A Microwave Photonic Notch Filter Based on Semiconductor Optical Amplifier and Optical Filter

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ABSTRACT

A novel microwave photonic notch filter structure is proposed and experimentally demonstrated. The structure is based on a recirculating delay line loop consisting of an optical variable delay line, a semiconductor optical amplifier (SOA) and a tunable narrowband optical filter. Negative tap is generated using wavelength conversion based on cross-gain modulation of amplified spontaneous emission spectrum of the SOA. A narrow bandpass response with negative coefficients and a broadband all-pass response are combined to achieve a narrow notch response with flat passband which can eliminate interference with minimal impact on the expected signal. Experimental results show good agreement with theoretical analysis.

Keywords: microwave photonics, photonic filter, photonic signal processing, delay line, semiconductor optical amplifier, cross-gain modulation, amplified spontaneous emission

INTRODUCTION

Microwave photonic filters have attracted significant interest in the past few years. Compared with traditional electronics-based radio-frequency (RF) circuits, microwave photonic filters provide advantages such as low loss, light weight, broad bandwidth, immunity to electromagnetic interference, and the ease of the tunability and reconfigurability. Furthermore, such structures have the benefit of being inherently compatible with fiber based transmission system and can be incorporated into the optical fiber network. Various microwave filter structures based on infinite impulse response or finite impulse response have previously been presented and demonstrated [1-5]. Among them, notch filters for interference suppression of microwave signals are very useful components in several applications such as fiber-radio links and phased array antennas, because microwave fiber-optic systems carry not only the desired signal but also unwanted interfering signals that are picked up by the antenna.

Several microwave photonic notch filter structures have been presented and demonstrated [6-8]. However, these previous structures are mostly based on a few taps. Hence they have some drawbacks such as producing a slow variation response and causing significant frequency-dependent attenuation in the required passband, which can corrupt the wanted information signal itself. This makes such filter structures inappropriate for interference suppression in some applications. There have been some photonic filter structures [9-12] which can provide both a narrow stopband for rejecting RF interference and at the same time to transmit the wanted signal over a flat passband. But they are not in the optical domain; they need extra electrical components such as an electrical bandpass filter [9], or one more photo-detector, electronic subtracter or adder [10-12]. This makes the filter structure complex and expensive.

In this paper, we present a microwave notch filter with a flat passband, which is operated in the optical domain. The filter is based on a recirculating delay line (RDL) loop containing a semiconductor optical amplifier (SOA) followed by a tunable narrowband optical filter (TNOF). Converted signal serving as negative tap is generated through wavelength conversion based on cross-gain modulation (XGM) of amplified spontaneous emission (ASE) spectrum of the SOA without a probe light [13-15]. A narrow bandpass response with negative coefficients and a broadband all-pass response

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for microwave signal are combined [16-17] to achieve a narrow notch response with flat passband. The notch filter with flat passband can eliminate interference with minimal impact on the wanted signal. The notch frequency response can be tuned if inserting an optical variable delay line (OVDL) in the RDL loop. The structure is simple compared to the previous proposed structure [18].

PRICINPLE

The schematic diagram of a new SOA-based microwave photonic notch filter is shown in Fig.1. The output of a laser diode (LD) with wavelength λ_p is external modulated by a Mach-Zehnder modulator (MZM) which is driven by microwave signal generated by the output port of the vector network analyzer (VNA). The power of the modulated optical signal is controlled by the followed erbium-doped fiber amplifier (EDFA) and a tunable attenuator (ATT). Then the modulated optical signal is split into two paths by a 50:50 optical coupler (OC). One path is sent to photo-detector (PD) directly, which provides broad-band all-pass microwave signal. A broadband all-pass response is obtained after photodetection, as shown in Fig.2 (a).

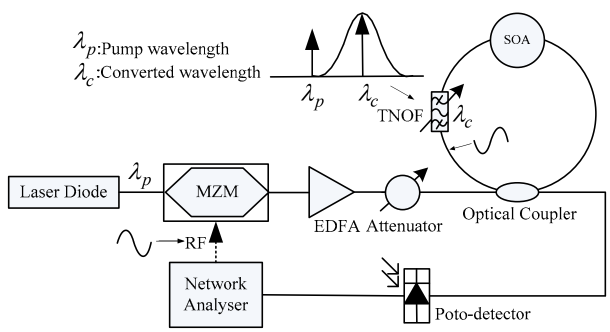

Fig.1 Schematic diagram of a new SOA-based microwave photonic notch filter. MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier, SOA: semiconductor optical amplifier, TNOF: tunable narrow-band optical filter

