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Ultra-narrow bandwidth and large tuning range single-passband microwave photonic filter based on Brillouin fiber laser

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ABSTRACT

A scheme to perform ultra-narrow filter bandwidth and high frequency selectivity microwave photonic filter (MPF) with wide tuning range is proposed and experimentally demonstrated. The ultra-narrow bandwidth of the MPF is implemented by a Brillouin laser resonator, which is composed of a cascaded ring Fabry–Pérot (CR-FP) resonator formed by a main cavity with a cavity length of 100 m and a secondary cavity with a cavity length of 10 m. A Brillouin laser resonator is formed by the main cavity to obtain an extremely narrow comb-shaped Brillouin gain spectrum. The Vernier effect of the double ring cavity can effectively suppress the side modes, thereby realizing the narrow linewidth Brillouin laser filtering. Besides, two identical tunable lasers provide the stimulated Brillouin scattering (SBS) pump light and optical carrier signal for this device respectively. After the interaction between the Brillouin gain spectrum and the optical modulation signal, the filter passband can be stably tuned by simply changing the wavelength of SBS pump light. The experimental results show that the microwave photonic filter can be stably tuned in the frequency range of 0–20 GHz, the out-of-band rejection ratio is about 20 dB, and the minimum 3 dB bandwidth is about 114 Hz.

1. Introduction

Microwave photonic filter (MPF) features with the advantages of low loss, large bandwidth and anti-electromagnetic interference has gradually developed into a key technology for high-frequency broadband signal control and processing [1–3]. With the increasing requirements for filter frequency selectivity in frontier technologies such as high-purity spectrum microwave signal generation, high-sensitivity microwave photonic sensing, and high-resolution microwave photonic radar [4–6], MPF with large tuning range and ultra-narrow bandwidth (kHz or even sub-kHz) has gradually become a hot and difficult research topic in the field of microwave photonic technology in recent years.

The importance of MPF for improving the capacity of microwave system is self-evident. The filter with ultra narrow bandwidth means it is able to provide high frequency selectivity, and with the wide tunable range means that it can achieve high-performance flexible filtering. Up to now, a variety of schemes and strategies to realize narrow band tunable filtering are proposed such as specially designed fiber Bragg grating [7], Fabry–Pérot cavity [8], high birefringency fiber loop mirror [9], Mach Zehnder interferometer [10,11], cascaded microring resonator [12] and narrow-band optical filter based on SBS effect [13]. Among them, stimulated Brillouin scattering (SBS) effect has the characteristics of narrow linewidth, low threshold and high gain, which makes the microwave photonic filter based on SBS effect become the most potential direction to achieve high resolution, high rejection ratio and single pass band filtering. The basic principle of this kind of MPF is employing the interaction between Brillouin Stokes gain and modulated optical sideband signal to realize MPF high frequency selective filtering through SBS phase intensity (PM-IM) modulation conversion [14–16]. Therefore, the response of band-pass filtering bandwidth depends on the linewidth of SBS stokes. However, due to the natural SBS linewidth is defined by the phonon lifetime in the optical fiber material [17], the Brillouin gain spectrum bandwidth of the order of MHz cannot extract the fine frequency components below the order of MHz, which limits its further application in ultra-high resolution filtering. For this reason, various methods of further compressing the filter bandwidth have been reported in the literatures [6,18,19]. Preussler et al. [18] superimposed Brillouin gain spectrum and Brillouin loss spectrum to reduce the gain spectrum linewidth to 3.4 MHz, about 17% of the natural Brillouin gain bandwidth. However, in order to compensate the maximum gain loss, this method needs higher pump power. Tang et al. [6] obtained about

