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Polarization dependence of stimulated Brillouin scattering-based switchable microwave photonic filter

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We propose and experimentally demonstrate a switchable microwave photonic filter based on polarization dependence of stimulated Brillouin scattering (SBS). The continuous optical wave from a tunable laser source is split into two branches. One branch serves as the SBS pump source and another branch serves as the signal source which are interactional to generate the SBS effect in the dispersion-shifted fiber. Only by adjusting the polarization direction of pump light and signal light, a frequency response switched between bandpass and notch filtering shape can be obtained.

Keywords: microwave photonic filter, stimulated Brillouin scattering, polarization dependence.

1. Introduction

The microwave photonic filter (MPF) has raised great attention due to its characteristic advantages, such as large bandwidth, light weight, flexible tunability, fast reconfigurability and immunity to electromagnetic interference (EMI) [1]. Most of the proposed MPFs are transversal photonics filters which exhibit periodic transfer function limiting the bandwidth of the radio frequency (RF) signals [2]. To overcome these drawbacks, several single bandpass filters have been implemented. The tunable MPFs have been proposed by means of a polarization modulator (PolM) with a fiber Bragg grating (FBG) [3], a broadband optical source (BOS) sliced by a Sagnac loop [4], a silicon opto-mechanical mirroring resonator (MRR) [5], a silicon photonic crystal (PhC) nanocavity [6], a polarization beam interferometer [7] and a flat passband based on phase modulation [8]. To meet the requirement of different signal shapes, a filtering shape switchable MPF is worth mentioning [9]. A filter is switchable and tunable based on stimulated Brillouin scattering (SBS), switching of the filter function is simply and conveniently obtained by changing the dc bias to the dual-driver Mach–Zehnder modulator (DDMZM) [10]. A MPF can be switched between low-pass and high-pass frequency responses using an optical phase modulator (PM) and two cascaded tunable optical bandpass filters (TOBFs), the switching function is implemented by tuning the position of the TOBFs [11]. Moreover, by tuning the power difference of two laser sources, a MPF of a bandpass, all-pass and notch filtering shape can also be obtained [12].

WEI LI *et al*. ever demonstrated a technique of utilizing the vector SBS process, which is different from the previously reported technique of using the scalar SBS process [13]. They proved the state of polarization (SOP) for the RF modulated sideband can be rotated by adjusting the SOP of pump light and signal light. According to the pioneering work of WEI LI *et al*., in this paper, a filtering shape switchable MPF based on phase modulation and polarization dependence of SBS is proposed and experimentally demonstrated. The filter can be switched between bandpass filtering shape and notch filtering shape only by adjusting the polarization direction of pump light and signal light. The bandpass frequency response has an out-of-band rejection ratio about 20 dB and a 3-dB bandwidth of 112 MHz, the notch frequency response has a depth of the notch about 30 dB and a 3-dB bandwidth of 21 MHz.

2. Principle

The structure of the proposed MPF is shown in Fig. 1. A light from a tunable laser source (TLS) is divided into two parts by using a 3-dB optical coupler (OC). The upper part includes polarization controller (PC1) and erbium-doped fiber amplifier (EDFA1), the lower part includes PC2, phase modulator (PM), EDFA2, isolator and dispersion -shifted fiber (DSF). The PM is driven by the RF sweep frequency signal f_{RF}, which is emitted from the vector network analyzer (VNA). After amplified by the EDFA2, the RF modulation signal is injected into a coil of DSF which combines the pump light to generate the SBS in DSF. The isolator is used to insulate the pump light transmitting through the optical circulator and the DSF into the TLS. After an optical attenuator (ATT), the RF modulation signal is detected by a photodetector (PD). The frequency response of the proposed MPF is also measured by the VNA.

