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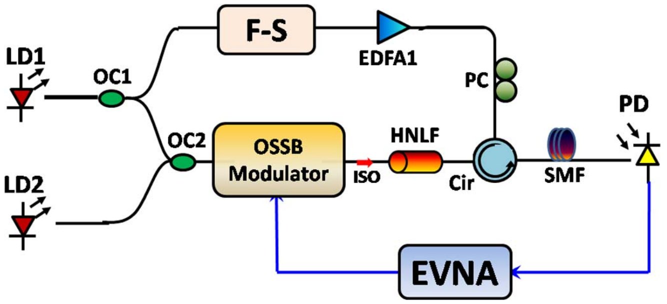

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Microwave Photonic Filter With Complex Coefficient Based on Optical Carrier Phase Shift Utilizing Two Stimulated Brillouin Scattering Pumps

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Abstract: A microwave photonic filter (MPF) with complex coefficient based on the frequency transparent magnitude response by independent control of the frequency and power of two stimulated Brillouin scattering (SBS) pumps is proposed and experimentally demonstrated. The motivation of this paper lies in the fact that the operation bandwidth of the previous SBS-based complex coefficient MPFs is unavoidably limited by the Brillouin frequency shift. In our scheme, the complex coefficients are obtained by a broadband microwave photonic phase shifter based on the two SBS pumps. The two SBS pump signals are located at the same side of the optical carrier. In principle, the working bandwidth of the proposed MPF is infinite. One pump is used to introduce a controllable phase shift on the optical carrier, whereas the other pump is used to retain the power of the optical carrier invariant. By simply changing the phase shift of a complex coefficient, the frequency response of the two-tap complex coefficient MPF is continuously tuned over the full free spectral range (FSR), keeping shape and FSR invariant.

Index Terms: Complex coefficient microwave photonic filter, stimulated Brillouin scattering (SBS).

1. Introduction

Microwave photonic filters (MPFs) under incoherent operation have attracted extensive attention during the past few years thanks to the inherent characteristics in terms of low loss, light weight, wide bandwidth, large tunability, reconfigurability, and immunity to electromagnetic interference compared with electrical counterparts [1]–[3]. Various researches have been devoted to realize positive or negative coefficients MPF with delay-line structures. Up to now, the MPF with positive or negative coefficients have been reported to implement low-pass and bandpass filters. The low-pass or bandpass filters could be implemented based on optical variable attenuators [4]; cross polarization modulation in a highly nonlinear fiber [5]; polarization modulator (PolM) [6]; dual-output EOM; which need to be specifically designed [2]; and a joint use of EOM with a dispersive element [7]. Compared with the MPF with positive coefficients, that with negative coefficients could partially overcome the drawback related to the range of available frequency response.

However, it is worth noting that the frequency response of the MPFs with positive or negative coefficients could not be tuned over the full free spectrum range (FSR) in the above mentioned methods when the basic delay time keeps constant. However, a precise manipulation the center frequency of the passband without changing the shape and the FSR of the MPFs is highly desirable to meet some realistic applications. In order to widely tune the frequency response of the MPFs, at least one complex coefficient is required. The MPF with complex coefficients provide tunability of their frequency response over the whole FSR while keeping the spectral shape, FSR invariant. A vast variety of structures have been proposed to achieve complex coefficients MPF based on dual-parallel Mach-Zehnder modulator (DPMZM) conjunction with an optical bandpass filter (OBPF), dual-drive Mach-Zehnder modulator (DMZM) combining with arrayed waveguide grating (AWG) [8], a joint use of PolM with OBPF [9], a reconfigurable optical filter [10]. However, the operation bandwidth of the MPFs is inevitably limited by the OBPF which is a wavelength dependently optical component. To overcome this problem, the complex coefficients MPF have also been proposed based on 2-D liquid crystal on silicon [2], all-optical differentiator [11], and slow and fast light effect in the SOA [8]. However, the above mentioned approaches suffer from the stability problem. A. Loayssa et al. proposed a complex coefficient MPF based on optical single sideband (OSSB) modulation conjunction with SBS [12]. In this MPF, the Stokes wave and pump wave are simultaneously applied to process the optical carrier leading to an unwanted SBS response on the sideband. Therefore, the working bandwidth of the proposed MPF is inevitably limited by the Brillouin frequency shift. Moreover, the complex coefficients MPF with multitap is highly desirable for many applications. It is worth noting that the complex coefficient MPF with multitap is a real challenge. Up to now, the multitap complex coefficients MPF have only been proposed based on phase-shifted gratings [10] and SBS [13], and both of these methods have a restricted tuning range.