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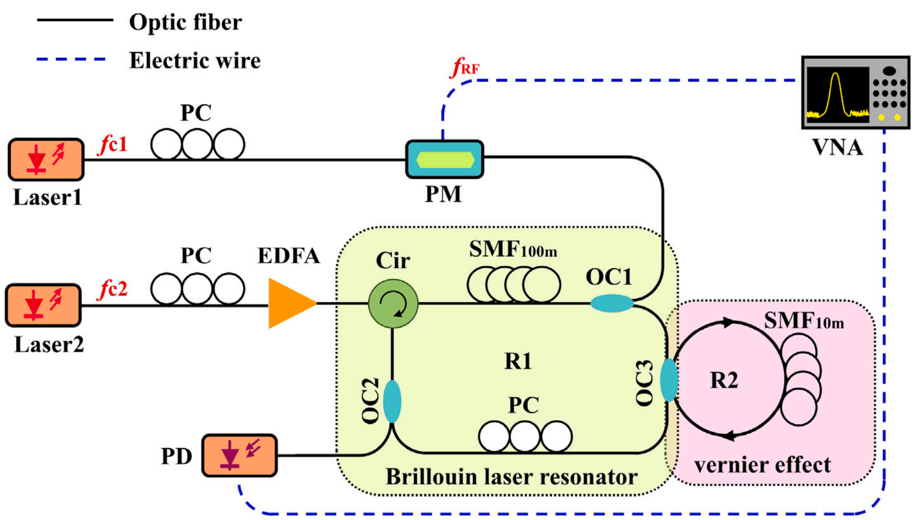

Fig. 1. Experimental setup of the MPF. OC,optical coupler; PM, phase modulator; EDFA, erbium-doped fiber amplifier; PC, polarization controller; Cir, circulator; SMF, Single mode fiber; PD, photodetector; VNA, vector net analyzer; OSA, optical Spectrum Analyzer.

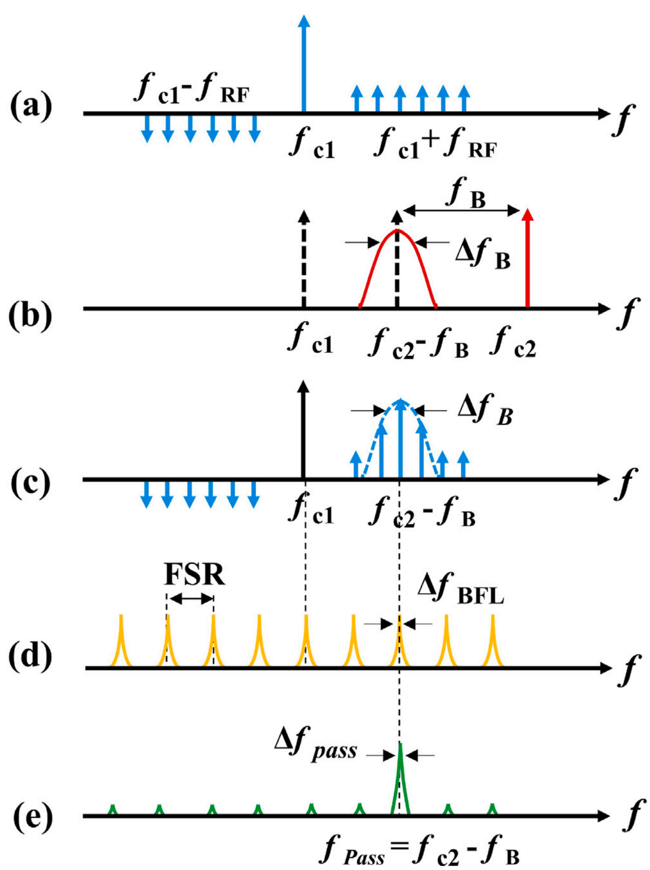

Fig. 2. Schematic of the MPF. (a) and (b) Illustrated optical spectra of the DSB modulated signal and SBS respectively. (c) Illustrated amplification of the upper sideband of the DSB modulated signal using SBS. (d) Illustrated response of the FRR. (e) Illustrated response of the MPF.

150 kHz ultra narrow linewidth by cascading SBS based microwave photonic filter and infinite impulse response based microwave photonic filter, but the structure of this method is relatively complex. Wen et al. [19] used the ultra narrow resonance linewidth of the fiber ring resonator to greatly compress the filter bandwidth of the MPF, and the final obtained filter bandwidth is about 900 kHz. Inspired by this method, if the Brillouin laser resonator can be exploited in the design of MPF, it not only does not need an external fiber ring resonator, but also can directly use the natural narrow linewidth characteristics of Brillouin laser to obtain ultra-narrow filter bandwidth.