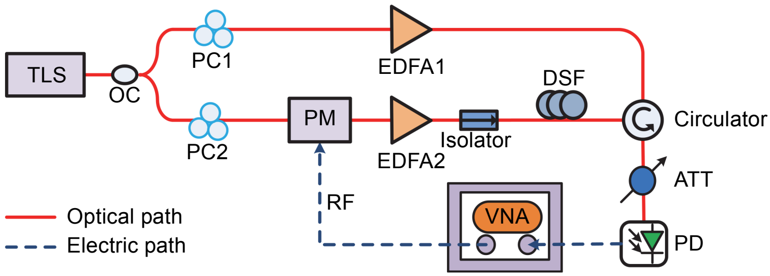

Fig. 1. Schematic diagram of the proposed switchable MPF; TLS – tunable laser source, OC – optical coupler, PC – polarization controller, PM – phase modulator, EDFA – erbium doped fiber amplifier, DSF – dispersion-shifted fiber, ATT – attenuator, PD – photodetector, VNA – vector network analyzer, and RF – radio frequency.

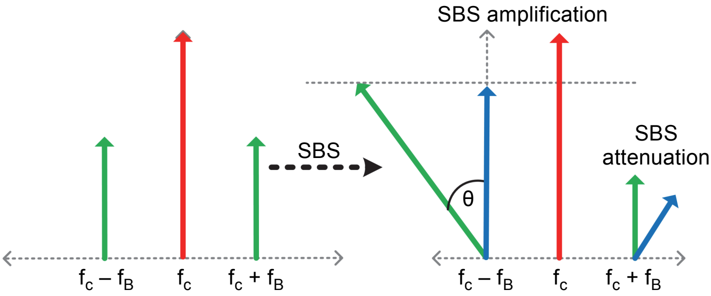

Fig. 2. Evolution of the RF modulated signal in the SBS interaction.

The SBS interaction is efficient only when the difference between the optical frequencies of the pump and signal waves is very close (within a few tens of MHz) to a fiber-dependent parameter, the Brillouin shift f_B, which is of the order of 10–11 GHz in silica fibers at room temperature and at telecommunication wavelengths [14]. As shown in Fig. 2, an input signal wave whose frequency is lower than that of the pump (Stokes wave) experiences SBS amplification. If the input signal frequency is above that of the pump (anti-Stokes wave), SBS-induced signal attenuation is obtained instead [15]. Moreover, the SBS interaction is found to be polarization-dependent and it is up to the input SOPs of both pump light and signal light [16]. Under high Brillouin gain conditions, the output SOP of arbitrarily polarized input signals would tend to converge towards that of maximum SBS gain [17]. In the case of high SBS attenuation, the output SOP of an arbitrarily polarized signal would approach the output SOP corresponding to minimum attenuation [16, 18]. After amplified by the SBS gain, the SOP rotation of the signal wave is denoted by θ. When the SOPs of the signal light and pump light are parallel, the SOP of the signal light will not be changed, which means that θ is 0. However, if the SOPs of the signal light and pump light are orthogonal, the SOP of the signal light will be driven by the pump light and the SOP rotation satisfies that $0 < \theta < \pi/2$. The SBS efficiencies for parallel and orthogonal polarizations can be expressed as $\eta_{\text{SBS-P}} = 2\cos(\theta)/3$ and $\eta_{\text{SBS-O}} = \cos(\theta)/3$, respectively [19, 20]. It can be concluded that the polarization pulling effect will decrease the SBS gain related to the MPF. Therefore, the SOPs of the pump and the probe waves will affect the SBS gain and further influence the frequency response of the MPF [21].

Through the phase modulation and the polarization dependence of SBS, the phase modulated signal can be expressed as [21]

$$\begin{aligned} E_{\text{PM}}(t) \;=\; & \sqrt{P_1}\, J_0(m_{\text{RF}}) \exp(j2\pi f_c t) + \sqrt{P_1}\, J_1(m_{\text{RF}}) \exp\left[j2\pi(f_c + f_m)t\right] \\ & - \sqrt{P_1}\, J_1(m_{\text{RF}}) \exp\left[j2\pi(f_c - f_m)t\right] \end{aligned} \tag{1}$$

where P_1 is the optical power of the continuous wave (CW) light λ_c, m_{RF} is the phase modulation index, J_n is the n-th order Bessel function of the first kind, f_c and f_m are the frequencies of the optical carrier and the RF signal emitted from the VNA, respectively.

