Tunable multi-wavelength microwave photonic filter based on the superposition of transfer functions

Yang Yu (俞 杨), Xiaoping Zheng (郑小平)*, Hanyi Zhang (张汉一), and Bingkun Zhou (周炳琨)

Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

*Corresponding author: xpzheng@tsinghua.edu.cn

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A microwave photonic filter (MPF) with reconfigurability and tunability resulting from the superposition of the transfer functions is proposed. Based on the Vernier effect between the optical frequency combs and the periodic optical filters, each comb line can be mapped into a sub-filter in the electronic field. The sub-filters are superposed to obtain the total transfer function of the MPF. By manipulating a few comb lines, we can reconfigure the passband shape, tune the bandwidth, and adjust the center frequency independently. Experiments verify that the bandwidth can be tuned from 224.8 to 674.3 MHz, and that the center frequency ranges from 1 to 4 GHz.

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Microwave photonic filter (MPF) is a promising technique because of its wide band, tunability, reconfigurability, and immunity to electromagnetic interference. MPF is currently a popular research topic, and it has a number of potential applications in many fields, such as in radar systems, wireless communication, and radio astronomy[1,2].

Numerous MPF approaches have been reported[3−12]. The finite impulse response MPF (FIRMPF) exhibits tunability and reconfigurability and is typically implemented based on a dispersive medium and an optical source, such as optical frequency combs (OFCs)[1−4]. To improve selectivity, a large number of comb lines must be employed. Another approach is the infinite impulse response MPF, which has a higher Q value[5,6]. This approach typically considers recirculating delay lines or resonators. Consequently, its tunability is poor. The approach based on stimulated Brillouin scattering can obtain a bandwidth of approximately 20 MHz and its passband is not reconfigurable[7]. Several new approaches that employ optical filters have been proposed recently[8−13]. Some of these approaches are based on phase-modulation to intensity-modulation (PM–IM) conversion and have the advantages of a single branch, a simple structure, and a flexible tunability. In Ref. [12], a MPF with a tunable center frequency and bandwidth is reported. This MPF uses a phase modulator (PM) and a tunable optical passband filter that consists of two cascading fiber Bragg gratings (FBGs), which results in a wide bandwidth. In Ref. [13], a MPF with a tunable center frequency is implemented by employing a phase-shifted FBG. The FBG serves as an optical notch filter. The bandwidth of the MPF is approximately 60 MHz and is fixed with the FBG.

In this letter, we demonstrate a tunable and reconfigurable MPF that is implemented by employing OFCs, a pulse shaper, a PM, and an optical filter. The proposed MPF offers a periodic notch response. As a result of the PM–IM conversion via the notch filter, each comb is mapped into a corresponding sub-filter in the electronic field. The sub-filters differ from one another because of the Vernier effect between the optical filter period and the OFCs. By superposing the transfer function of these sub-filters, the MPF becomes tunable and reconfigurable. In this scheme, only a few lines of optical combs are required.

The schematic diagram of the proposed MPF is illustrated in Fig. 1(a). The optical combs from the OFC source are manipulated line-by-line by a pulse shaper[14]. By using a liquid-crystal spatial light modulator (SLM), the pulse shaper can spatially separate combs and focus them on different pixels of the SLM. These pixels can independently control the optical intensity of individual combs. The shaped optical

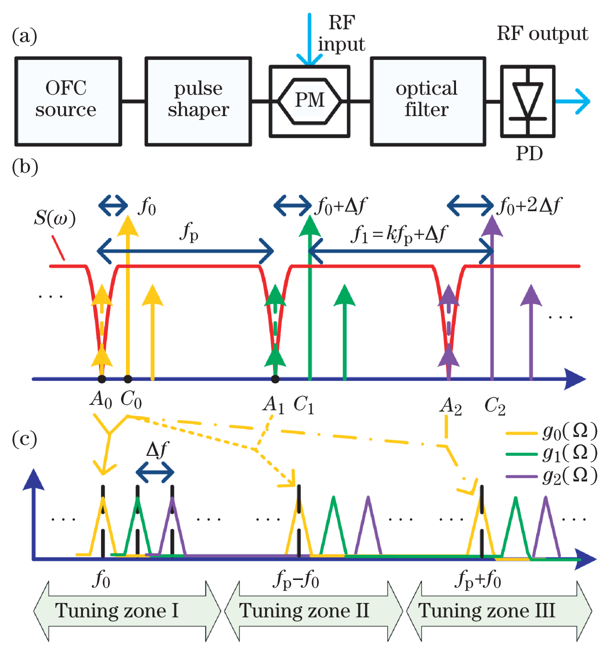

Fig. 1. Operation principle. (a) Schematic diagram. (b) PM–IM conversion and comb lines with phase modulation. $S(\omega)$ is the response of the optical filter. (c) Vernier effect and sub-filters. The sub-filters have the same color as their corresponding combs.

