A cascaded microwave photonic filter based on a low-coherence infinite-impulse-response filter*

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A cascaded filter combining active and passive filters is proposed. The active filter acts as a low-coherence infinite-impulse-response (IIR) filter and achieves a sharp frequency response. The low-coherence IIR filter is realized by employing the cross-gain modulation (XGM) of the amplified spontaneous emission (ASE) spectrum of the semiconductor optical amplifier (SOA). The passive filter is an *n*-section unbalance Mach-Zehnder (UMZ) structure, which is used to increase free spectral range (FSR) and *Q* factor further. The low-coherence IIR filter cascaded with one section of UMZ passive filter is experimentally demonstrated, and a *Q* factor of 1268 is obtained.
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Microwave photonic signal processing has attracted special attention[1-4]. The microwave photonic filter with high-*Q* bandpass response is required in many applications, and it generally needs a large number of taps. Two basic structures have been proposed to achieve high-*Q* microwave photonic filters, which are the finite-impulse-response (FIR) structure[5-8] and the infinite-impulse-response (IIR) structure[9-12]. For the FIR filter, the *Q* factor is increased at the cost of increasing the optical components[5-8], while the IIR filter can generate a large number of optical taps by using an active recirculating delay line (RDL), and the net gain is close to 1. However, the *Q* value of the IIR filter is often restricted by the lasing threshold[9-12]. Furthermore, due to the discrete sampling process in the time domain, most of the previously reported microwave photonic filters[5-12] are fundamentally limited by the presence of multiple harmonic passbands in the desired spectral range, which is common in the discrete time signal processor. This is a serious drawback, because the free spectral range (FSR) where the filter can be employed is very limited. Cascaded filter has been used to increase FSR[13-15]. However, to assure the cascaded filter operating in the incoherent domain, the increase of FSR is limited due to the laser source with narrow linewidth[14,15].

In this paper, an active filter cascaded with a passive filter is proposed. The active filter operates as a low-coherence IIR filter and realizes a sharp frequency response, which is achieved by employing the cross-gain modulation (XGM) of the amplified spontaneous emission (ASE) spectrum of the semiconductor optical amplifier (SOA)[16]. The passive filter is an *n*-section unbalance Mach-Zehnder (UMZ) filter, and acts as an FIR filter. The FIR filter is used to increase FSR and *Q* factor by selecting the corresponding desired filter frequencies and eliminating the intermediate peaks. The proposed cascaded filter based on the low-coherence IIR filter has the potential to achieve a large FSR and a high *Q* factor in the incoherent domain. The IIR filter cascaded with a two-tap FIR filter is experimentally demonstrated. A *Q* factor of 613 and an FSR of 14.05 MHz for the low-coherence IIR filter are obtained, and a *Q* factor of 1268 and an FSR of 28.1 MHz for the cascaded filter are achieved.

Fig.1 shows the schematic diagram of the cascaded filter, and an active filter in the cascaded filter is shown as the dashed line block of Fig.1. The FSR_{act} of the active filter is given by

$$FSR_{\text{act}} = \frac{c}{n_{\text{act}} L_{\text{act}}}, \tag{1}$$

where c is the speed of light in vacuum, n_{act} is the refractive index, and L_{act} is the total length of the RDL loop.

When the central wavelength of the optical bandpass filter (OBPF) is detuned larger from the laser wavelength, the transfer function of the active filter can be simply written as

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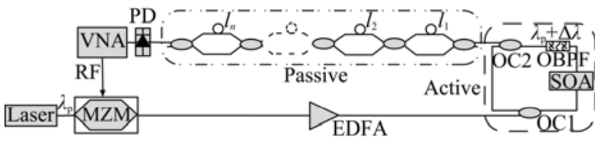
$$H_{\mathrm{act}}(\omega) \propto \frac{\eta(1-\kappa_1)(1-\kappa_2)g_{\mathrm{c}}L_{\mathrm{c}}}{1-\kappa_1\kappa_2 g_{\mathrm{c}}L_{\mathrm{c}}\mathrm{e}^{-\mathrm{j}\omega T_{\mathrm{act}}}}, \tag{2}$$

where η represents the XGM conversion coefficient of the microwave signal, κ_1 and κ_2 are the coupling coefficients of optical coupler1 (OC1) and OC2, respectively, g_{c} is the effective gain of the converted signal, and L_{c} is the corresponding optical loss coefficient caused by the OBPF. ω is the modulating angular frequency of the microwave signal, and T_{act} is the delay time of the RDL loop.



MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; OC: optical coupler; SOA: semiconductor optical amplifier; OBPF: optical bandpass filter; PD: photo-detector; VNA: vector network analyzer; RF: radio frequency

Fig.1 Schematic diagram of the cascaded filter

According to the definition of 3 dB bandwidth, the corresponding frequency of $\omega_{3\ \mathrm{dB}}$ is given by

$$\omega_{3\ \mathrm{dB}} = \frac{1}{T_{\mathrm{act}}}\arccos\frac{-3b^2 g_{\mathrm{c}}^{\ 2} + 8bg_{\mathrm{c}} - 3}{2bg_{\mathrm{c}}}, \tag{3}$$

where $b = \kappa_1\kappa_2 L_{\mathrm{c}}$.

The 3 dB bandwidth is

$$\Delta f_{3\ \mathrm{dB}} = \frac{2}{T_{\mathrm{act}}}\arccos\frac{-3b^2 g_{\mathrm{c}}^{\ 2} + 8bg_{\mathrm{c}} - 3}{2bg_{\mathrm{c}}}. \tag{4}$$

The Q_{act} of the active filter is expressed as

$$Q_{\mathrm{act}} = \frac{FSR_{\mathrm{act}}}{\Delta f_{3\ \mathrm{dB}}} = \frac{\pi}{\arccos\dfrac{-3b^2 g_{\mathrm{c}}^{\ 2} + 8bg_{\mathrm{c}} - 3}{2bg_{\mathrm{c}}}}. \tag{5}$$

It can be seen from Eq.(4) that the bandwidth of the frequency response can be narrowed by increasing the delay time T_{act} of the RDL loop. However, this is not a good choice because the increase of L_{act} will reduce the FSR_{act}.

Assume the passive filter with n-section UMZ structure is connected after the active filter, and each UMZ realizes a tow-tap frequency response. The overall transfer function of the cascaded filter can be written as

$$H_{\mathrm{cas}}(\omega) \propto \underbrace{\left(\frac{\eta(1-\kappa_1)(1-\kappa_2)g_{\mathrm{c}}L_{\mathrm{c}}}{1-\kappa_1\kappa_2 g_{\mathrm{c}}L_{\mathrm{c}}\mathrm{e}^{-\mathrm{j}\omega T_{\mathrm{act}}}}\right)}_{H_{\mathrm{act}}(\omega)} \cdot \underbrace{\prod\left(1+\mathrm{e}^{-\mathrm{j}\omega T_n}\right)}_{H_{\mathrm{pas}}(\omega)},$$

$$(n=1, 2, 3,\cdots), \tag{6}$$

where $H_{\mathrm{act}}(\omega)$ and $H_{\mathrm{pas}}(\omega)$ are the active and passive filter transfer functions, respectively. T_n is the delay time difference of two arms of the nth section UMZ filter, which is caused by the length difference.

In the condition of n-section UMZ filter cascaded after the active IIR filter, the relationship of the (m+1)th UMZ length difference l_{m+1} and the RDL loop length L_{act} should satisfy

$$l_{m+1} = \frac{L_{\mathrm{act}}}{2^{n-m}},\ m = 0,\ 1,\ 2\ \cdots\ n-1. \tag{7}$$