In order to improve the flexibility of MPF, a large number of methods have been proposed in recent years to achieve its wide tunable range [16,19–25]. To sum up, there are two main ways to achieve tunability: (1) The center frequency of MPF can be adjusted by adjusting the propagation time of the signal loaded light in the dispersive medium. Among them, the most common is to change the length of dispersive media (such as dispersive fiber). For instance, in the literature [20], the loop length is changed by adjusting the optical variable delay line to change the FSR accordingly, so as to achieve MPF tunability. However, the tuning process of this kind of tunable MPF is relatively troublesome, and it is difficult to achieve continuous tuning. (2) The center frequency of MPF can be tuned by adjusting the wavelength of SBS pump. For example, Li et al. [16] proposed a dual passband tunable microwave photonic filter based on the realization of dual wavelength Brillouin pump by using the carrier suppression of electro-optic modulator. The tuning of MPF passband is realized by adjusting the RF oscillation frequency applied to the electro-optical devices. Wen et al. [19] and Tao e al. [26] achieved MPF center frequency tuning by directly changing the pump wavelength of the SBS respectively. Compared with the previous tunable MPF, this tunable MPF is more convenient to operate and can realize continuous tuning.

Therefore, in order to meet the urgent application requirements of ultra-narrow band and flexible tunable MPF in photonics fields such as high-purity spectrum microwave photonic generation, high-sensitivity microwave photonic sensing, high-precision microwave photonic radar, etc, an tunable ultra-narrow band tunable MPF based on narrow linewidth Brillouin laser is proposed in this paper. The basic idea is to use narrow linewidth Brillouin laser gain to realize ultra-narrow band microwave photonic filtering, which is different from the method of directly using Brillouin gain to complete optical microwave signal processing. The specific implementation method is to introduce Brillouin laser resonator into the structure design of MPF to realize the ultra-narrow band characteristics. On this basis, the wide tuning range of MPF is achieved by changing the wavelength of stimulated Brillouin scattering pump light.

2. Operation principle

The realization of the ultra-narrow bandwidth and large tuning range of the MPF in this paper is based on the single longitudinal

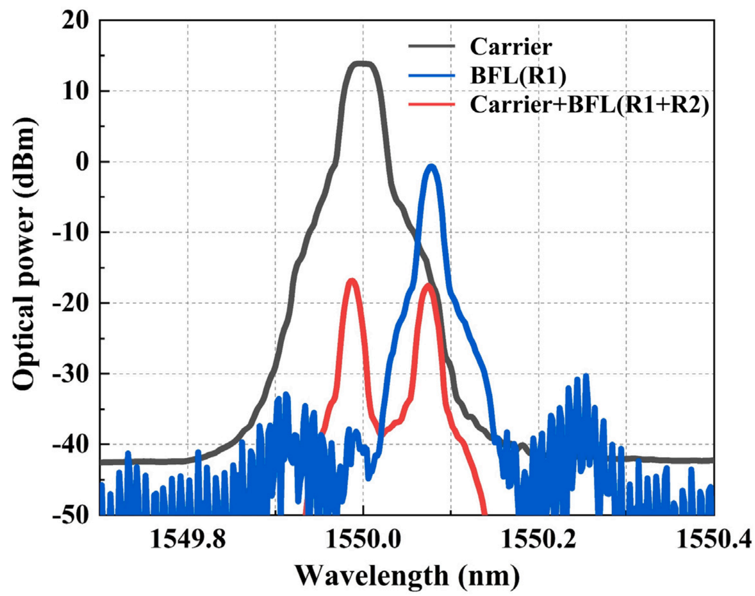

Fig. 3. Optical spectra of pump (laser2) injected into the SMF, the frequency-downshifted SBS from the SMF and combined signals of DSB modulated signal and SBS.