In this paper, we propose a new method to achieve MPF with complex coefficients based on the frequency transparent magnitude response using two SBS pumps, which enable independent manipulation the magnitude and phase of an optical carrier. The complex coefficient is obtained by a microwave photonic phase shifter. The proposed approach is theoretically analyzed and experimentally demonstrated. The forward-propagated OSSB modulated signals and counter-clockwise propagated Brillouin pump optical signals are simultaneously injected into a highly nonlinear fiber (HNLF) to occur the SBS process. As a result, one of optical carriers is processed by the Brillouin pump optical signals and imparted an additional phase shift, while the corresponding sidebands and another optical carrier are not affected by the SBS pump signals. Since the two SBS pumps with a Brillouin frequency shift above the optical carrier locate at the same side of the optical carrier, the operation bandwidth of the proposed MPF is theoretically infinite. The experimental results indicate that the frequency response of the complex coefficient MPF could be continuously tuned over the whole FSR without changing its shape and FSR over a frequency range from 1 to 18 GHz.

2. Principle

The schematic configuration of the proposed MPF based on OSSB modulation and frequency transparent magnitude response using two Brillouin pumps is illustrated in Fig. 1. An optical carrier1 from a laser diode (LD1) with tunable angular frequency ω_{c1} is separated into two branches via an optical coupler (OC1) by splitting ratio 1 : 1 (see Fig. 2). The upper branch of the proposed scheme is dedicated to supply the Brillouin pumps. The optical carrier in the upper branch is firstly frequency shifted with a fixed angular frequency of Brillouin frequency shift ω_{SBS} as the Brillouin pump wave. An erbium doped fiber amplifier (EDFA1) is added to compensate the loss of the F-S and boost the SBS pump signals. A polarization controller attached after the EDFA1 is used to optimize the SBS effect. The optical carrier2 emitted from another laser diode (LD2) with tunable angular frequency ω_{c2} is fiber-coupled to an OSSB modulator, which is driven by a sinusoidal microwave signal from an electrical vector network analyzer (EVNA) to be filtered. The EVNA works at the frequency sweeping mode. The optical signal is then launched to

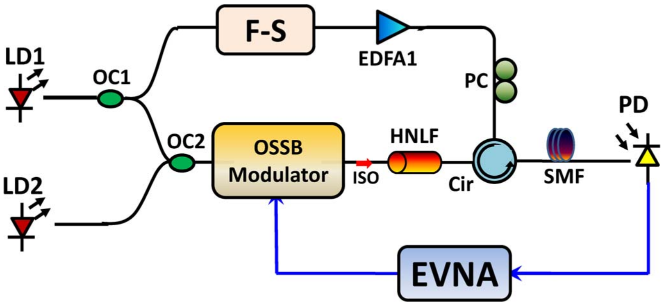

Fig. 1. Schematic diagram of the proposed complex coefficient microwave photonic filter. F-S: frequency shifter; OSSB Modulator: optical single-sideband modulator.