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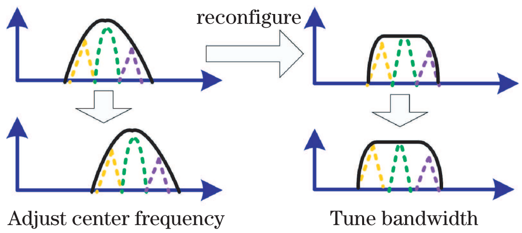

Fig. 2. Tunability and configurability.

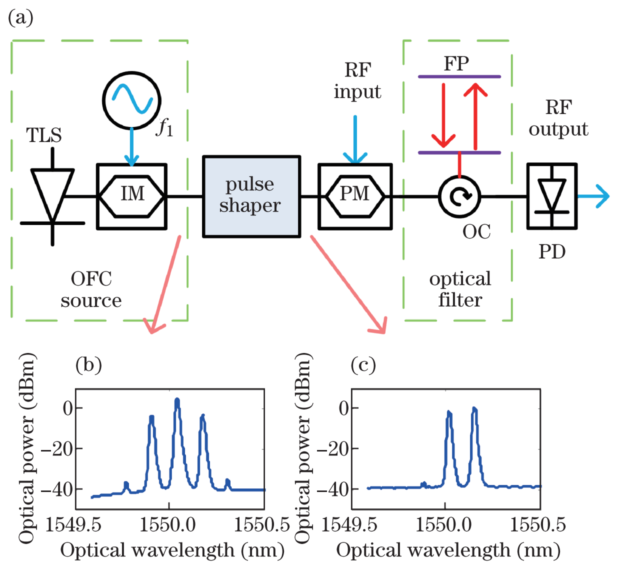

Fig. 3. Experimental setup. (a) Schematic diagram. (b) The optical spectrum of the OFC. (c) An example of a shaped OFC spectrum.

combs are injected into the PM to carry the radio frequency (RF) signal and is launched into a periodic notch optical filter for modification. The output light is finally fed into a photodetector (PD) for measurement.

The sub-filter is associated with PM–IM conversion[12,13]. As shown in Fig. 1(b), the first-order sidebands of individual combs are anti-phase because of phase modulation. No RF signal output if it is detected directly by the PD. When it is passed through the optical filter, the intensity-phase relationship between the two sidebands is altered. Thus, each comb will take a sub-filter, as shown in Fig. 1(c). The first peak of the sub-filter is attributed to the PM–IM conversion between comb C_0 and notch A_0, the second peak is attributed to that between C_0 and A_1, and so on. If the free spectrum range (FSR) of the optical filter is f_p and the interval between C_0 and A_0 is f_0, then the peaks of the MPF appear around $nf_p \pm f_0$, wherein n is an integer. The MPF is also periodic given the periodicity of the optical filter. As such, the MPF has the same FSR as the optical filter. Accordingly, one period has two peaks.

The periodicity of the MPF results with respect to the concept of the Tuning zone that is similar to Nyquist zone in Ref. [4]. In this letter, the Tuning zone is defined as the frequency range wherein only one passband occurs during tuning. Therefore, the working frequency range of the MPF is limited by the Tuning zone. The nth Tuning zone should be from $(n-1)\cdot f_p/2$ to $n \cdot f_p/2$. In practical applications, the useless peaks can be easily removed by electronic filters.

The Vernier effect[6] causes sub-filters to differ from one another. The transfer function for nth sub-filter is defined as $g_n(\Omega)$. As shown in Fig. 1(c), the first peak of $g_n(\Omega)$ is around $f_0 + n\Delta f$. In this letter, the space between $g_n(\Omega)$ and $g_{n+1}(\Omega)$ is defined as Δf, and it can be written as

$$\Delta f = f_1 - k \cdot f_p, \tag{1}$$

where f_1 is the repetition frequency of the comb lines, and k is an integer that satisfies $2\,|\Delta f| < f_p$. If $\Delta f =$ 0 Hz, all the sub-filters are congruent; otherwise, the sub-filters diverge from one another.