Thus, the FSR_{cas} of the cascaded filter increases to $2^n FSR_{\mathrm{act}}$, and the Q_{cas} factor of the cascaded filter increases to $2^n Q_{\mathrm{act}}$. As an example, when UMZ section number is chosen as n=3, the delay length differences of UMZ filters are $l_1 = \frac{L_{\mathrm{act}}}{8}$, $l_2 = \frac{L_{\mathrm{act}}}{4}$ and $l_3 = \frac{L_{\mathrm{act}}}{2}$. Fig.2 shows the theoretical active and passive filters frequency responses with different UMZ section numbers, and Fig.3 shows the corresponding theoretical cascaded filter frequency responses. As can be seen from Fig.3, with the UMZ section number increasing to 1, 2, 3, the FSR_{cas} of the cascaded filter can increase to $2FSR_{\mathrm{act}}$, $4FSR_{\mathrm{act}}$, $8FSR_{\mathrm{act}}$, respectively.

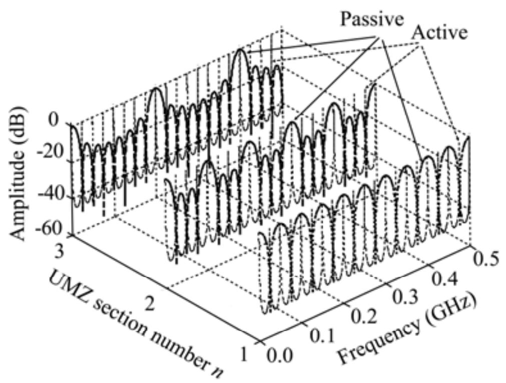


Fig.2 Theoretical frequency responses of active and passive filters with different UMZ section numbers

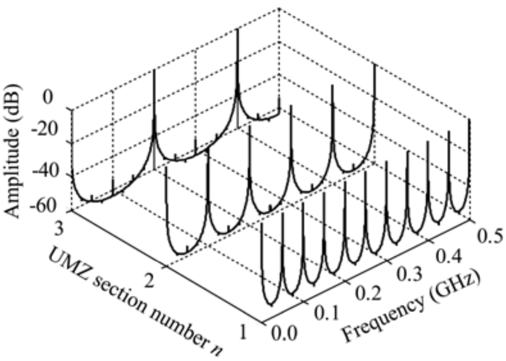


Fig.3 Theoretical frequency responses of cascaded filter with different UMZ section numbers

A simplified cascaded structure consisting of an active filter and a passive filter with one-section UMZ filter is set up, which is shown in Fig.4. A laser diode centered at

1560 nm is externally modulated by a Mach-Zehnder modulator (MZM) driven by the microwave signal from a vector network analyzer (VNA). After being amplified by the erbium-doped fiber amplifier (EDFA), the modulated optical signal enters the RDL loop. The RDL loop consists of a 50:50 OC1, an SOA, an OBPF, and a 10:90 OC2. The ASE of the SOA is inversely modulated by the pump signal (λ_p) due to the XGM effect, and then the information at pump wavelength λ_p is inversely copied onto the ASE at the output of SOA. An OBPF with 3 dB bandwidth of 1.2 nm centered at 1557.8 nm is used to extract the converted signal, which is a low-coherence ASE signal and serves as a negative tap. A 10:90 coupler is employed to extract 10% optical power from the RDL loop, and the other 90% is re-amplified and delayed to obtain the subsequent recursive taps. The converted signal circulating in the RDL loop realizes a high-*Q* frequency response. The one-section UMZ passive filter after the IIR filter realizes a two-tap frequency response. The UMZ filter is designed by connecting two 50:50 optical couplers (OC3 and OC4) in series with length difference between the two arms. The length difference is designed to satisfy $L_{act}/2$, so that the UMZ filter can select the desired frequencies of the IIR filter and eliminate the intermediate peaks. In our experiment, the delay time difference is controlled by inserting an optical variable delay line (OVDL) in one arm. The processed optical signal of the cascaded filter is detected by a photodetector (PD), and the frequency response is measured by the VNA.

