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A high-*Q* microwave photonic filter by using an SOA-based active mode-locked fiber ring laser*

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A high-*Q* microwave photonic filter using a semiconductor optical amplifier (SOA)-based mode-locking fiber ring laser is proposed, analyzed and experimentally demonstrated. The proposed microwave photonic filter can realize a high-*Q* frequency response, it is compact without an optical source, and it can be easily tuned by adjusting an optical variable delay line in a ring cavity. A result with a *Q*-factor of about 236 and a rejection ratio of about 45 dB is obtained. The measured results and the theoretical estimations agree very well.

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Using photonic technology to realize microwave and millimeter-wave processing has attracted considerable attention in recent years[1-4]. Compared with traditional electronics-based microwave circuits, microwave photonic processing provides some advantages, such as low loss, light weight, broad bandwidth, good tunability and immunity to electromagnetic interference. Furthermore, it can break through so-called electronic bottleneck, and has many potential applications in ultra-bandwidth wireless mobile communication, array phase radar, sensors of microwave and millimeter-wave, and microwave and millimeter-wave signal processing. Microwave photonic processing not only provides the possibility of processing microwave and millimeter wave signals directly in optical domain without electro-optical (E/O) or opto-electrical (O/E) conversions, but also has the benefit of being inherently compatible with fiber-based transmission system and optical fiber network. The microwave photonic filter with high rejection ratio and high-*Q* bandpass filtering is required in many applications. Many approaches have been reported to implement high-*Q* microwave photonic filters[5-12], including finite-impulse-response (FIR) and infinite-impulse-response (IIR) delay line fitlers, but a large number of taps are required. For an FIR filter, the *Q*-factor is increased by increasing the number of optical components[5,6]. Compared with FIR filter, the IIR filters can generate a large number of optical taps by using an active recursive delay line, in which the net gain is set close to 1[7-11]. The high-*Q* filters mentioned above are conventional delay line filters, which are generally composed of an optical source, a modulator, an optical processing portion and an optical receiver. Recently, a microwave photonic filter based on a mode-locked fiber laser has been demonstrated[12]. However, the filter has some drawbacks, such as a limited *Q*-factor of about 140, a limited rejection ratio of about 20 dB and a high unwanted noise level.

In this paper, we propose a new high-*Q* microwave photonic filter which is based on an active mode-locking fiber ring laser (MLFRL) with a semiconductor optical amplifier (SOA). In addition to the characteristics of the mode-locking-assisted microwave photonic filter such as compact, cost-effective and without needing an additional optical source, compared with the previously proposed filter[12], the proposed microwave photonic filter can realize high-*Q* and high rejection ratio frequency response, and the unwanted noise level is greatly improved. Furthermore, the proposed microwave filter can be easily tuned by adjusting an optical variable delay line (OVDL) in the ring cavity. Measured results of a *Q*-factor of about 236 and a rejection ratio of 45 dB are obtained.

The schematic configuration of the proposed high-*Q* microwave photonic filter is shown in Fig.1. Generally, the harmonic mode-locking technology in an active MLFRL can be characterized by[12-14]

$$f_{\mathrm{m}} = N f_{\mathrm{c}}, \tag{1}$$

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where f_{m} is the modulation frequency, and N is a positive integer.

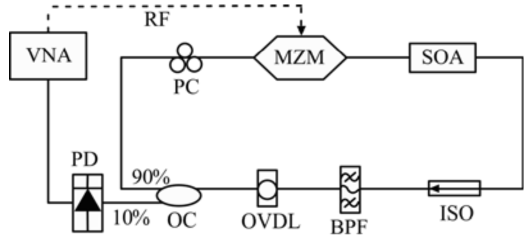


Fig.1 Schematic configuration of the proposed microwave photonic filter (VNA: vector network analyzer; PC: polarization controller; OC: optical coupler; OVDL: optical variable delay line; BPF: bandpass filter; ISO: isolator)

The fundamental cavity frequency can be written as

$$f_{\mathrm{c}} = c / nL , \tag{2}$$

where c is the light velocity in vacuum, n is the refractive index of the cavity medium, and L is the cavity length.

As can be seen from Eq.(1), for an active MLFRL, mode-locking condition is fulfilled when the modulation frequency is a harmonic of the fundamental frequency which is the inverse of the round-trip travel time of the cavity. The MLFRL is still mode-locked if the small detuning from the ideal locking modulation frequency is within the mode-locking range. As a result, the radio-frequency (RF) signal within the mode-locking range can be recovered by employing a photo-detector (PD) to detect the output of the MLFRL, while the RF signal out of the mode-locking range can not be recovered. Thus, an active MLFRL together with a PD operates as a microwave photonic filter. The free spectral range (FSR) is equal to the fundamental frequency f_{c}, and the filter frequency response of 3 dB bandwidth depends on the mode-locking range of the active MLFRL. Using an approximation analysis with a self-consistence condition similar to the method in Ref.[14], the mode-locking range of the MLFRL can be derived as follows.