The total transfer function of the MPF can be obtained by combining all sub-filters. Similar to FIRMPF, the total transfer function is a linear combination of all sub-filters and can be written as

$$G_{f_0,f_1}(\Omega) \propto \sum_{n=0}^{N-1} a_n g_n(\Omega), \tag{2}$$

where the weight a_n is the optical intensity of nth comb, and N is the number of combs.

MPF can be tuned with a_n, f_1, f_0, as shown in Fig. 2. First, MPF is reconfigurable by manipulating the weights, as shown in Eq. (2). The gain of the sub-filters depends on the optical intensity of each comb, which can be controlled by the pulse shaper. By tuning the weights, the sub-filters can be superposed to obtain various passband shapes. Second, the bandwidth of the MPF is tunable by changing the repetition frequency. According to Eq. (1), when increasing or reducing f_1, the space between the sub-filters (Δf) changes with it. Thus, the bandwidth can be tuned. Third, the center frequency of the MPF is adjusted by tuning the frequency of the optical combs. When f_0 is shifted, the center frequency of the first sub-filter is shifted, followed by the center frequency of all the sub-filters. After superposition, the center frequency of the entire filter changes.

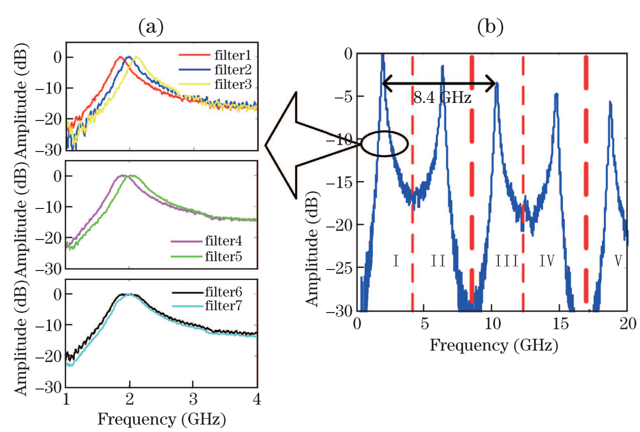

Fig. 4. Normalized responses of the MPF. (a) Tunable and reconfigurable responses (Tuning zone I in Fig. 4(b)). The weights of filters 1 to 7 are [1, 0, 0], [0, 1, 0], [0, 0, 1], [1.68, 1, 0], [0, 1, 1.18], [0.95, 1, 0.68], and [1.25, 1, 0.89], respectively. (b) Full span of the MPF response with five Tuning zones.

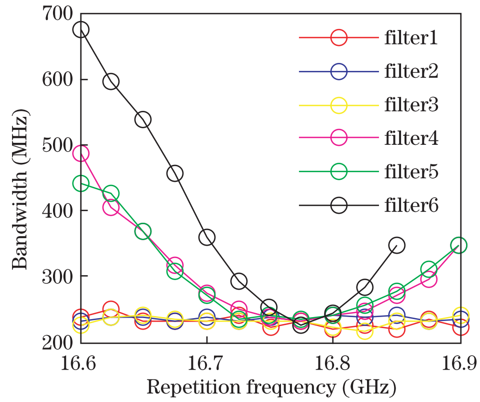

Fig. 5. Bandwidth for filters 1 to 6 tuned with the OFC repetition frequency. The experimental conditions and weights for each curve are the same as those in Fig. 4(a).

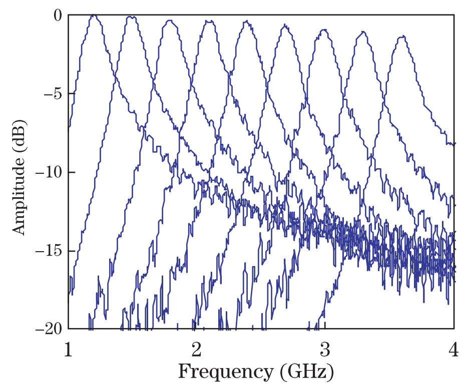

Fig. 6. Normalized response of filter 2 in Tuning zone I when the laser wavelength is swept from 1550.0120 to 1550.0336 nm. The experimental condition is the same as that in Fig. 4(a).

