Broadly Tunable SOA-Based Active Mode-Locked Fibre Ring Laser by Forward Injection Optical Pulse

YAN Shuang-Yi(延双毅)1,2**, ZHANG Jian-Guo(张建国)3, ZHAO Wei(赵卫)1, LU Hong-Qiang(陆红强)1,2, WANG Wei-Qiang(王伟强)1

1 State Key Laboratory of Transient Optics and Photonics, Xi’an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi’an 710119
2 Graduate School of Chinese Academy of Sciences, Beijing 100039
3 Department of Electrical, Computer and Communications Engineering, London South Bank University, 103 Borough Road, London SE1 0AA, UK

(Received 2 April 2008)

We present a broadly tunable active mode-locked fibre ring laser based on a semiconductor optical amplifier (SOA), with forward injection optical pulses. The laser can generate pulse sequence with pulsewidth about 12 ps and high output power up to 8.56 dBm at 2.5 GHz stably. Incorporated with a wavelength-tunable optical bandpass filter, the pulse laser can operate with a broad wavelength tunable span up to 37 nm with almost constant pulsewidth. A detailed experimental analysis is also carried out to investigate the relationship between the power of the internal cavity and the pulse width of the output pulse sequence. The experimental configuration of the pulse laser is very simple and easy to setup with no polarization-sensitive components.

PACS: 42.55.Wd, 42.55.Px, 42.60.Fc

Short pulsewidth pulse lasers are key elements for the WDM/OTDM networks. Actively mode-locked fibre ring lasers based on semiconductor optical amplifier (SOAs) are promising candidates to generate picosecond pulses around 1550 nm at a high repetition rate, which can easily realize synchronization between optical pulses and electrical signals. Use of an SOA as an active medium in the fibre ring cavity is really attractive for its high nonlinear effect and wide gain span. Several technologies have been proposed to generate active mode-locked pulse trains with high repetition rate with embodied modulator in the cavity, such as electro-absorption modulator (EAM),[1] LiNbO3 Mach–Zehnder modulator,[2] or direct modulate the injection current of the SOA;[3] or with external pulse trains to modulate the gain material of SOA based on cross gain modulation,[4,5] or cross phase modulation.[6] The embodied modulator in the cavity will enable the lasers to have a compact structure, but the modulator will affect the cavity operation state. For example, the EAM in the cavity will introduce a big loss in the cavity and the Q-switching effect tends to saturate the EAM and prevent it from mode-locking the laser.[1] LiNbO3 Mach–Zehnder modulators show a polarization sensitive characteristic, to make the laser realize mode-locking and operate stably cumbersome polarization controlling device is necessary in the cavity. Due to SOA’s high nonlinear property, the external pulse sequence can easily modulate the gain material of SOA at a high speed by cross gain modulation (XGM) and cross phase modulation (XPM). For the XPM scheme, a Mach–Zehnder interferometric structure setup is required to convert the phase variation to amplitude variation to realize mode-locking. The experimental setup is polarization sensitive and need to be integrated for stable operation. Compared to the XPM scheme, the XGM of SOA is independent of the polarization states of the input light and has a very simple experiment setup. Thus the favourable method to achieve active mode-locked fibre ring lasers is based on XGM of the SOA with external pulse sequence.

For most cases of SOA based active mode-locked fibre ring lasers with external pulses, they operate with a backward injection pulse, which will cause harmful reflection from the cavity and need additional isolators to protect the external pulse generator. The experimental setup will leak cavity power at the input port of the external pulse, which lowers down the efficiency of the mode-locked laser.

In this Letter, we demonstrate a broadly tunable SOA based fibre ring laser with forward inject pulse sequence with a simple experimental setup, which are composed of all commercial available pigtailed components, and even a commercial EDFA with standard bench-top packet in the cavity. Incorporating a high nonlinear SOA with low polarization dependent gain and no polarization sensitive components, the experimental setup is insensitive to the polarization. Without any pulse compression, a pulse sequence with 12 ps
pulsewidth at 2.5 GHz repetition frequency is achieved with an external pulse sequence, which is generated by modulating the cw laser by a LiNbO$_3$ Mach–Zehnder modulator. By embedding an optical band pass filter in the fibre ring cavity, the mode-locked laser can realize a wide wavelength tunable span more than 37 nm continuously. In the experiment, we find the power in the cavity pose a great effect to the pulse shape, especially the pulsewidth of the generated pulses. Thus some experimental researches are carried out to investigate the relationship between the pulsewidth and the internal power of cavity.

