Characteristics of active mode-locked fiber ring laser based on semiconductor optical amplifier

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ABSTRACT

An active mode-locked fiber ring laser based on XGM in SOAs is demonstrated with an external pulse sequence. The laser operates at a variable repetition rate from 1GHz to 15GHz, even up to 40GHz with an additional fiber-based multiplexer. By a wavelength tunable filter, a wide wavelength tunable span about 37nm is achieved continuously between 1528nm to 1565nm. Without any pulse compression device, the pulse sequence with low pulsewidth about 12ps and high output power about 9dBm can be obtained in different operation repetition rate. The output pulses show a time jitter lower than 180fs in all operation repetition rate. A detailed analysis is done experimentally to investigate the relationship between parameters of the SOA-based fiber ring laser and pulsewidth of the generated mode-locked pulses.

Keywords: mode-locked lasers, wavelength tunable, repetition tunable, semiconductor optical amplifier

1. INTRODUCTION

Optical sources that capable of generating short pulse trains at high repetition rates are key elements for high-speed optical communication systems. A variety of applications have been developed, such as all optical logic circuits\textsuperscript{[1]}, all optical signal processing\textsuperscript{[2]}, ultrahigh-speed OTDM transmission systems\textsuperscript{[3]}, as well as test and measurement systems\textsuperscript{[4]}. In all these applications, the synchronizations between the optical pulses and the electronics signal are very important. As a promising candidate, actively mode-locked lasers can generate picosecond pulses at a high repetition rate, which can be easily synchronized to electrical signals. Several technologies are proposed to generate active mode-locked pulse trains based on mode-locking in monolithic laser diodes\textsuperscript{[5]}, on active and hybrid mode locking of external semiconductor lasers\textsuperscript{[6]} and on mode-locked solid state lasers\textsuperscript{[7]}. Another promising technology to generate high repetition pulse trains is based on active mode-locking fiber ring laser with active media in the ring cavity. The mode-locking fiber ring lasers show some excellent advantages, such as capability to generate high quality pulse with picosecond and subpicosecond duration, wide wavelength tunable span over several tens nanometers. The mode-locked fiber lasers have a compact size and simple setup with commercial available and low cost devices, and it also shows a great potential to be integrated in a monolithic chip in future. These features make mode-locked fiber ring laser a potential candidate of pulse lasers for engineering application. Several mode-locked fiber laser are demonstrated with some active media, such as electro-absorption modulators (EAMs)\textsuperscript{[8]}, lithium niobate modulators\textsuperscript{[9]} and Semiconductor optical amplifiers (SOAs)\textsuperscript{[10,11]}, or combine two of them as a mode-locking element\textsuperscript{[12,13]}. Because SOA can provide both gain over a broad wavelength range and modulation due to its fast gain and refractive index dynamics, it is really attracting for researchers to use it in the cavity of the active mode-locking fiber ring laser as an active mode-locking element. The SOAs serve as a modulator in the cavity of the fiber ring laser based on cross-gain modulation or cross-phase modulation phenomenon. Generally speaking, in order to use cross-phase modulation in fiber ring laser, additional complex device, such as Mach-Zehnder interferometer with integrated SOAs is need to realize the phase modulation to amplitude modulation\textsuperscript{[14]}, which adds the

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complexity of the system and limits the application field of this scheme. However, the mode-locking technologies based on XGM scheme show a simple experimental setup and allow easy wavelength tuning over the whole SOA gain region. Therefore, in most case the SOA-based modulator in fiber ring cavity is designing based on the cross-gain modulation (XGM). With external pulse sequence, the optical control mode-locker can operate in high repetition rate with limited bandwidth of commercial modulators and driving electronics device.

In this paper, an active mode-locked fiber ring laser based on XGM in SOAs is demonstrated with an external pulse sequence, which is generated by modulating the CW laser with a LiNbO3 Mach-Zehnder modulator driven by a frequency tunable synthesizer. Without any pulse compression device, the pulse sequence with pulsewidth about 12ps and high output power about 9dBm is achieved in different operation repetition frequency. By embodying an optical tunable bandpass filter, the lasers operate with a wide wavelength tunable span up to 37nm. With a few adjustments, the mode-locked laser can vary its operation repetition rate in a wide frequency span from 1GHz to 15GHz. Multiplexing the external source with a fiber-based multiplexer, a 40GHz pulse sequence is also generated with a wide wavelength tunable span. The output pulses show a time jitter lower than 180fs in all operation repetition rate. Experimental analyses have been done to investigate the relationship between various parameters of SOA-based fiber ring laser and the characteristics of the output pulse sequences. The mode-locked laser is easy to setup with all commercial available products. No polarization-sensitive components are integrated in the cavity for long term stability.