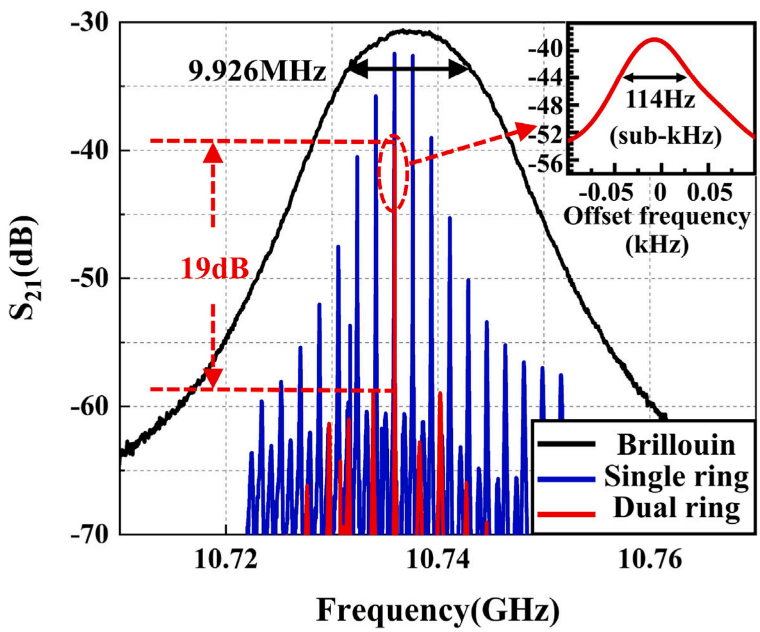

Fig. 4. Frequency responses corresponding to different MPF structures. (Black line, no ring cavity; blue line, single ring Brillouin laser resonator; red line, cascaded double ring (CR-FP) Brillouin laser resonator.).

mode fiber stimulated Brillouin oscillator. The basic principle is that the Brillouin gain interacts with the modulated optical sideband signal, and then the signal amplified by the Brillouin gain is narrowed under the natural frequency selection and linewidth compression mechanism of the Brillouin laser resonator. Finally, the ultra-narrow filter bandwidth is obtained through beat frequency. By changing the wavelength of SBS pump light, the Brillouin gain position is shifted to solve the widely tunable problem of MPF. Fig. 1 shows the scheme adopted to experimentally demonstrate the proposed MPF. On the whole, the experimental setup can be roughly divided into two branches, i.e., the upper branch is the carrier and signal modulation part, and the lower branch is the Brillouin laser resonator signal processing part. The optical carrier is from a tunable laser (NKT X15, linewidth 100 Hz) and centered at 1550 nm. A swept RF signals f_{RF} from a vector network analyzer (VNA) is double sideband modulated (DSB) by the phase modulator (PM, ixblue MPZ-LN-20) to the optical carrier. The optical spectrum of DSB modulated signal is exhibited in Fig. 2(a). The upper sideband, $f_{c1}+f_{RF}$ and the lower sideband, $f_{c1}-f_{RF}$, together with the optical carrier is then launched into the Brillouin laser resonator through a coupler (OC1, 50:50).

In the lower branch, laser2, f_{c2}, emitted from the other tunable laser (NKT X15, linewidth 100 Hz) is amplified by erbium-doped fiber amplifier (EDFA) as pump light and injected into 100 m single-mode fiber (SMF) through a circulator (Cir). Adjusting the EDFA output to make the power of the injected light is greater than the Brillouin threshold, which guarantees self-induced SBS in the SMF. As displayed in Fig. 2(b), the pump light is frequency downshifted to $f_{c2}-f_B$, where f_B (about 10.737 GHz in our experiment) is the Brillouin frequency shift. The linewidth of Brillouin gain spectrum is Δf_B. During the interaction between the optical modulation signal and the SBS gain

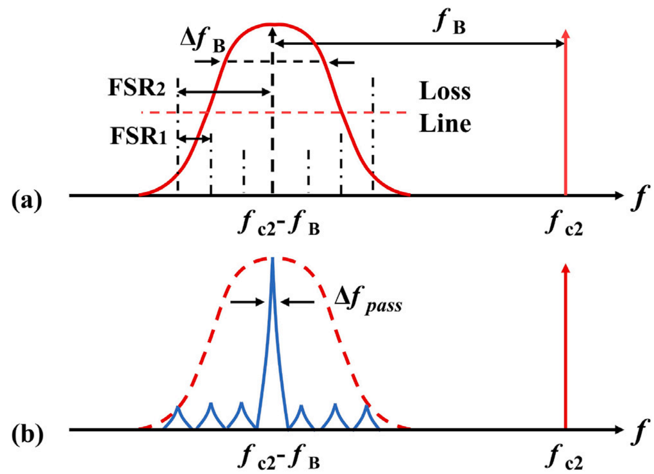

Fig. 5. Schematic of the principle of suppression of side mode via the Vernier effect.