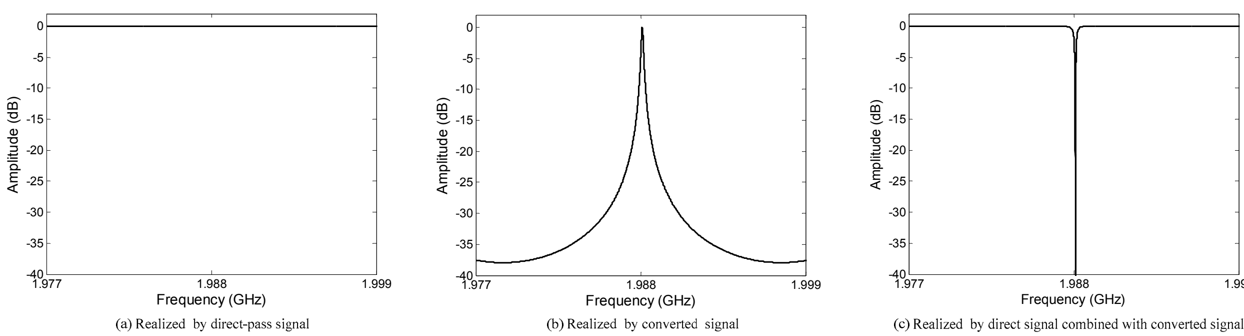

Fig.2 The derivation of the notch filter with flat passband

The other path goes into the RDL loop consisting of an SOA followed by a TNOF with 3 dB bandwidth of 0.3 nm. The ASE spectrum of the SOA is inverse modulated by the pump signal λ_p due to the XGM effect, as shown in Fig.3, the modulation information at pump wavelength λ_p is inverse copied onto other wavelengths of the ASE spectrum. The TNOF can extract out the converted signal at any other wavelength λ_c by tuning the TNOF within the wavelength operation range of the SOA. The converted signal is used for negative tap. Then, the extracted converted signal is divided into two parts by the OC; one part goes to the PD. The other part re-enters into the RDL loop to generate delay and obtain the subsequent recursive taps. When the converted signal arrives at the SOA, it can not modulate the ASE spectrum again because its power is small; it is amplified only by the SOA to compensate for the loss of the loop. The converted signal circulating in the RDL loop realizes a bandpass response with negative coefficients, as shown in

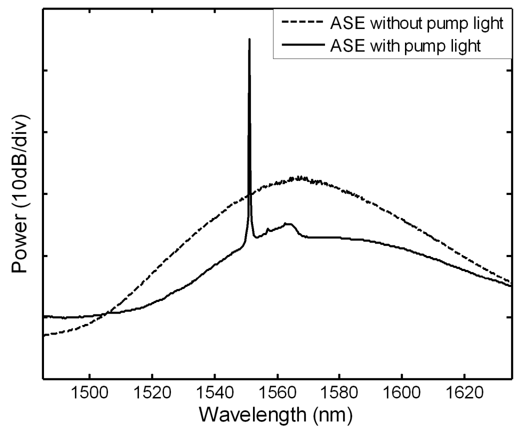

Fig.3 Measured ASE spectrum of the SOA with and without pump light

Fig.2 (b). Since the two different wavelengths (pump and converted wavelength) modulated optical signals have 180° RF phase difference, the two photocurrents generated by the two modulated optical signals are subtracted at the photodetector. As a result, the bandpass response with negative coefficients and the broadband all-pass response are combined to achieve a notch response with flat passband, as shown in Fig.2 (c). At the output of the PD, the filter frequency response is measured using the input port of the VNA.

However, because the TNOF has a Gaussian shape and a limited rejection ratio, when the central wavelength of the TNOF is detuned from the pump wavelength a little, the pump signal can not be filtered out completely. Then, a bandpass response with positive coefficients can also be realized by the pump signal circulating in the RDL loop. Hence, two bandpass responses with opposite polarity coefficients are realized by the pump signal and the converted signal circulating in the same RDL loop. The two photocurrents generated by the two modulated optical signals are then subtracted at the photodetector. However, the converted signal is dominant. The bandpass response realized by the converted signal is much sharper than that realized by the pump signal due to the effect of the pump signal being injected continuously into the SOA.

The transfer function realized by the pump signal can be written as

$$H_1(\omega) = \kappa + \frac{(1-\kappa)^2 L_1 g_1 e^{-j\omega T}}{1 - L_1 \kappa g_1 e^{-j\omega T}} \tag{1}$$

where κ is coupling coefficient of the coupler, L_1 is the optical loss coefficient of pump signal caused by the TNOF, g_1 is the effective gain of the SOA for the pump signal in the RDL loop, $T = n_{eff} l / c$ is the delay time corresponding to the RDL loop length l, n_{eff} is the fiber refractive index, and c is the speed of light in vacuum.