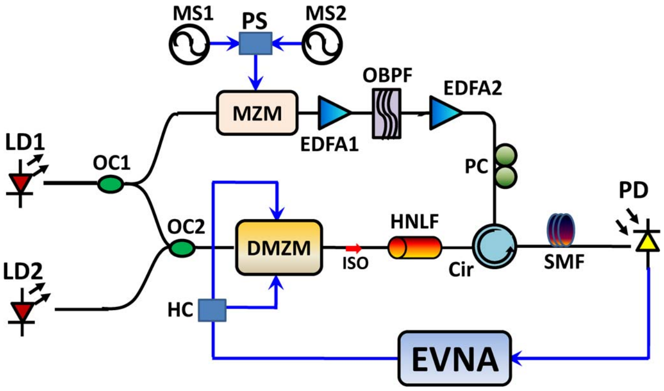

Fig. 2. Experimental setup. LD1, LD2: Laser diode; OC1, OC2: optical coupler; DMZM: dual-drive Mach-Zehnder modulator; MS: microwave source; MZM: Mach-Zehnder modulator; PS: power splitter; EDFA1, EDFA2: erbium doped fiber amplifier; OBPF: optical bandpass filter; ISO: isolator; HNLF: highly nonlinear fiber; Cir: circulator; SMF: single mode fiber; PC: polarization controller; HC: hybrid coupler; PD: photodetector; EVNA: electrical vector network analyzer.

a dispersion-shifted highly nonlinear fiber (HNLF) via an optical isolator (ISO) which is employed to stimulate the Brillouin process. The optical carrier1 is phase shifted and amplified by two SBS pumps, while the optical carrier2 is not affected since the SBS process is a narrow effect [14], [15] and the power of that could be adjusted by simply changing the output power of the LD2. The optical carrier1 and optical carrier2 are simultaneously injected into the OSSB modulator to achieve the OSSB modulation. The frequency shifted optical signal is circulated into an opposite port of the HNLF via an optical circulator (Cir) to pump the forward-propagating OSSB modulated signals, which are never affected by undesirable SBS responses. The OSSB modulated optical signals are then sent into the photodetector (PD) to recover the microwave signals, where a phase shift imposed on the optical carrier1 is converted into the phase of the recovered microwave signal without the limitation of the electrical bandwidth. The single mode fiber (SMF) connected after the Cir is used to introduce a basic time delay between the two taps of the MPF. The frequency response of the propose MPF is measured by the EVNA connected after the PD. Two frequency shifted optical signals are used to shift the phase of the optical carriers and keep the constant power of that. The previously reported complex coefficients MPF based on gain-transparency inevitably limits the working bandwidth to twofold Brillouin frequency shift due to simultaneously stimulating loss and gain spectra at frequencies up and down-shifted from the pump, which result in an unwanted response on the modulated sideband. Another important note is that a strong pump will induce a considerable back-scattering optical signal which will further compress the working bandwidth of the MPF to Brillouin frequency shift. In this scheme, the working bandwidth is only restricted by the working bandwidth of the measurement equipment, as well as the linewidth of the laser source. In principle, the optical carrier linewidth should be narrower than the Brillouin gain spectrum. The key element in the complex coefficient MPF is a widely tunable microwave photonic phase shifter. Pagani proposed and demonstrated a promising and powerful wideband microwave photonic phase shifter using two SBS pumps [16]. We apply the similar working principle proposed in that phase shifter to achieve the complex coefficient MPF.

We consider the optical signal sent to the OSSB modulator has a normalized electrical field given by $\exp(j\omega_{c1}t)$ and $\exp(j\omega_{c2}t)$ where ω_{c1} and ω_{c2} is the angular frequency of the optical signal emitted from LD1 and LD2. In our scheme, the OSSB modulation is realized based on a DMZM cascading a 90 degree hybrid coupler (HC). The electrical field at the output of the DMZM can be expressed as

$$E_{\text{DMZM}}(t) = \exp j\omega_{c1}t\,\{\exp[jm_1\sin(\omega_{\text{RF}}t+\theta)] + \exp[jm_2\sin(\omega_{\text{RF}}t)+j\varphi]\} \tag{1}$$