For the purpose of convenience, a parameter δ is introduced to describe the detuning extent which is defined by

$$\delta = \frac{\Delta L}{L} , \tag{3}$$

where ΔL is the variation of the cavity length.

If the detuning is small enough, the modulation effect can reach a balance finally. According to the self-consistence and the balance condition, the maximal δ is written as[14]

$$\delta_{\max} = \frac{c}{4nL} \cdot \frac{\sqrt{m}}{\left(\sqrt{m} f_{\mathrm{m}} + B_{1/e}\right)} , \tag{4}$$

where m is the modulation depth, and $B_{1/e}$ is the $1/e$ bandwidth of the optical filter. Usually, $B_{1/e} >> \sqrt{m} f_{\mathrm{m}}$, then Eq.(4) can be simplified as

$$\delta_{\max} = \frac{c\sqrt{m}}{4nLB_{1/e}} . \tag{5}$$

The relation of $B_{1/e}$ and the 3 dB bandwidth $B_{3\ \mathrm{dB}}$ is

$$B_{1/e} = \frac{B_{3\ \mathrm{dB}}}{2\sqrt{\ln 2}} . \tag{6}$$

Substituting Eq.(6) into Eq.(5) and considering Eqs.(1) and (2), one can obtain

$$\delta_{\max} = \frac{f_{\mathrm{m}} \sqrt{m \ln 2}}{2NB_{3\ \mathrm{dB}}} . \tag{7}$$

In the case of $L >> \Delta L$, the variation of the frequency can be written as

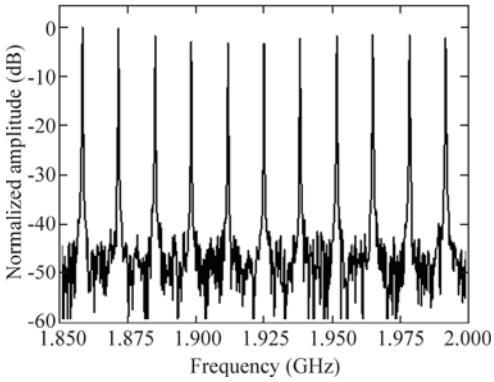
$$\Delta f_{\mathrm{m}} = \Delta L \frac{Nc}{nL^2} . \tag{8}$$

Combining Eqs.(3) and (7), and considering Eqs.(1) and (2), the locking range is approximately expressed as

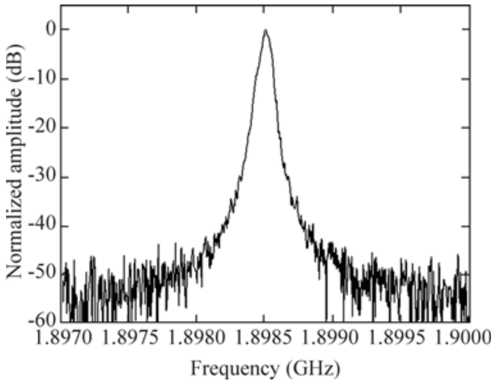
$$\Delta f_{\mathrm{m}} = \frac{f_n^2 \sqrt{m \ln 2}}{2NB_{3\ \mathrm{dB}}} . \tag{9}$$

The experimental setup of the proposed microwave photonic filter is shown in Fig.1. The microwave photonic filter consists of a PD and an active MLFRL. The structure of the MLFRL is mainly composed of a Mach-Zehnder modulator (MZM) driven by the RF signal from one port of the vector network analyzer (VNA), an SOA, and an optical bandpass filter (BPF) with a central wavelength of 1557.8 nm and 3 dB bandwidth of 1.26 nm. A polarization controller (PC) and an optical isolator (ISO) are used to optimize the polarization orientation of the circulating light wave and ensure the unidirectional propagation, respectively. An OVDL is used to adjust the length of the laser cavity to realize the tunability. The 10% coupling ratio port of the 10:90 optical coupler (OC) is used as the output of the MLFRL. The output of the MLFRL is detected by a PD, and the characteristics of the proposed filter are measured by the other port of the VNA. An oscilloscope and an optical spectrum analyzer are employed to investigate the characteristics of the MLFRL. When the OVDL is set to be 130 ps, the measured frequency responses of the proposed microwave photonic filter with the frequency spans of 150 MHz and 3 MHz are shown in Fig.2. One of the frequency response peaks is at 1898.92 MHz, as shown in Fig.2(b), and its 3 dB bandwidth is about 56.50 kHz. The FSR of the filter is about 13.33 MHz, which is also the fundamental frequency of the MLFRL. Thus, the Q-factor of the microwave photonic filter is about 236.

The maximum rejection ratio of about 45 dB is achieved.



(a) 150 MHz



(b) 3 MHz

Fig.2 Measured frequency responses of the proposed microwave photonic filter with the frequency spans of 150 MHz and 3 MHz

The proposed microwave photonic filter based on the MLFRL can be easily tuned by adjusting an OVDL to change the length of the MLFRL cavity. In the initialized case of the OVDL of 130 ps, the frequency response with the FSR of 13.33 MHz is shown in Fig.3. When the cavity length is reduced by 25 ps each time, the frequency responses of the microwave filter are changed by reducing the OVDL to 105 ps and 80 ps with a frequency shift of about 3.98 MHz, as shown in Fig.3.