When the phase modulated signal is injected into the DSF, the optical amplitude and phase are both affected by SBS. From (1), the forward-propagating optical field of the signal wave after the DSF can be achieved and expressed as

$$E(t) = \sqrt{P_1}\exp(j2\pi f_c t)\left\{J_0(m) + J_1(m)\exp\left[\left(g_B(f_m) + \alpha_B(f_m)\right)L + j2\pi f_m t\right] - J_1(m)\exp\left[-j2\pi f_m t\right]\right\} \quad (2)$$

where g_B and α_B represent the SBS gain factor and loss factor, respectively.

Then the optical signal is applied to PD and converted into electrical signal, which is recorded by VNA and the frequency response of the MPF is obtained. According to (2), the transfer function of the MPF can be obtained by neglecting the DC and higher order components and expressed as

$$H(f) = \Re\alpha_{ATT} P_1 J_0(m) J_1(m)\left\{G(f)A(f)\exp\left[j\left(\Phi_g(f) + \Phi_\alpha(f)\right)\right] - 1\right\} \quad (3)$$

where $\Re$ is the responsivity of PD, α_{ATT} is the attenuation efficient of ATT, $G(f)$ is the SBS gain, and $A(f)$ is the SBS loss, $\Phi_g(f)$ and $\Phi_\alpha(f)$ are the phase shift caused by SBS gain and SBS loss, respectively [14].

For small signal phase modulation, the passband at the lower frequency experiences SBS amplification and the passband at the higher frequency experiences SBS attenuation, so, the amplitude balance of sideband was broken. For the case of SBS gain, the amplitude of the +1st order sideband is amplified to a sufficiently large value. Correspondingly, the amplitude of the –1st order sideband is attenuated [2]. Hence, the beat between the ±1st order sideband and the optical carrier can achieve a bandpass frequency response. According to [21], the SOP of the signal light and the pump light affect the efficiency of SBS, which further influence the frequency response of the MPF. Therefore, by adjusting PC1 and PC2 to change the SOP of signal light and the pump light, the frequency response of the MPF was switched from the bandpass shape to the notch shape in the process. According to [22, 23], it can be seen that the notch shape is related to the phase shift of the SBS and the dispersion of the optical fiber.

3. Experimental results

The experimental setup for the switchable MPF is shown in Fig. 1. A continuous wave (CW) light emitted from a TLS (Yenista Optics Inc.) at 1564.496 nm with an output power of 14.5 dBm is divided into the two parts by using a 3-dB OC. The upper

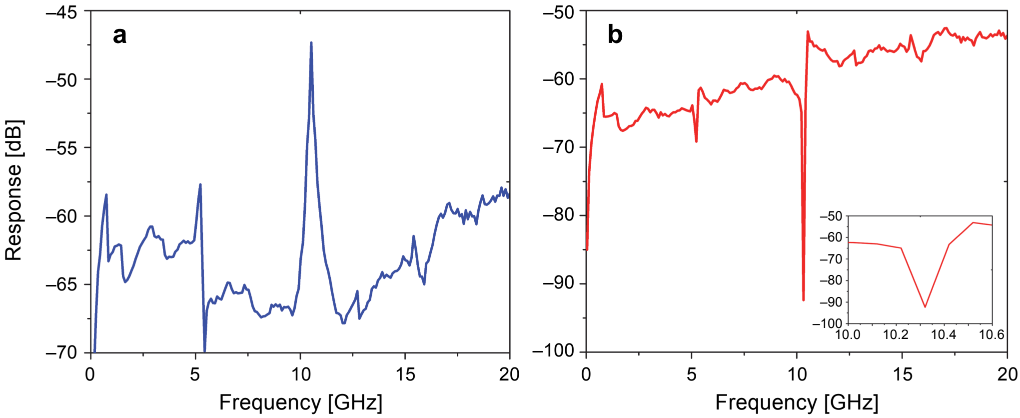

Fig. 3. Measured output frequency response of the filtering shape switchable MPF. The bandpass frequency response (**a**); the notch frequency response, inset: the zoom-in view of the notch response (**b**).