![Fig. 1. Experimental setup of the actively mode-locked fibre ring laser based on SOA. OBPF: optical bandpass filter; EDFA: erbium-doped fibre amplifier; VOA: variable optical attenuator; ODL: optical delay line.](image)

Figure 1 shows the experimental configuration of the active mode-locking fibre ring laser based on SOA. The external pulse is generated by modulating the cw light with a LiNbO$_3$ Mach–Zehnder modulator driven by 2.5 GHz radio frequency with power about 7.4 dBm. After amplified by an EDFA, the external pulse sequence is coupled into the cavity by a 3 dB coupler. An isolator is used to block the unidirectional operation of the laser. In the experimental setup, the operation direction of the mode-locked laser is the same as the propagation direction of external pulse, which eliminates the additional loss due to leaking power out of cavity from the input port of the external pulse. Then an SOA is used as an optically controlled mode-locker based on XGM. The SOA (CIP Company, United Kingdom) 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. Then a wavelength tunable optical bandpass filter (OBPF) with a 3 dB bandwidth about 1.5 nm and a 40 nm tunable span is employed to perform wavelength selection and tune the central wavelength of output pulse. Due to its narrow bandwidth, it causes a big loss in the cavity. An EDFA is used to compensate for the cavity loss and offer the gain in the cavity. The EDFA we used in our experiment is a commercial product with standard bench-top packet, which makes the fibre ring laser very easy to setup. The high gain of EDFA makes high output power of the generated pulses possible. However, it also introduces some problems, such as unable to customize the gain and manage the dispersion in the cavity precisely, which will affect the output pulse quality. A 3 dB coupler couples some part of the power as the output of mode-locked laser and couples remain power back to the cavity. A variable optical attenuator (VOA) is incorporated in the cavity to control the internal loss of cavity. An optical delay line with a maximum tuning range of 300 ps is used in the cavity to adjust the cavity length in order to obtain 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 OBPF. The length of the cavity is about 41 m and has a fundamental frequency about 4.9 MHz. Based on the rational harmonic mode locking technology, a 2.5 GHz pulse sequence is obtained. At the output port, a 70 GHz sampling oscilloscope with a 50 GHz photodetector, an optical spectrum analyser and a signal spectrum analyser are used to measure the output pulse train.

![Fig. 2. (a) Output pulse train measured by a wideband sampling oscilloscope with a 50 GHz photodetector. The input pulse train is presented in the inset for comparison. (b) Single output pulse curve.](image)

In order to tune the output wavelength continuously in a large span, we set the wavelength of the external pulse at 1568 nm, where the external pulse can be amplified by the EDFA (we need adequate power to modulate the gain medium of the SOA). In this wavelength region, SOA shows a high gain level, so it is easy to modulate the gain material with external
pulses, which is verified by our experimental results. With this setup, we can tune the wavelength of output pulse continuously from 1528 nm to 1565 nm, which is limited by the tunable span of the optical bandpass filter used in our experiment. In the absence of the external pulse, the fibre ring laser source operation in cw mode and is tuned from 1530 to 1570 nm with almost constant 10.46 dBm output power across its full tuning span. When the external pulse train with the power of 6.13 dBm with central wavelength at 1568 nm is coupled into the cavity, the cavity length is tuned precisely by adjusting the delay time of the optical delay line to make a harmonic of the fibre ring laser oscillator frequency equal to the external pulse repetition rate, and the ring laser source will break into stable mode-locked operation with power about 9.13 dBm, which is slightly lower than the output power when laser operates in cw mode. The laser operates at 1545 nm and has a 12 ps pulsewidth without any pulse compression progress. Figure 2(a) shows the 2.5 GHz pulse train measured by a wideband sampling oscilloscope of 70 GHz (Tektronix CSA8000) with a 50 GHz photodetector (U2T model number XPDV 1020R). For comparison, the input pulse is also shown in the inset of Fig. 2(a). In Fig. 2(b), we show the single pulse form by solid line and the Gaussian fitting curve by dotted line. The output pulse show a good amplitude jitter with a clear waveform and the time jitter of the generated pulses is less than 150 fs. Figure 3 shows the corresponding optical spectrum of the pulse train in solid line measured by an optical spectrum analyser with a 0.05 nm resolution. The cw output spectrum is also presented in Fig. 3 by the dotted line for comparison. The central wavelength of the output pulses is 1545.35 nm with a 3 dB bandwidth about 0.322 nm, indicating that the output pulse is not transform-limited pulse and the pulse is chirped. Thus the pulsewidth can be further compressed if a pulse sequence with much narrower pulsewidth is required. To address the pulse quality, a 42.98 GHz rf spectrum analyser (Agilent E4447A) is used to measure the phase noise of the output pulse. In Fig. 4, the phase noise test result is presented and the signal-to-noise ratio we measured is more than 50 dB.