spectrum, the part falling in the Brillouin gain spectrum in the upper sideband of the optical modulation signal is amplified by the SBS gain, as shown in Fig. 2(c). The mixed optical signal enters the Brillouin laser resonator (R1) through cir. The resonator exhibits periodic resonance, and the linewidth of each resonance is extremely narrow as illustrated in Fig. 2(d), which is because the narrow linewidth Brillouin gain spectrum as the natural frequency selection mechanism of Brillouin oscillator makes it have significant linewidth compression effect. Brillouin laser resonator is connected with a 10 m long single-mode fiber ring (R2) through coupler (OC3, 50:50). Owing to the Vernier effect of the cascaded ring Fabry–Pérot (CR-FP) resonator, the FSR of Brillouin laser resonator is expanded from 1.86MHz to 18.6MHz, and the linewidth is further compressed as presented in Fig. 2(e). By tuning the wavelength of laser2 to shift the frequency of the pump, the central frequency of SBS gain spectrum will move accordingly. Therefore, the designated part of the upper sideband can be selectively amplified to realize the tunable function of MPF. Finally, the output light passes through a coupler (OC2, 10:90). Among them, 90% of the light is injected counterclockwise into the R1 cavity to continue resonating, and 10% of the output light is detected by a photodetector (PD, Finisar XPDV21). The frequency response of proposed MPF is characterized by the VNA.

3. Experiment results and discussion

A proof-of-concept experiment is carried out on the configuration illustrated in Fig. 1. Before measuring the frequency response of the proposed MPF filter, optical spectra of pump (laser2) injected into the SMF, the frequency-downshifted SBS from the SMF and combined signals of DSB modulated signal and SBS are tested respectively. The test results are compared in Fig. 3. In this measurement, the wavelength of the pump light (laser2) is set to 1550.00 nm, and its spectrum is shown as the black line. Set the output power of the EDFA to 29 dBm, the output spectrum of the Brillouin light oscillator is shown as the blue line, and the wavelength is about 1550.08 nm. Therefore, the wavelength difference between the pump light and the SBS passband is about 0.08 nm, corresponding to the amount of 10 GHz Brillouin shift in the frequency domain. When the VNA is operated with sweep signal. The combined signals of DSB modulated signal and SBS spectrum is shown as the red line, appearing as a dual-wavelength spectrum. Among them, One beam (left) is the optical carrier output by laser1, the other beam (right) is the Brillouin laser output of the CR-FP resonator because its wavelength is equal to the wavelength of Brillouin Stokes.

By inputting the proposed MPF optical signal into the PD, it is input into the VNA after photoelectric conversion. The passband responses of the MPF only through Brillouin gain, single ring Brillouin laser resonator and cascaded double ring (CR-FP) Brillouin laser resonator are measured respectively, and the results are shown in Fig. 4. Among them, the black line indicates the frequency response when MPF with no ring cavity, i.e. the MPF processes the sideband signal only by Brillouin gain, so the bandwidth at this time is equal to the Brillouin gain linewidth. It can be observed that the 3 dB bandwidth of the Brillouin gain is about 9.926 MHz. The blue line indicates the frequency response when MPF with single ring Brillouin laser resonator. When only R1 is added to the optical path to form a Brillouin fiber resonant cavity, the Brillouin stokes is amplified many times in the resonator. At this time, the R1 exhibits periodic resonance. The 3 dB linewidth of each resonant peak is greatly narrowed than Brillouin gain obviously, but the laser side mode is not suppressed. Therefore, the passband response of the MPF shows a comb like shape. The red line indicates the frequency response when MPF with cascaded double ring (CR-FP) Brillouin laser resonator. The side mode of the Brillouin laser is well suppressed by the Vernier effect of the CR-FP, and the side mode suppression ratio exceeds 19 dB. So the MPF exhibits an ultra-narrow single pass band response. The bandwidth of the corresponding frequency response is zoomed-in as the insert shows, and the 3 dB bandwidth of 114 Hz (sub-kHz level) is obtained.