2. EXPERIMENT SETUP AND RESULTS

Figure 1 shows experimental configuration of the active mode-locking fiber ring laser based on SOA. The external pulses are generated by modulating the CW light with a LiNbO3 Mach-Zehnder modulator driven by a frequency tunable synthesizer. The pulsewidth of the external pulse is about 30ps and the repetition frequency can be tuned from 1GHz to 15GHz by tuning the frequency of the synthesizer. After amplified by an EDFA, the external pulse sequence is coupled into the cavity by a 3dB coupler. An isolator is used to ensure the unidirectional operation of the laser. In the experimental setup, we set the operation direction of the mode-locked laser is the same as the propagation direction of external pulse, which eliminate additional loss due to leaking power out of cavity from the input port of the external pulse. Then a SOA act as an optically controlled mode-locker based on cross gain modulation. The SOA (CIP Company, United Kingdom) has a typical small signal gain of 32dB at 200mA current bias with an associated saturation output power of 10.4dBm and a typical gain difference of 0.5dB between TE and TM modes. Then a wavelength tunable optical bandpass filter (OBPF) with a 3dB bandwidth about 1.5nm is employed in the cavity to perform wavelength selection and tune the central wavelength of output pulse. An EDFA is used to compensate the 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 make 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 precisely, which will affect the quality of the output pulse. A 3dB coupler couples some part of the power as the output of mode-locked laser. A variable optical attenuator is incorporated in the cavity to control the internal loss of cavity. An optical delay line which could give a maximum tuning range of 300ps is used in the cavity to adjust the cavity length finely in order to get high quality pulse output. It was also used to adjust the optical length of the cavity slightly to keep it constant during the process of tuning the central wavelength of filter. The length of the cavity is about 41m and has a fundamental frequency of \( f_c \approx 4.9\text{MHz} \). The length of cavity could be significantly reduced and improve the performance of long term stability. Based on the rational harmonic mode locking technology, a pulse sequence with the same repetition frequency as the external pulse is obtained when the external pulse repetition is close to an integer times of \( f_c \). This can be done by slightly fine-tuning the optical delay line in the cavity or tuning the repetition frequency of external pulse. At the output port, a 70GHz sampling oscilloscope with a 70GHz photodetector and an optical spectrum analyzer are used to measure the output pulse train. An radio frequency analyzer is also used to measure the performance.

In order to tune the output wavelength continuously in a larger span, we set the wavelength of the external pulse at 1568nm, where the pulse can be amplified by EDFA (we need adequate power to modulate the SOA gain material) and the SOA shows a high gain level in this wavelength region, so it’s easy to modulate the gain material in here, which is also verified by our experiment. With this setup, we can continuously tune the wavelength of output pulse from 1528nm 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 fiber ring laser source operation in CW mode and is tuned from 1528 to 1570nm with almost constant 10.46dBm output power across its 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, tune the cavity length precisely by adjusting the delay time of the optical delay line to make a harmonic of the fiber 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 9.13dBm, which is slightly
lower than the output power when laser operates in CW mode. The laser operates at 1545nm and has a Gaussian-like pulse about 12ps without any pulse compression progress. Figure 2(a) show the Gaussian-like pulse in 2.5GHz. The repetition frequency of the generated pulse sequence can be tuned by adjusting the frequency of the synthesizer from 1GHz to 2.5GHz. Figure 2(b) present the relationship between the pulsewidth of output pulse and the operation repetition frequency of the mode-locked fiber laser. It can be observed in Figure 2(b) that the pulsewidth of output pulses keep almost constant around 12ps from 2.5GHz to 15GHz. At different repetition frequency, the power in the cavity should be controlled precisely to get high quality pulse. At low repetition frequency, a low cavity power is required to obtain pulses with narrow pulsewidth. Excessive power in the cavity will cause the long tail of the pulse and broaden the pulsewidth. When increasing the gain level in the cavity, such as increasing the injection current of SOA up to 200mA, pulse sequences with twice or triple of external pulse frequency are observed with 10GHz external pulse sequence. This characteristic could be used to develop high repetition rate pulses [15]. However, the pulse sequences show an obvious amplitude variation, which is caused by the different positions of the phase shifted pulses [16]. In addition, the rational harmonic pulse sequences are more unstable, and little perturbations may result pulsetrain loss [15]. For these reasons, in the follow part we will focus on the harmonic mode-locked pulse with same repetition frequency as the external pulse.