part as the SBS pump source includes a PC1 and an EDFA1 (KG-EDFA-P-O-D-FA). The PC1 is used to control the SOP of pump light and the EDFA1 is used to tune the power of pump light. A PC2 and a PM (Photoline, MPZ-LN-20) are comprised in the lower part. The PC2 is used to control the SOP of signal light. The PM is driven by the RF input signal f_{RF} which is emitted from the VNA (CETC, AV3629D). After amplified by an EDFA2, the RF modulation signal is injected into a coil of DSF (G.655 B8F14970DC10) whose length is about 1.025-km. The isolator in the lower part is used to insulate the pump light transmitting through the optical circulator (CIR-3-1550-900 -1-FA) and the DSF into the TLS. The SBS process occurs in the DSF between the signal light and the pump light. After the circulator, an ATT is used to keep the input power into the PD under 0 dBm for the sake of security of the system. Finally, the RF modulation signal is detected by a PD (u2t, XPDV2120R). The frequency response is measured via a VNA whose maximum sweeping frequency is 20 GHz. We adjust PC1 and PC2 to get a bandpass response, as shown in Fig. 3**a**, the frequency response exhibits a bandpass filtering shape as it is clearly appreciated for the filter centered at 10.537 GHz, a 3-dB bandwidth is about 112 MHz and an out-of-band rejection ratio is about 20 dB. Similarly, in Fig. 3**b**, the frequency response exhibits a notch filtering shape with a center frequency at 10.352 GHz, a 3-dB bandwidth is 21 MHz and the depth of the notch is about 30 dB.

4. Conclusion

A filtering shape switchable MPF based on phase modulation and polarization dependence of SBS is proposed and experimentally demonstrated. The MPF can be switched from bandpass filtering shape to notch filtering shape via changing the polarization direction of pump light and signal light. If the device and equipment in the system is further optimized, the filtering shape switchable MPF with wider adjustment range and deeper rejection ratio can be achieved.

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References

[1] CAPMANY J., ORTEGA B., PASTOR D., *A tutorial on microwave photonic filters*, Journal of Lightwave Technology **24**(1), 2006, pp. 201–229, DOI: 10.1109/JLT.2005.860478.

[2] RUICHEN TAO, XINHUAN FENG, YUAN CAO, ZHAOHUI LI, BAI-OU GUAN, *Widely tunable single bandpass microwave photonic filter based on phase modulation and stimulated Brillouin scattering*, IEEE Photonics Technology Letters **24**(13), 2012, pp. 1097–1099, DOI: 10.1109/LPT.2012.2195486.

[3] ENMING XU, XIUYOU HAN, *Microwave photonic single-passband filter with highly flexible tunability of bandwidth and frequency*, Optical Fiber Technology **33**, 2017, pp. 51–55, DOI: 10.1016/j.yofte.2016.11.007.

[4] JUN GU, FEI WANG, YOUXI LU, MENGMENG PENG, LUN SHI, CHANG-HEE LEE, *Cascaded fiber Sagnac loop-based microwave photonic multiband bandpass filter with a selectable passband frequency*, Chinese Optics Letters **15**(11), 2017, article ID 110603, DOI: 10.3788/COL201715.110603.

[5] LI LIU, YUE YANG, ZHIHUA LI, XING JIN, WENQIN MO, XING LIU, *Low power consumption and continuously tunable all-optical microwave filter based on an opto-mechanical microring resonator*, Optics Express **25**(2), 2017, pp. 960–971, DOI: 10.1364/OE.25.000960.

[6] YUN LONG, JINSONG XIA, YONG ZHANG, JIANJI DONG, JIAN WANG, *Photonic crystal nanocavity assisted rejection ratio tunable notch microwave photonic filter*, Scientific Reports **7**, 2017, article ID 40223, DOI: 10.1038/srep40223.

[7] YANBING JIN, ERWIN H. W. CHAN, XINHUAN FENG, XUDONG WANG, BAI-OU GUAN, *Tunable negative coefficient microwave photonic filter based on a polarization modulator and a polarization beam interferometer*, Chinese Optics Letters **13**(5), 2015, article ID 050601, DOI: 10.3788/COL201513.050601.

[8] YUAN YU, ENMING XU, JIANJI DONG, LINA ZHOU, XIANG LI, XINLIANG ZHANG, *Switchable microwave photonic filter between high Q bandpass filter and notch filter with flat passband based on phase modulation*, Optics Express **18**(24), 2010, pp. 25271–25282, DOI: 10.1364/OE.18.025271.