Fig. 5 shows the linewidth narrowing mechanism of cascaded CR-FP structure. Δf_B is the SBS linewidth and f_B is the Brillouin frequency shift related to the SBS pump light, which is defined as $f_B = 2n\upsilon_a/\lambda$, where υ_a is the speed of sound in the medium, n is the effective refractive index in the fiber, and λ is the wavelength of the pump light. When the pump wavelength is 1550 nm, the Brillouin frequency shift f_B of the excitation is 10.737 GHz. According to the Vernier effect, the effective FSR of the double-ring cavity structure is the least common multiple of R1 and R2,

$$\mathrm{FSR} = n_1\mathrm{FSR}_1 = n_2\mathrm{FSR}_2 \tag{1}$$

FSR_1 corresponds to the 100 m SMF of the ring cavity R1, FSR_2 corresponds to the 10 m SMF of the ring cavity R2, and n_m (m=1, 2) is an integer. The effective FSR of R1, R2 is expressed as,

$$\mathrm{FSR} = \frac{c}{nL_m} \tag{2}$$

Where L_m (m=1, 2) is the ring length of R1 and R2, and n is the effective refractive index of the fiber (here n =1.468 in our experiment). Therefore, the FSRs of R1 and R2 are 1.86 MHz and 18.6 MHz, respectively. According to Eq. (2), the effective FSR is 18.6 MHz. To avoid the multiple passbands of the MPF, the FSR determined by the double-ring cavity structure should not be smaller than the linewidth of the Brillouin gain spectrum. When the effective FSR exceeds the Brillouin gain linewidth and the gain is greater than the loss, the lasing mode oscillates only at frequencies that satisfy both the R1 and R2 resonance conditions.

As demonstrated in Fig. 2, the center frequency of the microwave photonic filter, f_{pass}, can be expressed as,

$$f_{pass} = f_{c2} - f_B \tag{3}$$

Fig. 6 shows the center frequency response of the MPF when the pump light wavelength varies from 1550.2320 to 1550.3920 nm. It is clearly that, by changing the wavelength of the pump light, the MPF filter passband is stably tuned in the frequency range of 2–20 GHz with the tuning step size of approximately 2 GHz, which is attributed to the frequency difference between the Brillouin gain and the pump light is relatively fixed. By tuning the wavelength of laser2, the frequency of SBS gain will move accordingly. Therefore, the designated part of the upper sideband of the modulated optical signal can be selectively amplified to realize the tunable function of MPF. It is worth noting that according to the Brillouin frequency shift formula $f_B = 2n\upsilon_a/\lambda$, when the laser wavelength λ changes by 0.1 pm, the Brillouin frequency shift will change by 600 Hz accordingly. At the same time, in this scheme, when the pump wavelength is tuned by 0.1 pm, the frequency shift of

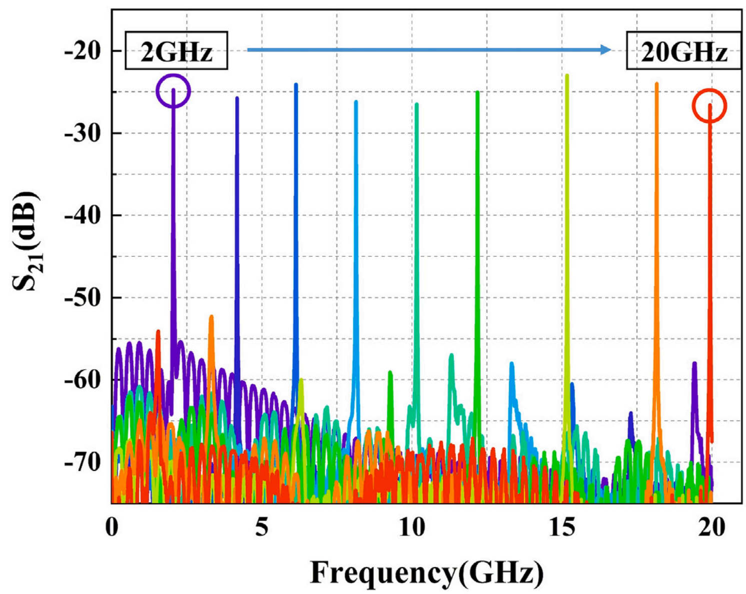

Fig. 6. The frequency response of the MPF when the wavelength of the modulated light is between 1550.2320 nm and 1550.3920 nm.