The transfer function realized by the converted signal can be given by

$$H_2(\omega) = -\frac{(1-\kappa)^2 \eta L_2 g_2 e^{-j\omega T}}{1 - L_2 \kappa g_2 e^{-j\omega T}} \tag{2}$$

where η represents the XGM conversion coefficient of the RF signal from λ_p to λ_c, L_2 is the optical loss coefficient of converted signal caused by the TNOF, g_2 is the effective gain of the SOA for the converted signal in the RDL loop.

Combining the expression (1) and (2), the overall transfer function of the filter structure is then expressed as

$$H(\omega)=\underbrace{\kappa+\frac{(1-\kappa)^2 L_1 g_1 e^{-j\omega T}}{1-L_1\kappa g_1 e^{-j\omega T}}}_{H_1(\omega)}\underbrace{-\frac{(1-\kappa)^2 \eta L_2 g_2 e^{-j\omega T}}{1-L_2\kappa g_2 e^{-j\omega T}}}_{H_2(\omega)} \tag{3}$$

$H_1(\omega)$ and $H_2(\omega)$ represents the frequency response realized by the pump signal and converted signal respectively.

As can be seen from equation (3) that the characteristic of the overall frequency response is related to the optical loss coefficients L_1, L_2, coupling ratio κ, SOA effective gain g_1 and g_2 for the pump signal and the converted signal respectively. Because the inversely modulated ASE spectrum of the SOA has a nonflat shape, as shown in Fig. 3, tuning the central wavelength of the TNOF will lead to different optical losses L_1, L_2 and different effective gains g_1, g_2 at the given coupling coefficient κ and SOA current. Thus, different frequency response will be obtained. In the case of the pump signal being not filtered out by the TNOF completely, i.e. $L_1 \neq 0$, the overall frequency response of the filter is the subtraction of the two bandpass responses after photodetection. A microwave flat passband notch filter with small humps closed to the notches is obtained. On the contrary, if the pump signal is filtered out by the TNOF completely, i.e. $L_1 = 0$, the overall frequency response of the filter is the subtraction of the all-pass response and the bandpass response after photodetection. In this case, a microwave notch filter with flat passband can be obtained.

Fig.4 shows the different calculated frequency responses with different L_1. It can be seen that, with the reduction of L_1, the notch rejection ratios become higher and the small humps slowly diminish. The notch width is proportional to the width of the bandpass response with negative coefficients. And the rejection ratio is determined by the two output microwave signal powers generated by the optical power of the direct path signal and the passband of the bandpass filter response. When the output microwave signal power generated by optical power of the direct path signal has the same amplitude as the passband of the bandpass filter response, high rejection ratio could be obtained. The variation of the rejection ratio can be observed and can be optimized in the experiment by adjusting TNOF, the SOA current or the attention. In addition, since the two outputs of the coupler are equal, the cancellation in the modulated power envelope will also take place at the SOA input at the notch frequency. After many passing round the loop, the converted signal will cause cross-gain modulation in the SOA at this frequency, and it will have a certain effect on the notch response characteristics. The delay length of the RDL loop is chosen to give a delay time corresponding to the filter center frequency. As we know, the free spectrum range (FSR) is inversely proportional to the delay time of the RDL loop. Thus, the notch frequency can be tuned by adjusting the OVDL to change the length the RDL loop.

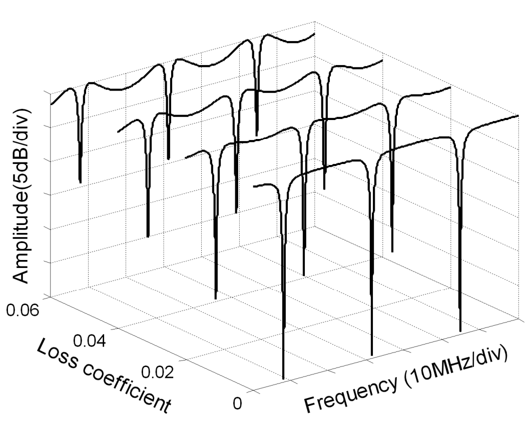

Fig.4 Theoretical overall frequency responses of the filter structure as the function of L_1

EXPERIMENT RESULTS AND DISCUSSION

A tunable LD with wavelength centered at 1551.2 nm is used as the optical source. The length of the RDL loop is about 9.04 meter, and the total delay time is about 43.10 ns, which is larger than coherent time of the input laser, so that the structure is operated in an incoherent regime. Thus, the FSR is about 23.2 MHz. When the current of the SOA is adjusted to about 87.5 mA and the central wavelength of the TNOF is tuned to 1550.96 nm, blue detuning about 0.24 nm from the pump wavelength, a notch filter with flat passband and high notch rejection is obtained. The theoretical and measured frequency responses are shown in Fig. 5. It can be seen that theoretical and measured frequency responses agree well. The notch rejection ratio is around 31.63 dB. The 3 dB notch bandwidth of the filter is about 42.48 kHz. Some humps are visible close to the notches, corresponding to the case that the pump signal is not filtered out completely, i.e. $L_1 \neq 0$. However, an extra slight notch appears on the right side of the notch frequency, as shown in Fig.5; it is caused by the nonlinearities of the SOA, and the slight notch will be disappeared if the nonlinearities are eliminated. In this structure, we could not obtain a high rejection, narrow bandwidth and flat passband simultaneously. This is because the TNOF is a