where m_1, and m_2 are the phase modulation indices in the two arms of the DMZM, θ is the phase difference between two microwave signals which are fed into the two arms of the DMZM. ω_{RF} is the angular frequency of the microwave signal from the EVNA. In our scheme, θ is equal to 90 degree. φ is the static phase difference between the two arms, which is adjusted by changing the DC bias of the DMZM. Applying Jacobi–Anger expansion to (1) and only considering two first-order sidebands under small signal condition, we have

$$\begin{aligned}E_{\text{DMZM}}(t) = {} & (J_1(m_1)\exp(-j\theta) + J_1(m_2)\exp(j\varphi))\exp[j(\omega_{c1}-\omega_{\text{RF}})t + j\pi] \\ & + (J_0(m_1) + J_0(m_2)\exp j\varphi)\exp j\omega_{c1}t \\ & + (J_1(m_1)\exp(j\theta) + J_1(m_2)\exp(j\varphi))\exp[j(\omega_{c1}+\omega_{\text{RF}})t].\end{aligned} \tag{2}$$

J_n is the Bessel function of the first kind of order n. The corresponding optical powers are listed as follows:

$$P_{-1} = J_1^2(m_1) + J_1^2(m_2) + 2J_1(m_1)J_1(m_2)\cos(\varphi+\theta) \tag{3}$$

$$P_0 = J_0^2(m_1) + J_0^2(m_2) + 2J_0(m_1)J_0(m_2)\cos\varphi \tag{4}$$

$$P_1 = J_1^2(m_1) + J_1^2(m_2) + 2J_1(m_1)J_1(m_2)\cos(\varphi-\theta). \tag{5}$$

In order to achieve OSSB modulation, the follow condition should be satisfied:

$$\begin{cases} m_1 = m_2 \\ \varphi + \theta = \pi \\ \varphi - \theta = 0. \end{cases} \tag{6}$$

From (6), θ and φ should be equal to $\pi/2$ and the power of the microwave signals injected into the two arms of the DMZM should be identical. $\varphi = \pi/2$, which can be implemented by adjusting the DC bias of the DMZM. Therefore, the conjunction of the DMZM with the 90 degree HC could be used to realize OSSB modulation. The electrical filed of the optical carrier and the first order sidebands can be rewritten as follows:

$$E_{\text{DMZM}}(t) = \sqrt{2}J_0(m_1)\exp(j\omega_{c1}t + \pi/4) + 2J_1(m_1)\exp[j(\omega_{c1}+\omega_{\text{RF}})t + j\pi/2]. \tag{7}$$

Then, the SBS pumps are amplified and counter-propagate with the forward-propagated OSSB modulated optical signals. The SBS process takes place in the HNLF and induces an additional phase shift to impose on the optical carrier which could be tuned by simply tuning the frequency of the microwave signal around the Brillouin frequency shift of the HNLF. Moreover, the power of the optical carrier remains constant which is achieved by controlling the power of another microwave signal. The two SBS pumps cause the constant SBS amplitude contributions. It is worth noting that the SBS pump whose state of polarization (SOP) is controlled by a PC to optimum the SBS effect is polarization-dependent. When the SOP of the SBS pump is parallel to that of the optical carrier, the SBS operation could be enhanced [17]. The OSSB modulated optical signal is launched into the PD to achieve optical to electrical conversion. The output current is given by

$$I(t) \propto E_{\mathrm{DMZM}}(t) \cdot E^{*}_{\mathrm{DMZM}}(t) \propto 4\sqrt{2}GJ_0(m_1)\cos\left(\omega_{\mathrm{RF}}t + \pi/4 + \delta\right). \tag{8}$$

As can be seen from (4), the phase of the generated microwave signal could be tuned and hence the microwave photonic phase shifter is achieved. It is noted that G is a gain coefficients which is remained constant by the combination of the two SBS pumps. When the microwave photonic phase shifter is used to process one of the two taps of the MPF, the complex coefficient could be obtained.