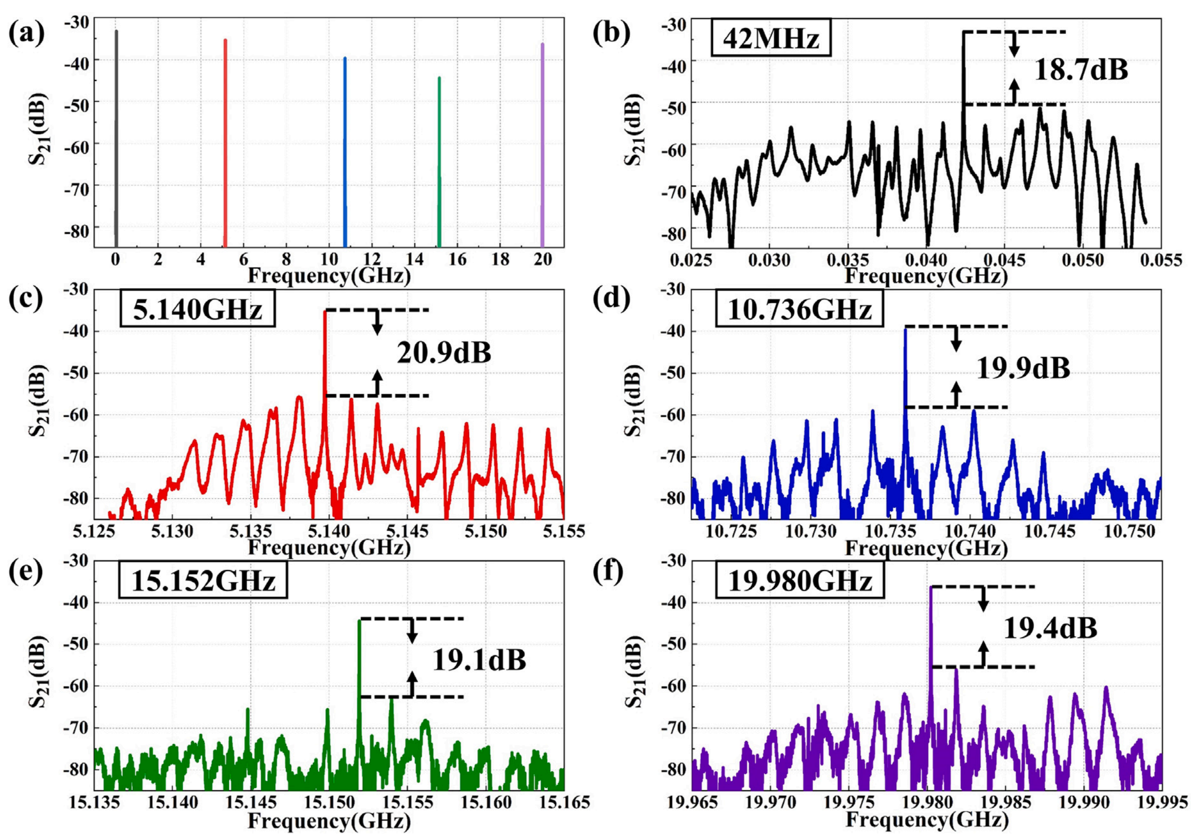

Fig. 7. Measured stability and out of band rejection ratio of MPF at different frequency responses.

the center frequency of the filter passband is 12.5 MHz, it can be seen that the influence of the Brillouin frequency shift caused by the change of the pump wavelength on the tuning of the passband is basically negligible.

In order to analyze the narrow-band tunable filtering effect of this scheme, the filter passband width is further tested experimentally. Fig. 7(a) is a comparison diagram of the MPF center frequency tuning response. It can be seen from the figure that the center frequency of the filter passband is stably tuned within the range of 42 MHz to 19.98 GHz with a tuning interval of about 5 GHz in steps. In this frequency range, the MPF has a stable out-of-band rejection ratio. In the experiment, the narrowest 3 dB bandwidth of MPF is only about 100 Hz. Compared with the bandwidth of about 900 kHz in [19], it means that the proposed MPF has higher frequency selectivity. The MPF responses at different center frequencies are shown in Fig. 7(b–f). It can be clearly observed from the images that the passband side modes of the CR-FP resonator MPF are significantly suppressed, and the measured side mode suppression ratios in the tuning range are 18.7, 20.9, 19.9,