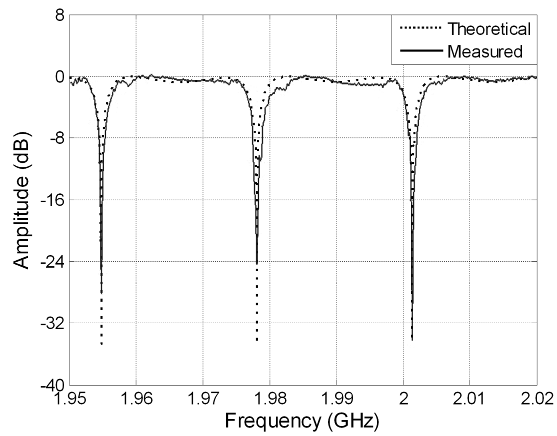

Fig.5 Theoretical and measured frequency responses of SOA-based microwave notch filter with 50:50 coupler

Gaussian-shaped filter, if one wants to obtain a flat passband microwave filter, one must detune the central wavelength of the TNOF much larger, however, the two microwave signal powers are different largely, and the notch rejection ratio will be very small. Another limitation is that the conversion coefficient of the converted signal is smaller, which will make the overall frequency response deteriorated.

To improve the flatness of the passband of the notch filter, we substitute 50:50 coupler with 30:70 coupler, the 70% optical power output is sent to the PD, and 30% is coupled into the RDL loop. Maintaining the SOA current and TNOF detuning, the improved passband of the notch filter is obtained, the measured frequency responses are shown in Fig.6. It can be seen that humps closed to the notches are unobvious. Compared with the structure with 50:50 coupler, the notch rejection ratio is higher and the 3 dB bandwidth is wider. This is because the bandpass response of this structure is not sharper as that with 50:50 coupler. In this structure, flat passband can be obtained; one reason is that the gain of ASE spectrum is higher than that with 50:50 coupler because of lower pump power coupled into the RDL loop and smaller suppression of ASE spectrum, the negative tap is much more dominant. The other reason is that the direct-pass signal power is higher and dominant.

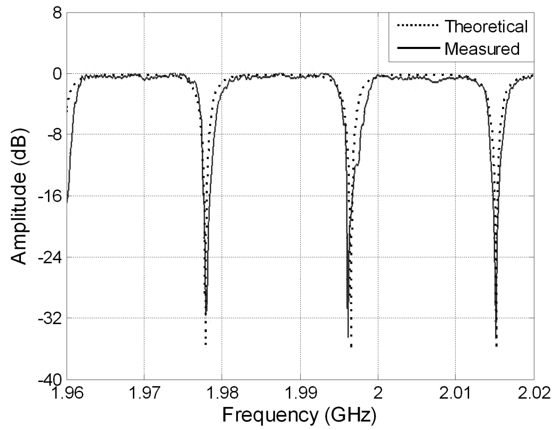

Fig.6 Theoretical and measured frequency responses of SOA-based microwave notch filter with 30:70 coupler

In the above experiments, pigtailed devices are used to achieve notch filter with flat passband, it is difficult to reduce the cavity length and increase the width of passband. In real applications, the total delay length of the RDL loop could be reduced so that the flat passband could be wider and the filter still operate in an incoherent regime, which can eliminate interference with minimal impact on the wanted signal over a wide microwave range.

CONCLUSION

A simple microwave photonic notch filter with flat passband has been proposed and experimentally demonstrated. The proposed filter is based on an RDL loop with an SOA followed by a TNOF. Converted signal is generated using wavelength conversion based on XGM of ASE spectrum in SOA. The converted signal is used for negative tap. The converted signal circulating in the RDL loop realizes a bandpass response with negative coefficients. A notch filter with flat passband can be realized by subtracting the bandpass response from the all-pass response after photodetection. The small visible humps close to the notches is caused by the pump signal which has not been filtered out completely. The experimental results show the notch rejection ratio in excess of 30 dB and 3 dB bandwidth of about 42.78 kHz. The frequency response can be tuned if inserting an OVDL in the loop. The flat passband of notch filter is optimized by substituting the 50:50 coupler with the 30:70 coupler. The flat passband will be wider if the total length of the RDL loop is optimized, which can eliminate interference with minimal impact on the wanted signal over a wide microwave range.

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