulse, shorter pulses are obtained from the SOA-based mode-locked fiber laser. This is the result of the stronger gain saturation imposed on the SOA by the external pulses. A deeper gain modulation will result in a narrow-pulse-width output. Figure 6 shows the wavelength tunability of the actively mode-locked pulse laser. Limited by the wavelength tunable span of the OBPF, a 40-nm wavelength tunable span is achieved. Theoretically, the tuning rage can be extended to cover the entire gain bandwidth of the SOA using present scheme. Because the wavelength of external pulse trains is centered at 1550 nm, the laser shows a narrow pulse width when it operates around 1550 nm. When increasing the operation wavelength, a tendency to wider pulse width is observed. The reason is that SOA shows a higher amplified spontaneous emission (ASE) noise at longer wavelength, which leads to a broadening pulse width.

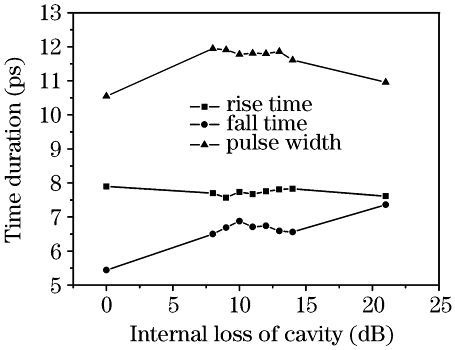

Fig. 4. Relationship between the pulse characteristics and the additional internal loss of cavity caused by the optical attenuator.

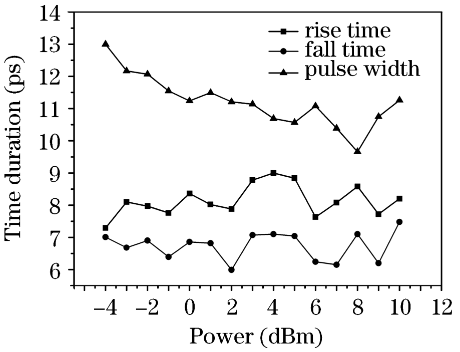

Fig. 5. Pulse characteristics versus the input power of external pulse.

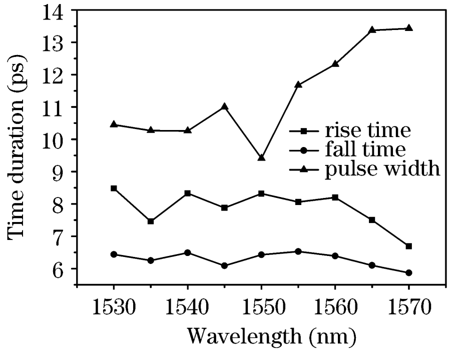

Fig. 6. Pulse train characteristics versus the central wavelength of the OBPF. The central wavelength of external pulse is around 1551 nm.

In conclusion, a 40-GHz actively mode-locked SOA-based fiber ring laser with an external pulse is presented in this letter. A 40-nm wavelength tunable span is achieved with a tunable optical bandpass filter. We also analyze how the key parameters of laser, such as internal cavity loss and external power input, affect the output pulse train characteristics. All the results in this paper are achieved without precise adjustment, and it is believed that high quality pulses will be obtained with further optimization, included precise designing the cavity length, the dispersion management, and also a temperature stabilizer.

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