The experiment setup is shown in Fig. 3. Given that only a few comb lines are required, the OFC source is implemented by using a highly stable tunable laser source (TLS, HP Agilent 81680A, Agilent Technologies, USA), an electro-optic intensity modulator (IM), and a sinusoidal microwave source. After the light is double-sideband modulated by a sinusoidal signal, an output with three spectral lines that are equivalent to the OFCs are obtained. The OFC repetition frequency is equal to the frequency of the sinusoidal signal and can be tuned easily. More combs can be obtained from mode-locked lasers according to Ref. [15]. In the experiment, the optical filter is constructed by employing an optical circulator (OC) and a Fabry–Pérot (FP) cavity that serves as a reflection filter with an 8.4-GHz FSR. A vector network analyzer is used to measure the frequency response of the MPF.

A full-span response of the MPF is shown in Fig. 4(b). The MPF exhibits a periodic response, with a FSR of approximately 8.4 GHz. One period has a pair of symmetric passbands, because the optical filter is periodic and symmetric. Obviously, five Tuning zones exist, and each Tuning zone is similar to the others. The size of the Tuning zones is half of the FSR.

The response of the MPF is tuned and reconfigured by manipulating the weights. An example of an operation on combs is illustrated in Figs. 3(b) and (c). When the OFC repetition frequency is fixed at 16.65 GHz, seven groups of weight coefficients, called filters 1 to 7, are chosen. The frequency responses of these filters are exhibited in Fig. 4(a). Filters 1 to 3 are sub-filters and basic units for superposition. Each of these filters represents a comb. Filter 4 is obtained by superposing filters 1 and 2. Filter 5 is obtained from filters 2 and 3; thus, their center frequencies differ. Comparing flat-top filter 6 with non-flat-top filter 7, their shapes are found to be different because they are superposed with different weights. In the experiment, the optical power into the PD is about 4 dBm, the passband gain is approximately −34 dB, the band rejection is approximately 17 dB, and the spurious-free dynamic range is 91.8 dB·Hz$^{2/3}$ with a two-tone (1.999 and 2.001 GHz) test.

The bandwidth of the MPF can be tuned by changing the OFC repetition frequency. To avoid rippling the passband, the repetition frequency is swept from 16.6 to 16.9 GHz with a 25-MHz step. The experimental results are illustrated in Fig. 5. The bandwidths for the three sub-filters are almost invariable. The bandwidths of filters 4 to 6 positively correlate with $|\Delta f|$. An intersection is found at 16.775 GHz, where all bandwidths achieve the same minimum value. The reason is that $\Delta f = 0$ and all sub-filters are congruent. The bandwidth of filter 6 can be increased from 224.8 to 674.3 MHz. In the experiment, the minimum bandwidth is limited by the optical filter; thus, bandwidth can be improved by using higher Q optical filter, such as optical resonators with whispering-gallery modes[16].

The center frequency of the MPF can be adjusted independently by tuning the frequency of the OFCs. As a result of the OFC source used in this experiment, the frequency of the OFCs is determined by the TLS used to generate the OFCs. When the laser wavelength is shifted, f_0 and the center frequency of the sub-filters are also shifted. The experimental results shown in Fig. 6 indicate that the center frequency can be increased from 1 to 4 GHz.

In conclusion, a programmable MPF with tunability and reconfigurability is experimentally demonstrated by employing OFCs, phase modulation, and a FP optical filter. Based on PM–IM conversion, sub-filters are mapped from the optical filter and each sub-filter that corresponds to a comb. The Vernier effect causes sub-filters to differ from one another, and the total filter response is a combination of all sub-filters. The passband shape of the MPF is reconfigured by manipulating the optical intensity of each comb. The bandwidth can be tuned by sweeping the repetition frequency of the OFCs. The center frequency is tuned by changing the tunable laser wavelength used to generate the OFCs. In the experiment, the bandwidth can be increased from 224.8 to 674.3 MHz, and the center frequency is tunable from 1 to 4 GHz. Our future work will involve realizing negative weight coefficients to improve the performance of the MPF.

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