For a two taps incoherent complex coefficient MPF, the transfer function could be given as

$$H(f_{\mathrm{RF}}) = a_0 + a_1\exp(j\delta)\exp(j2\pi f_{\mathrm{RF}}T) = H\left(f_{\mathrm{RF}} - \frac{\delta}{2\pi T}\right) \tag{9}$$

where a_n is the filter tap coefficient. As can be seen from (9), the center frequency of the MPF could be tuned without changing the shape and the FSR of the MPF. Since the microwave photonic phase shifter can obtain a phase shift over a full 360 degree, the center frequency of the MPF can be tuned over the full FSR of the MPF. It is worth noting that the magnitude response of the SBS pump is intrinsically correlated with to its phase response. Therefore, when the phase response is changed, the corresponding magnitude response will unavoidably change to impose an undesired effect on the optical carrier. Another SBS pump with an exactly Brillouin frequency shift above the optical carrier is required to introduce a SBS gain to compensate for the amplitude variation whereas its phase response is zero. Since the microwave photonic phase shifter is not restricted at the high-frequency operation, the complex coefficient MPF, as a consequence, can operate over a broadband. The bandwidth of the MPF is only limited by the linewidth of the laser and the spectrum bandwidth of the SBS process and the largest bandwidth of the measurement instrument, respectively.

3. Experiments and Results

We carried out an experiment to verify the proposed two-tap complex coefficient MPF, which is shown in Fig. 2. Two optical signals with wavelengths of 1550.032 and 1553.932 nm were generated as two incoherent optical carriers. The optical carrier1 with the output power of 183.5 mW and the linewidth of 100 Hz was firstly divided into two parts injected into the MZM in the upper arm conceiving as the SBS pumps and the DMZM in the lower arm, respectively. The MZM biased for suppressed-carrier operation was driven by two independent sinusoidal microwave signals. One of the two microwave signals has a fixed frequency at Brillouin frequency shift of 9.205 GHz. The frequency of the other one could be adjusted around Brillouin frequency shift to impose a different phase shift on the optical carrier1. The carrier-suppressed double sideband modulated optical signals were first boosted by an EDFA1 and were then fed into a tunable optical bandpass filter (TOBPF) to select out the lower two sidebands due to requiring the SBS pumps to be at a frequency higher than the optical carrier. The MZM has a bandwidth of 40 GHz and a half-wave voltage of 5.5 V. The TOBPF with a remarkable edge roll-off of 800 dB/nm is widely tunable in terms of the center wavelength and bandwidth from 1480 to 1620 nm and from 32 to 650 pm, respectively. The filtered optical signals were boosted by another EDFA2 to compensate the insertion loss of the TOBPF. The optical carrier2 with the output power of 13 mW was sent into the OC2 and combined with the optical carrier1. For the lower arm, the two optical signals were sent into the DMZM. The DMZM has a bandwidth of 40 GHz and a half-wave voltage of 5.2 V. The joint use of DMZM with the 90 degree HC regarded as the OSSB modulator, which was driven by the microwave signal to be filtered generated by the EVNA. The EVNA has a working bandwidth from 50 MHz to 40.05 GHz. The working bandwidth of the HC is from DC to 18 GHz. The OSSB modulated optical signals were launched into the HNLF with a length of 1 km where the SBS process occurred. Since the two separate microwave signals could be independently controlled, the SBS pumps could be solely manipulated. The OSSB modulated optical signals