When much higher repetition frequency pulse sequences are required under some special conditions, we can easily increase the repetition frequency by multiplexing the external pulse. Based on a simple fiber-based multiplexer, a 40 GHz pulse sequence with pulsewidth about 12ps is also obtained with a 40GHz external pulse sequence multiplexed based on 10GHz pulse source. The output pulses show a good jitter performance and the RMS jitter of variable repetition rate pulses keep below 180fs. The phase noise of the 10 Gzh pulse is presented in Figure 3 and the signal-to-noise ratio we measured is more than 50 dB. The time jitter is about 150fs, which we calculate by integrating from 3 Hz to 100 MHz.

By tuning the central wavelength of the OBPF, the central wavelength of output pulse sequences can be adjusted in a wide span. Figure 4 shows the pulsewidth of the pulses at different central wavelength in different repetition rate. In full wavelength tunable span, the pulsewidth keeps almost constant, which is limited by the bandwidth of OBPF we used in the cavity. The bandwidth of the OBPF we used is about 1.5nm and the 3dB bandwidth of the output pulse is show in Figure 5, and the time-bandwidth product is also presented for comparison. The output Gaussian-like pulse is far from the transform-limited pulse and can be further compressed to much narrower pulse sequence if ultrashort pulses are required.

The mode-locked fiber lasers have a high output power about 9.13dBm. This feature makes the laser can be used in the network without additional EDFA. Because the feedback power needed in the cavity is small, the output power of mode-locked laser can further increase with a couple-ratio tunable coupler, which deliver more power to output port and less power to the cavity.

For long term stability, the locking bandwidth is an important factor for mode-locked laser. Figure 6 shows the output pulses when detuning the external pulse repetition rate away from the harmonic frequency of cavity of the mode-locked laser from 0 to 60MHz. It can be observed in figure 6 when the detuning up to 10MHz, the peak power of the output pulses decrease and strong amplitude jitter appears. The active mode-locked fiber ring laser show similar locking bandwidth performance in all operation frequency rates, due to the same cavity configuration.

### 3. The Characteristics of Mode-Locked Fiber Ring Laser

Pulsewidth is a key parameter of the mode-locked fiber ring laser. Under some application occasions, the pulsewidth of pulses needs to be specially designed. So in this part we will discuss the factors which affect the pulsewidth of the mode-locked pulses.

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 [17]. This relationship is deduced from the mode-locked fiber lasers which use SOA as both mode-locker and gain provider. However, this relation can also be applied into our mode-locker fiber ring laser, which is verified by experimental results. In our experiment, only is different from the definition of $\delta$ and it is decided by the SOA, the EDFA and the VOA used in the cavity.

The modulation frequency is decided by the external pulse sequence. It is observed in Figure 4 that a higher repetition rate lead to a narrower pulsewidth. The gain bandwidth of SOA is limited by the optical bandpass filter, which is fixed at 1.5nm in all our experiment.

For the modulation depth, it could be changed by varying the characteristics of the external pulse, such as wavelength, pulsewidth and waveform. At first, we adjust the central wavelength of the external pulse, which would
affect the modulation depth. Figure 7 show the relationship between the pulsewidth of 10GHz pulse sequence and central wavelength of the external pulse in black line with solid symbols. For comparison, the amplified spontaneous emission noise of the SOA is show in the picture in red line. It’s easy to observe that with increasing the wavelength of the external pulse much narrower pulsewidth is obtained. The SOA shows an unequal gain among its gain span, and a high ASE noise level means a high gain of SOA. With equal input power, higher gain leads to deeper modulation due to more consumption of the carrier. So for high efficiency modulation, the wavelength of external pulse should fix in long wavelength, where has a high ASE level. Given the gain bandwidth of the EDFA, we set the wavelength of the external pulse at 1568nm.

