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RESEARCH ARTICLE

All-optical filter for simultaneous implementation of microwave bandpass and notch responses based on semiconductor optical amplifier

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Abstract An all-optical filter structure to simultaneously implement microwave bandpass and notch filter is proposed and experimentally demonstrated. The structure is based on a recirculating delay line (RDL) loop consisting of a semiconductor optical amplifier (SOA) followed by a tunable narrowband optical filter and a 10∶90 coupler. The converted signal is generated in a wavelength conversion process based on cross-gain modulation of amplified spontaneous emission in the SOA. The converted signal circulating in RDL loop realizes a negative bandpass response. The negative bandpass filter and a broadband allpass filter are synthesized to achieve a notch filter with flat passband which can excise interference with minimal impact on the wanted signal.

Keywords microwave photonic, microwave filters, optical signal processing, semiconductor optical amplifier, cross-gain modulation, amplified spontaneous emission

1 Introduction

Photonic microwave filters (PMFs) have attracted great interest because incoming radio frequency (RF) signals can be processed in the optical domain with the advantages of wide bandwidth, immunity to electromagnetic interference, light weight, and low losses. Furthermore, such structures have the benefit of being inherently compatible with fiber-based transmission systems and can be incorporated into the optical fiber network.

Photonic microwave bandpass and notch filters are important components for processing microwave signal. Various photonic microwave bandpass filters [1,2] and notch filters [3,4] have previously been presented and demonstrated. However, the filter structure to simultaneously implement bandpass and notch responses has not been reported up to now, which makes the full use of the components and greatly reduces the cost of the components compared with the bandpass filter and notch filter being realized respectively. Furthermore, the previously proposed notch filters have some drawbacks, such as being based on a few taps [3,4], which can corrupt the wanted information signal itself in the required passband, or needing extra electronic components, which increase the cost and complexity [5–7].

In this paper, we presented and experimentally demonstrated a filter structure that simultaneously implement microwave bandpass and notch responses in the optical domain. The structure is based on a recirculating delay line (RDL) loop comprising a semiconductor optical amplifier (SOA) followed by a tunable narrowband optical filter (TNOF) and a 10∶90 coupler. Converted signal can be used as negative tap, which is generated based on wavelength conversion employing cross-gain modulation (XGM) of amplified spontaneous emission (ASE) of the SOA [8–11]. The converted signal circulating in RDL loop realizes a negative bandpass response. The bandpass response with negative coefficients combined with a broadband allpass response achieves a notch filter with flat passband which can excise interference with minimal impact on the wanted signal. Experimental results show bandpass response and notch response with flat passband are obtained simultaneously at different output ports.

2 Operation principle and experiment results

The experimental setup for the SOA-based microwave filter is shown in Fig. 1. The output of a tunable laser diode

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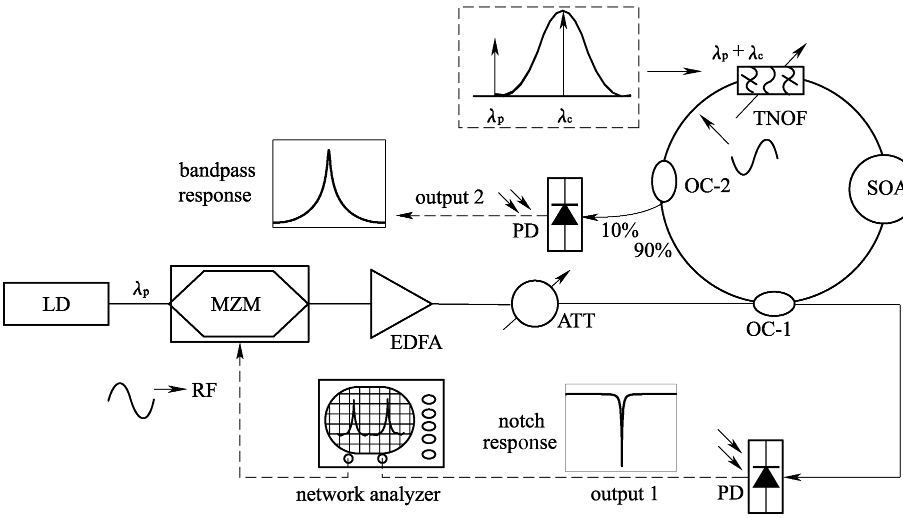