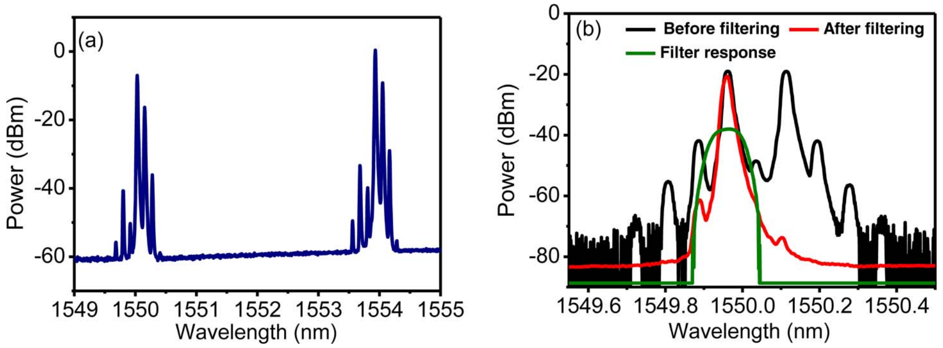

Fig. 3. Measured optical spectra of (a) the single sideband modulation at the output of the DMZM and (b) signals before and after filtering by the OBPF, as well as the filter response.

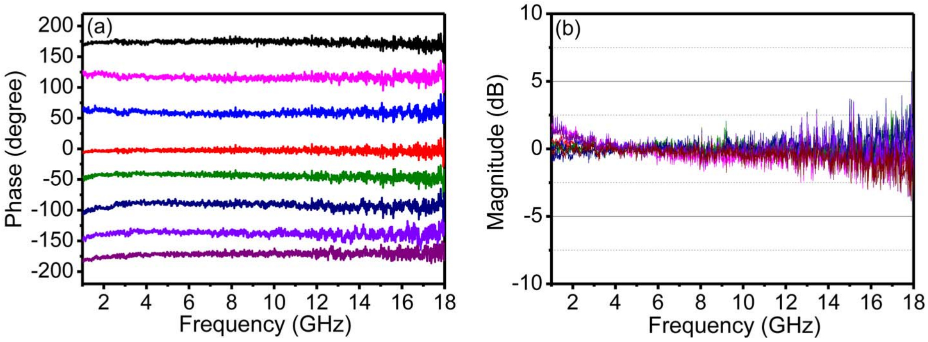

Fig. 4. Measured phase (a) and magnitude (b) responses of the microwave photonic phase shifter.

were circulated into a SMF with a length of 8.5 km to provide the basic delay imbalance of the two taps. A PD has a bandwidth of 18 GHz.

The optical spectrum of the OSSB modulated optical signals measured at the output of the DMZM is shown in Fig. 3(a) when the EVNA operated at a CW mode and generated the microwave signal at 10 GHz. It should be pointed out that the optical carrier at the right side is not affected by the SBS operation. The optical spectra at the output of the TOBPF are presented in Fig. 3(b). The carrier-suppressed double sideband and carrier-suppressed OSSB modulated optical signal are show in Fig. 3(b) in black line and red line, respectively. The transmission response of the TOBPF is also shown in Fig. 3(b) as a green line. The undesired higher-frequency sideband is suppressed by more than 40 dB. The selected optical signal consists of two optical components regarding as the two SBS pumps, which are controlled by the independent microwave sources.

Fig. 4(a) shows the measured phase responses of the SBS-based microwave photonic phase shifter. By changing the frequency of one SBS pump and the power of the other SBS pump, the phase response could be tuned from -180 to 180 degree over the frequency range from 1 to 18 GHz while the corresponding magnitude response keeps minimum amplitude variation. The lower boundary of the phase response is only restricted by the linewidth of the optical carrier, while the upper boundary of that is restricted by the operation bandwidth of the measurement equipment. The slight ripple of the phase response at the higher frequency range is attributed to the limited bandwidth of the PD. The magnitude responses corresponding to the conditions for the phase response are shown in Fig. 4(b). As can be seen from Fig. 4(b), the fluctuations of the magnitude response are mainly attributed to the response bandwidth of the PD. The OSSB modulated optical signal and the SBS pumps derived from the same laser, implying the ambient disturbance will not affect the stability of the proposed system.