Then we adjust the bias voltage of the modulator to change the waveform of the input pulses. Figure 8(a) show the relationship between the pulsewidth and the bias voltage of the modulator. In figure 8(b) we present the shape of the pulse for comparison. The narrowest pulsewidth is achieved at bias voltage 3.93V and the corresponding external input pulse is prominent in red line. So a special design pulse shape can narrow the open time window of the mode-locker and help to build up pulse with narrow pulsewidth. With optimization, the narrow pulse with pulsewidth about 11ps and optical spectrum bandwidth about 0.35nm is achieved without any pulse compression devices. Beside these internal parameters, we also analyze the influence of some external parameters of the mode-locked laser, such as the injection current of SOA, the input power of external pulse and the internal loss of the cavity on the pulsewidth of the mode-locked pulses. These parameters affect the pulsewidth in a composite way. The mode-locking process need to lock the internal energy of the cavity into pulses to achieve stable and short pulse. When excessive energy enters in the cavity, the mode-locking process can’t lock all the energy into the pulse and the redundant energy will cause long tail of the pulse and broaden the pulsewidth of the generated pulse.

Figure 9 shows the relationship between the pulsewidth and the internal power of the cavity with different power of external pulse in 2.5GHz. The external pulse can suppress the gain of SOA and lower the ASE level in rest of wavelength, which will decrease the gain and modulation depth of the SOA. However, too low cavity power will make the mode-locked process difficult to build up. Generally, a relative high cavity energy will required for the high repetition frequency lasers. So the power in the cavity should be optimised for different operation repetition frequency. For the injection current of SOA, it can affect the gain and the modulation efficiency of SOA. Figure 10 shows the experiment results about the relationship between the pulsewidth of output pulse and the injection current. It can be observed that pulsewidth of the output sequences keep almost constant in a wide tunable span. With a 30ps external pulse, the gain of SOA is clamped. So the pulsewidth of the mode-locked laser keep almost constant with increased injection current.

In mode-locked fiber ring lasers, there are still many factors which affect the quality of generated pulse, such as the nonlinear effect in SOA, the carrier recovery time of SOA, etc. The related work will be done and reported in the future.

4. CONCLUSIONS

In this paper, an SOA-based active mode-locked fiber ring laser with forward injection optical pulses is demonstrated with a wide wavelength tunable span at variable repetition frequency from 1 to 15GHz, and even up to 40GHz. The wavelength tunable span covers almost C-band from 1530 to 1565nm. A high output power up to 9dBm is obtained, which make additional EDFA is unnecessary for applications in real networks. An experimental analysis about the pulsewidth of the generated mode-locked lasers is done in variable repetition frequency and different operation conditions. In the experiment setup, all the components are commercial available products with standard pigtail fiber, which make the laser easy to setup and maintain. By incorporating an optical delay line, the precision calculating the length of cavity becomes unnecessary. No polarization-sensitive component is embodied in the cavity, which ensures the laser could operate stably in a long term.

5. REFERENCE

Figure captions

**Fig. 1.** Experimental setup of the actively mode-locked fiber ring laser based on SOA: OBPF: optical bandpass filter; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; ODL: optical delay line.

**Fig. 2(a)** Single output pulse at 2.5GHz.

**Fig. 2(b)** Relationship between the pulsewidth of output pulse and the operation repetition rate of the mode-locked fiber laser.

**Fig. 3** Phase noise of the 10GHz output pulses measured by an Agilent performance spectrum analyzer.

**Fig. 4** Pulsewidth vs the central wavelength of output pulses.

**Fig. 5** Bandwidth of output pulse sequence and the time-bandwidth product at variable repetition frequency.

**Fig. 6** Output pulses with different detuning between the repetition rate of external pulse sequence and the harmonic frequency of the mode-locked laser.

**Fig. 7** Pulsewidth of the generated pulse VS the central wavelength of the external pulse in black line; the ASE noise of SOA is presented in red line for comparison.

**Fig. 8(a)** Pulsewidth of the generated pulse with different external pulse shape by varying bias voltage of the LiNbO3 Mach-Zehnder modulator.

**Fig. 8(b)** Pulse shape of the external pulse generated by the LiNbO3 Mach-Zehnder modulator with different bias voltage. The red line is the pulse shape with bias voltage at 3.97V.

**Fig. 9** Pulsewidth of the generated pulse train versus the internal power of cavity with different input power of external pulse.

**Fig. 10** Pulsewidth of the mode-locked pulses with various injection current of SOA.
Figure 2(a)
Figure 2(b)

![Figure 2(b)](image1)

Figure 3

![Figure 3](image2)
Figure 6

![Plot 1](image1.png)

Figure 7

![Plot 2](image2.png)
Figure 9

![Graph showing the relationship between pulse width (ps) and power of internal cavity (dBm). The graph includes data for two different power levels: 9.92 dBm and 10.46 dBm.](image)

Figure 10

![Graph showing the relationship between pulse width (ps) and injection current (mA).](image)