[9] JIANPING YAO, *Photonics to the rescue: a fresh look at microwave photonic filters*, IEEE Microwave Magazine **16**(8), 2015, pp. 46–60, DOI: 10.1109/MMM.2015.2441594.

[10] WEIWEI ZHANG, MINASIAN R.A., *Switchable and tunable microwave photonic Brillouin-based filter*, IEEE Photonics Journal **4**(5), 2012, pp. 1443–1455, DOI: 10.1109/JPHOT.2012.2209114.

[11] YUAN YU, HAITAO TANG, LU XU, XIAOLONG LIU, FAN JIANG, JIANJI DONG, XINLIANG ZHANG, *Switchable microwave photonic filter between low-pass and high-pass responses*, IEEE Photonics Journal **8**(5), 2016, article ID 5501408, DOI: 10.1109/JPHOT.2016.2602081.

[12] ENMING XU, JIANPING YAO, *Frequency- and notch-depth-tunable single-notch microwave photonic filter*, IEEE Photonics Technology Letters **27**(19), 2015, pp. 2063–2066, DOI: 10.1109/LPT.2015.2450719.

[13] WEI LI, LI XIAN WANG, NING HUA ZHU, *All-optical microwave photonic single-passband filter based on polarization control through stimulated Brillouin scattering*, IEEE Photonics Journal **5**(4), 2013, article ID 5501411, DOI: 10.1109/JPHOT.2013.2271716.

[14] BOYD R.W., *Nonlinear Optics*, 2nd Ed., Academic Press, 2003.

[15] NIKLES M., THEVENAZ L., ROBERT P.A., *Brillouin gain spectrum characterization in single-mode optical fibers*, Journal of Lightwave Technology **15**(10), 1997, pp. 1842–1851, DOI: 10.1109/50.633570.

[16] ZADOK A., ZILKA E., EYAL A., THÉVENAZ L., TUR M., *Vector analysis of stimulated Brillouin scattering amplification in standard single-mode fibers*, Optics Express **16**(26), 2008, pp. 21692–21707, DOI: 10.1364/OE.16.021692.

[17] PREUSSLER S., ZADOK A., WIATREK A., TUR M., SCHNEIDER T., *Enhancement of spectral resolution and optical rejection ratio of Brillouin optical spectral analysis using polarization pulling*, Optics Express **20**(13), 2012, pp. 14734–14745, DOI: 10.1364/OE.20.014734.

[18] THEVENAZ L., ZADOK A., EYAL A., TUR M., *All-optical polarization control through Brillouin amplification*, OFC/NFOEC 2008 – 2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference, DOI: 10.1109/OFC.2008.4528363.

[19] YAO X.S., *Phase-to-amplitude modulation conversion using Brillouin selective sideband amplification*, IEEE Photonics Technology Letters **10**(2), 1998, pp. 264–266, DOI: 10.1109/68.655379.

[20] VAN DEVENTER M.O., BOOT A.J., *Polarization properties of stimulated Brillouin scattering in single -mode fibers*, Journal of Lightwave Technology **12**(4), 1994, pp. 585–590, DOI: 10.1109/50.285349.

[21] HAITAO TANG, YUAN YU, CHI ZHANG, ZIWEI WANG, LU XU, XINLIANG ZHANG, *Analysis of performance optimization for microwave photonic filter based on stimulated Brillouin scattering*, Journal of Lightwave Technology **35**(20), 2017, pp. 4375–4383, DOI: 10.1109/JLT.2017.2740948.

[22] XIAOQIANG SUN, SONGNIAN FU, KUN XU, JUNQIANG ZHOU, PERRY SHUM, JIE YIN, XIAOBIN HONG, JIAN WU, JINTONG LIN, *Photonic RF phase shifter based on a vector-sum technique using stimulated Brillouin scattering in dispersion shifted fiber*, IEEE Transactions on Microwave Theory and Techniques **58**(11), 2010, pp. 3206–3212, DOI: 10.1109/TMTT.2010.2074811.

[23] KOBYAKOV A., SAUER M., CHOWDHURY D., *Stimulated Brillouin scattering in optical fibers*, Advances in Optics and Photonics **2**(1), 2010, pp. 1–59, DOI: 10.1364/AOP.2.000001.

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