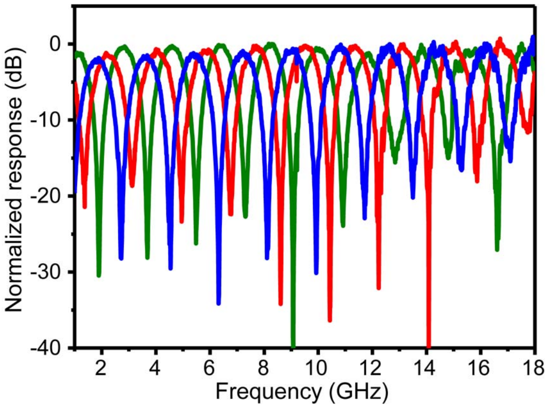

Fig. 5. Measured frequency responses of the proposed MPF.

With the help of a broadband microwave photonic phase shifter, the two-tap complex coefficient MPF could be implemented. Fig. 5 shows the frequency response of the propose MPF with the FSR of 1.77 GHz corresponding a basic delay time of $T = 17$ ps/nm/km $\times$ 8.5 km $\times$ 3.9 nm $= 563$ ps. In our experiment, one microwave signal's frequency is fixed at 9.205 exactly corresponding to Brillouin frequency shift of the HNLF, but the power of that is changed to make that the power of the optical carrier is not varied with the imparted phase shift. The other microwave signal's frequency is continuously changed to achieve different phase shift from 9.185 to 9.225 GHz. In a word, the two SBS pumps enable predictable manipulation of the magnitude and phase of the optical carrier. Moreover, the EDFA2 is used to boost the SBS pump aiming at obtaining the 360° phase shift. The frequency response of the MPF is tunable by changing the phase shifter over an entire FSR without changing the shape and the FSR of the MPF since there has been no need to change the basic delay time. The frequency responses of the MPF at the higher frequency appear some blemishes, which are attributed to the working bandwidth of the PD. In the MPF, two key elements should be noted that one SBS pump induces a gain response regarding as an optical amplifier and keeping the power of the optical carrier constant and the other SBS pump should introduce a linear phase shift imparting on the same optical carrier. Compared with the previously reported MPF based on gain transparency with a combination of SBS gain and loss response, the proposed scheme solves the limitation of the operation bandwidth. The operation bandwidth of the proposed MPF could be further expanded, if the measurement equipment with wider working bandwidth could be used. As can be seen from Fig. 5, the out-of-band suppression is around 20 dB, which is mainly attributed to the power ratio between the two recovered microwave signals. Therefore, by optimizing the power ratio of that reaching 1 : 1, the depth of the notch filter could be maximal. As we all know, for any microwave photonic link, the key figures of merit is noise figure (NF) which is mainly used to characterize the degradation of the input signal-to-noise ratio and spurious-free dynamic range (SFDR). In our experiment, the spontaneous emission noise of SBS effect could unavoidably back-propagate injecting into the PD to degrade the NF of that. However, due to the two pumps waves standing in the same side, an OBPF attached after the SMF could be used to effectively suppress the noise. Moreover, differential detection is also feasible to mitigate the NF of the proposed MPF [18]. The improvement of the noise of the whole system with the help of a EDFA and EA with a lower NF to replace the used amplifiers is also important. Moreover, the propose MPF could be easily extended to achieve multitap complex coefficient MPF.

4. Conclusion

We have proposed and experimentally demonstrated a complex coefficient MPF with an unlimited bandwidth based on frequency transparent magnitude response using two SBS pumps. The complex coefficient is obtained with the help of a broadband microwave photonic phase shifter. The experimental results indicate that the frequency response of the complex coefficient MPF could be continuously tuned over the whole FSR without changing the shape and FSR. The operation bandwidth, in principle, of the MPF is not limited. Moreover, the proposed scheme could be extended as potential candidates for multitap complex coefficient MPF.

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