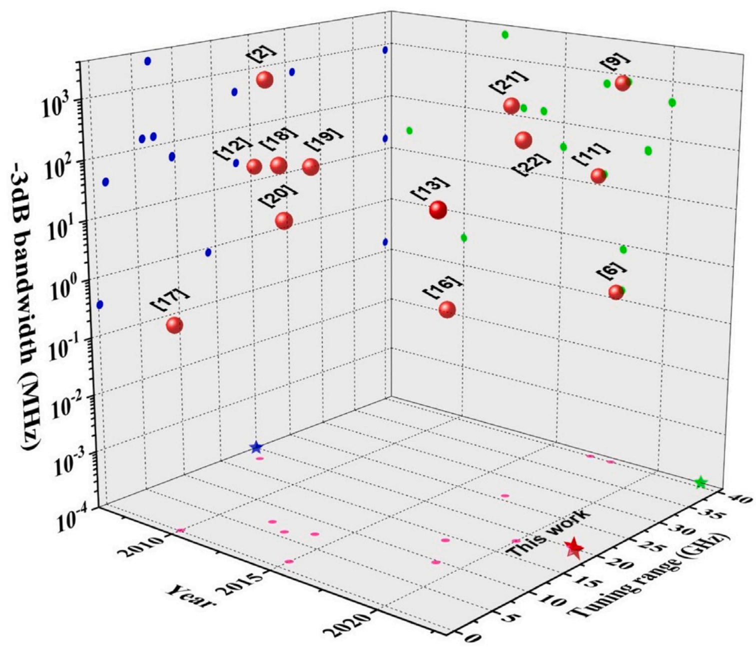

Fig. 8. Comparison of MPF passband width and tuning range reported in recent literatures.

19.1, 19.4 dB respectively, the fluctuation is less than 2.2 dB. The main reasons for this fluctuation are, on the one hand, changes in ambient temperature, and on the other hand, since the SBS coupling efficiency is closely related to the polarization directions of the pump light and Stokes light, the reason for this fluctuation may also originate from the error generated when the polarization controller in the fiber Brillouin resonator adjusts the polarization matching of the pump light and the Brillouin stokes light.

Fig. 8 displays the comparison of bandwidth and tuning range between the MPF proposed in this work and the MPFs reported in recent literatures. It is clear that, The bandwidth of existing MPFs is mostly in the order of MHz or sub-MHz, while the bandwidth of MPF proposed in this work is basically in the order of sub-kHz. In addition, the filter has a tuning range of more than 20 GHz and an out of band rejection ratio of about 20 dB. Thus it can be seen that the MPF proposed in this work has significant advantages in high frequency resolution, strong agility and high isolation filtering. Therefore, it has great potential for ultra-narrow linewidth microwave photonics generation and flexible processing.

4. Conclusion

In conclusion, a tunable narrow-band MPF based on SBS fiber resonator is proposed and verified experimentally. Different from the direct use of the Brillouin gain to complete the optical carrier microwave signal processing, this paper introduces the Brillouin oscillator into the design of the microwave photonic filter structure. The narrowband filtering of MPF is realized by utilizing the obvious spectral compression characteristic of Brillouin Stokes after multiple amplifications in the cavity. At the same time, the Vernier effect of CR-FP resonator formed by the main cavity length of 100 m and the secondary cavity length of 10 m is used to further narrow the filter bandwidth and achieve high out of band rejection ratio. Two different tunable lasers are used as SBS pump light and optical carrier signal, respectively. In the case of overcoming the influence of external environmental factors and maintaining the stability of the Brillouin frequency shift, the MPF stable tuning function can be realized by simply changing the wavelength of the SBS pump light through the beat frequency. The experimental results show that the minimum pass-band bandwidth of the single-pass MPF proposed in this paper is only 114 Hz, which can be continuously tuned in the range of 0–20 GHz, and has a stable out-of-band rejection ratio close to 20 dB. This study is of great significance for the development of microwave photonic filter devices with high frequency resolution and strong flexible filtering ability.

CRediT authorship contribution statement

Xin Xu: Conducted experimental work, Analyzed data, Writing – original draft, Writing – review & editing. **Yajun You:** Conceived the idea, Designed the experiments, Writing – review & editing. **Jiaxin Hou:** Conducted experimental work, Writing – review & editing. **Linyi Wang:** Conducted experimental work, Writing – review & editing. **Liuyan Feng:** Conducted experimental work, Writing – review & editing. **Wenjun He:** Analyzed data, Writing – original draft, Writing – review & editing. **Wenping Geng:** Analyzed data, Writing – original draft, Writing – review & editing. **Yi Liu:** Conceived the idea, Designed the experiments, Writing – review & editing. **Xiujian Chou:** Conceived the idea, Designed the experiments, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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