Fig. 1 Experimental setup for all-optical SOA-based microwave filter (λ_p: pump wavelength; λ_c: converted wavelength)

centered at 1551.12 nm is externally modulated by an electro-optic Mach-Zehnder modulator (MZM) that is driven by the radio frequency (RF) signal generated from the output port of a vector network analyzer. The laser source coherence time is smaller than the delay time of the RDL loop so that the structure is operated in an incoherent regime. The power of the modulated optical signal is controlled by the followed erbium-doped fiber amplifier (EDFA) and a tunable attenuator. Then the modulated optical signal is split into two paths by the 30:70 optical coupler (OC-1). The 70% power of the signal is sent to the photo-detector (PD) directly, which performs an allpass response. The residual 30% goes into the RDL loop consisting of an SOA followed by a TNOF with 3 dB bandwidth of 0.3 nm and 10:90 optical coupler (OC-2). The ASE spectrum of the SOA is inversely modulated by the pump signal λ_p due to the XGM effect, as shown in Fig. 2, and then the modulation information at pump wavelength λ_p is inversely copied into other wavelengths of the ASE spectrum. The TNOF is used to extract the converted signal and to reduce the noise of the SOA. The converted signal is π phase difference to the pump signal,

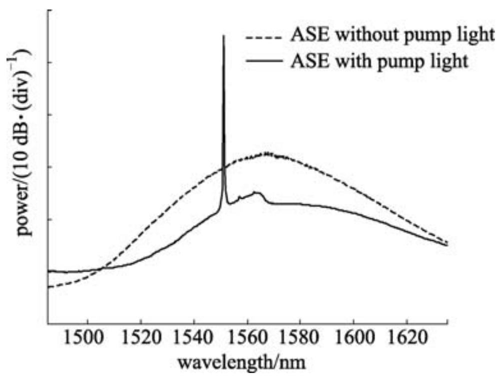

Fig. 2 Spectrum of ASE of SOA

and can be used as negative tap. After passing through the TNOF, the 10% converted signal is output at OC-2, and the residual 90% is divided into two parts at OC-1. One part is launched into the PD. The other part reentering the RDL loop is amplified and delayed to obtain the subsequent recursive taps. The converted signal cannot nearly modulate the ASE spectrum of the SOA again due to its small power. It is only amplified to compensate the loss in the loop by the SOA. The converted signal circulating in the RDL loop realizes a bandpass response with negative coefficients after photodetection, and is obtained at the output port of the OC-2. The transfer function can be expressed as

$$H_c(z) = -\frac{\eta(1-\kappa)^2 g L_c z^{-1}}{1-L_c g \kappa z^{-1}}, \tag{1}$$

where, η represents the XGM conversion coefficient of the RF signal from λ_p to λ_c, κ is coupling coefficient of the coupler, g is the effective gain of the SOA for converted signal, L_c is the optical loss coefficient of converted signal caused by the TNOF, $z = \exp(j2\pi fT)$, f is the microwave frequency, $T = nl/c$ is the delay time corresponding to the RDL loop length l, n is the fiber refractive index, and c is the speed of light in vacuum.

As is expected, a notch response with flat passband is obtained at the output port of OC-1. The notch frequency response is derived from the bandpass response combined with the allpass response. The cancellation in the modulated power envelope takes place at the coupler at the notch frequency without the need of optical-electrical conversion, and the transfer function of the notch filter can be written as

$$H(z) = \kappa - \frac{\eta(1-\kappa)^2 L_c g z^{-1}}{1-L_c \kappa g z^{-1}}. \tag{2}$$

The frequency responses corresponding to different outputs are illustrated in Fig. 1. We can see from Eqs. (1) and (2), the characteristic of the bandpass and notch frequency responses are related to the converted signal loss coefficient L_c, coupling coefficients of the OC-1, OC-2, and the effective gain of SOA for the converted signal. In addition, because the ASE spectrum of the SOA has a non-flat shape, as shown in Fig. 2, with the given coupling ratio κ and SOA current, tuning the TNOF will result in different effective gain g, and thus, will lead to different characteristics of the frequency responses.

In the experiment, we first set the SOA current to zero. The allpass frequency response is obtained at the output port of the OC-1 after photodetection, as shown in Fig. 3. In this case, the structure can be used as fiber link. In the case of the SOA of current of about 157.5 mA, the center wavelength of the TNOF of 1550.92 nm, and the bandpass filter response is obtained at the output port of the OC-2, as shown in Fig. 4. The free spectral range (FSR) is about 19.50 MHz and the quality factor of about 12.10 is achieved. As is expected, at the OC-1, the notch frequency response is also obtained, and the measured result is shown in Fig. 5. The 3 dB notch bandwidth is about 61 kHz, and the maximum notch rejection ratio is about 37.89 dB. It is noted that some small humps are visibly close to the notches; this is because the TNOF has a Gauss shape. When the central wavelength of the TNOF detunes from the pump wavelength a little, the pump signal cannot be filtered out completely. However, the pump signal passes around the loop for a very limited round due to the pump signal. The width of the notch depends on the characteristic of the bandpass response, and the rejection ratio is related to the allpass response power and the passband of the bandpass response power after photodetection. When the two powers are equal, high rejection ratio can be achieved.