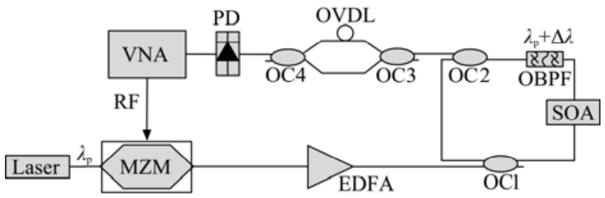


Fig.4 Schematic diagram of experimental setup

Due to the short coherent length of the modulated ASE signal, the stability of the cascaded filter can be assured. For the active filter, a measured high-*Q* frequency response with an FSR of 14.05 MHz and a 3 dB bandwidth of 22.90 kHz is shown in Fig.5. The resulting *Q* value is about 613, and the rejection ratio is about 50 dB. To our best knowledge, it is the highest *Q* factor for a single active delay line IIR filter. The measured frequency response of the one-section UMZ filter is also shown in Fig.5. The corresponding measured frequency response of the cascaded filter is shown in Fig.6. The FSR and the *Q* value of the cascaded filter are both increased to about 28.1 MHz and 1268, respectively, and the rejection ratio is 30 dB. One detailed peak of microwave passband with a frequency span of 0.3 MHz is shown in the inset of Fig.6.

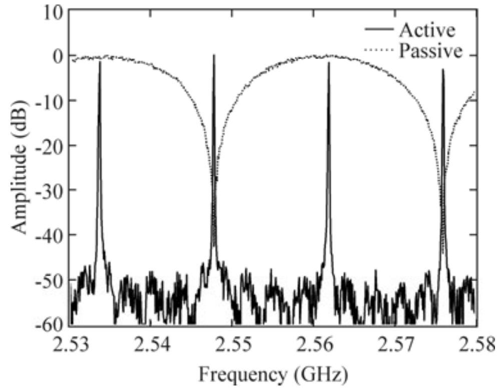


Fig.5 Measured frequency responses of active and UMZ filters

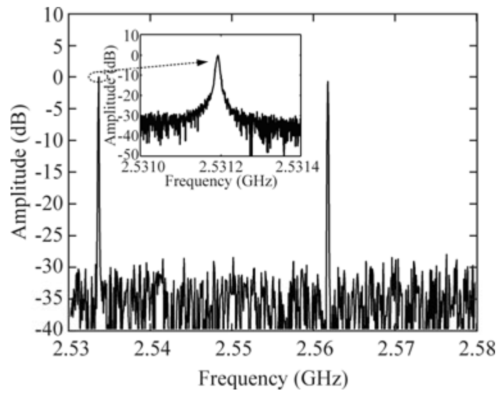


Fig.6 Measured frequency response of the cascaded filter

In a radio-over-fiber link, the telecommunication-type laser source with narrow linewidth is often employed. To assure the filter with a large FSR operating in the incoherent domain, an incoherent light source or additional O/E and E/O convertions are usually required, but not needed in our proposed filter. The reason is that a coherent laser source can be converted to a low-coherence light source due to the XGM of the ASE of the SOA. In addition, in the above experiments, the pigtailed devices are used to construct the IIR filter. It is difficult to reduce the cavity length to increase the FSR. In practical applications, the total delay length of the RDL loop can be reduced so that the FSR could be increased further.

An active filter cascaded with a passve filter is presented. The active filter acts as a low-coherence IIR filter through employing the XGM of the ASE of the SOA. A passive filter with *n*-section UMZ structure operates as an FIR filter, and is used to increase the FSR and *Q* factor by selecting the corresponding desired filter frequencies and eliminating the intermediate peaks. The proposed cascaded filter has the advantage that it has a potential large FSR and a high *Q* factor, while still operates in incoherent regimes due to the low-coherence IIR filter based on the XGM of the ASE of the SOA. The IIR filter cascaded with a two-tap FIR filter is experimentally demonstrated. The IIR filter with an FSR of 14.05 MHz and a rejection ratio of about 50 dB achieves the highest *Q* factor of 613 for a single active delay line filter for the first time to our best knowledge, and the cascaded filter with the result of an FSR of 28.1 MHz, a rejection ratio of 30 dB and a *Q* factor of 1268 is obtained.

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