To explore the wavelength tunability, we measure the pulse output with different central wavelengths. Figure 5 shows the relationship between the pulsewidth and the central wavelength of the output pulse sequence. We can observe from Fig. 4 that in a long wavelength tunable span up to 37 nm the pulsewidth of output pulses keep almost constant around 12 ps. At 1565 nm the pulsewidth shows an increasing trend, and the reason is that when the central wavelength of filter go close to the external pulse, it will leak some power of external pulse into the circle ring, which will destroy the mode-locking condition and will cause the broaden of the output pulse.

Due to the unequal gain of SOA among such wide wavelength span, the ASE noise power of SOA, which is filtered to form mode-locked pulses in our experiments, will vary in different wavelength region. In order to obtain stable output pulses, the power in the cavity should be control precisely.

Fig. 3. Spectrum characteristics of the output pulse train of the active mode-locked fibre ring laser (solid line) and the spectrum of the cw output (dotted line) when the laser operates in cw mode.

Fig. 4. Phase noise of the output pulse trains measured by an Agilent performance spectrum analyser.

There are many factors affect the power of the cavity, such as the injection current of SOA, the gain of SOA, the additional cavity loss, and the input power of external pulse. In principle, the mode-locking pulsewidth is directly proportional with \((g_0)^{1/4}/(\delta^2 \cdot f_m^2 \cdot \Delta \nu^2)^{1/4}\), where \(f_m\) denotes the modulation frequency, \(\Delta \nu\) represents gain bandwidth of SOA, \(g_0\) is single-pass integrated gain of SOA, and \(\delta\) denotes the modulation depth.\(^7\) In our experimental setup, the modulation frequency and the gain bandwidth of SOA are fixed. Thus only \(g_0\) and \(\delta\) can be adjusted to optimize pulse quality of the generated pulse sequence. In our experiment, we vary the power of the external pulses and the internal cavity loss (gain) to adjust the performance of the mode-locked pulse laser.
Fig. 5. Pulsewidth of the generated pulse train versus the central wavelength of output laser sequence. The central wavelength of external pulse is around 1568 nm.

Fig. 6. Pulsewidth of the generated pulse train versus the internal power of cavity with different input power of external pulse.

The external pulse can suppress the ASE noise of the SOA and a high input power will consume a huge quantity of the carriers heavily and cause a low ASE level at the desired output wavelength of laser, which means low cavity energy. The power of the external pulse will affect the modulation depth and the internal loss in the cavity. In order to monitor and tune the internal power of cavity in real time, we add a 95:5 coupler and a variable optical attenuator at point A in Fig. 1. Figure 6 show the result of different pulsewidth versus the internal power of the cavity with different input power of external pulse sequence. A high cavity power means a high single-pass gain in the cavity, which will lead to wide pulsewidth. Simply put, a broader pulsewidth is obtained with high internal cavity power due to the mode-locking progress cannot lock all the energy of the cavity, so the remnant energy cause long tail of the pulse. On the other hand, too low cavity power will prohibit it from forming the mode-locked pulse. In the experiment we find that cavity power about 1 dBm is an appropriate power level to form a stable mode-locked pulse output. Without any polarization sensitive components, the mode-locked laser operates stably in long period.

In summary, a broadly tunable SOA-based active mode-locked fibre ring laser by forward injection optical pulse is demonstrated in this study. Without any pulse compression installation, a pulse sequence with 12 ps is obtained with a sample experimental setup. The laser is setup without any polarization sensitive components, which make it operate stably in long period. With an optical bandpass filter, we achieved a 37 nm wavelength tuning span from 1528 to 1565 nm continuously. A detailed analysis of energy in the cavity is done to investigate how to obtain stable output pulse sequence.

References