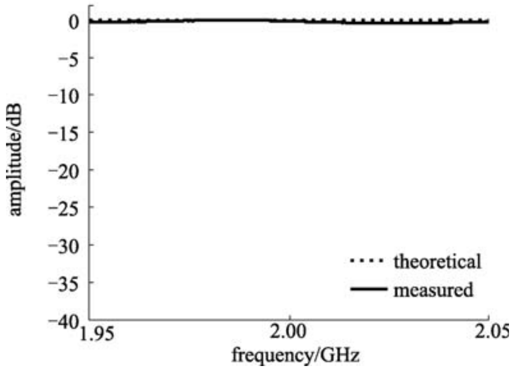

Fig. 3 Theoretical and measured allpass responses for SOA current of zero

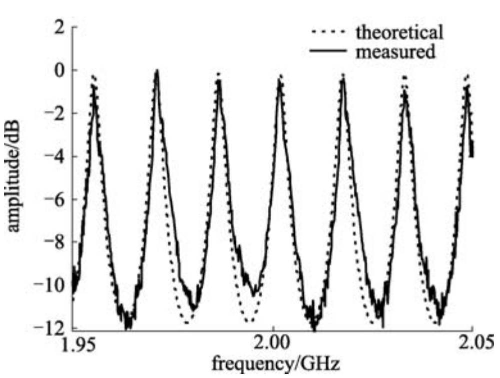

Fig. 4 Theoretical and measured bandpass responses for SOA current of 157.5 mA and TNOF of 1550.92 nm

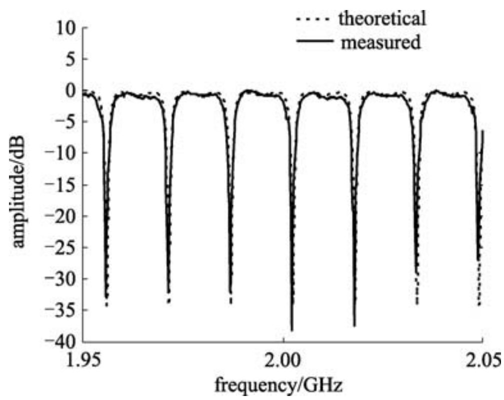

Fig. 5 Theoretical and measured notch frequency responses corresponding to the bandpass response in Fig. 4

With the SOA current maintained and the TNOF tuned to 1550.88 nm, a frequency response with a triangular shape [12] is obtained at the output of the OC-2, as shown in Fig. 6. At the OC-1, a corresponding notch response with flat passband is obtained, as shown in Fig. 7. It should be noted that, the rejection ratio of the bandpass response is higher, while the rejection ratio of the notch response is lower. The reason is that the power of the allpass response is fixed, while the effective gain for converted signal becomes larger and the power of the pump signal passing through TNOF is also slightly larger due to reduction of the detuning.

The delay length of the RDL loop is chosen to give a delay time corresponding to the filter design center

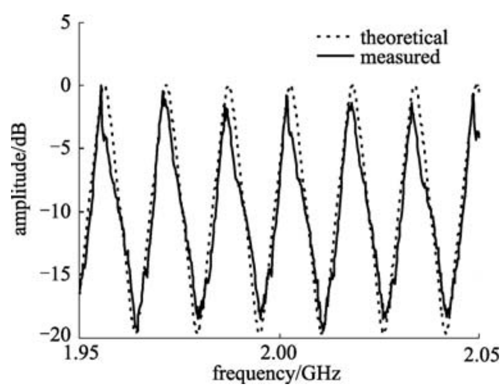

Fig. 6 Theoretical and measured frequency responses with a triangular shape

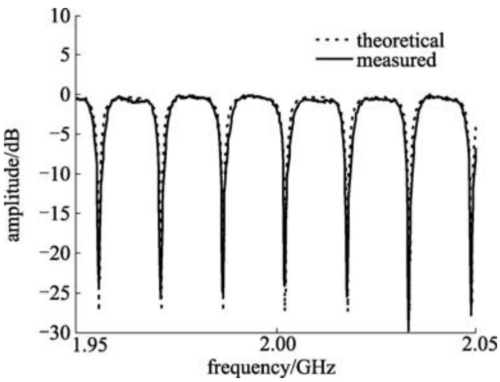

Fig. 7 Theoretical and measured notch frequency responses with flat passband corresponding to the response in Fig. 6

frequency and the tunability of the frequency response can be realized by inserting a variable optical delay line in the RDL loop.

3 Conclusion

A filter structure to simultaneously implement microwave bandpass and notch response is proposed and experimentally demonstrated. It is based on an RDL loop consisting of an SOA followed by a TNOF and OC-2. The converted signal used as negative tap is generated employing XGM of ASE spectrum of the SOA. The converted signal circulating in the RDL loop realizes a bandpass frequency response with negative coefficients at the OC-2 after photodetection, while the negative bandpass filter combined with a broadband allpass filter achieves a notch filter with flat passband and is simultaneously obtained at OC-1. The frequency response can be tuned by inserting a variable optical delay line in the RDL loop.

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