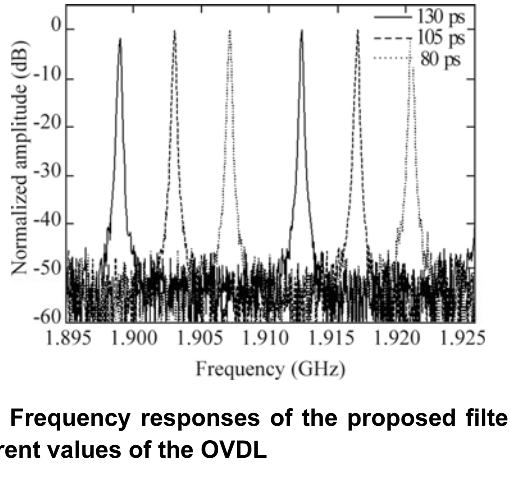


Fig.3 Frequency responses of the proposed filter for different values of the OVDL

The relationships between the frequency response of the filter and the characteristics of the MLFRL are also studied. To demonstrate the MLFRL, a signal generator is used to drive the MZM. When the frequency is set to be 1898.92 MHz as shown in Fig.2(b), according to the 142nd harmonic of the fundamental frequency, the pulse output with the pulse width of about 96 ps and the period of about 520 ps of the MLFRL is obtained, as shown in Fig.4. Similar output of the MLFRL can be observed when the modulation frequency is set at other peaks of the frequency response of the microwave photonic filter. The result indicates that the RF signal with the frequency

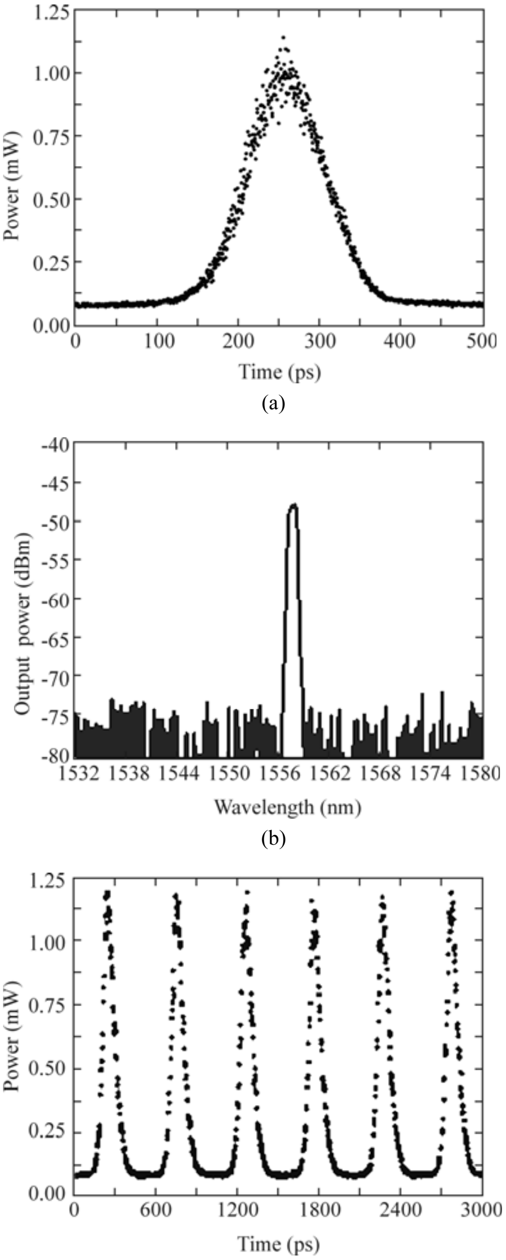


Fig.4 (a) Pulse waveform of the MLFRL; (b) Output optical spectrum of the MLFRL with 3 dB bandwidth of 1.08 nm; (c) Output pulse sequence of the MLFRL

being a harmonic of the fundamental frequency of the MLFRL can successfully pass the microwave photonic filter based on the mode-locking, and it can be recovered by PD. In additon, the RF signal within the mode-locking range can also be recovered, and the mode-locking range Δf_{m} can be estimated from Eq.(9). Assuming m=1 and B =157.5 GHz, the mode-locking range Δf_{m} is estimated to be 55.88 kHz, which is very close to the measured 3 dB bandwidth of the microwave photonic filter.

A mode-locking-assisted microwave photonic filter is proposed and demonstrated, and it can achieve high-Q and high rejection ratio frequency response. The frequency response with an FSR of about 13.33 MHz, the 3 dB bandwidth of about 56.50 kHz, the Q-factor of about 236 and the maximum rejection ratio of about 45 dB is experimentally obtained. Experimental results show that the performance of the proposed filter can be well characterized and estimated by the active mode-locking theory. The proposed filter can be easily tuned by adjusting the OVDL in the cavity.

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