# Multi-tap microwave photonic filter with positive and negative coefficients based on an unbalanced Mach-Zehnder modulator*

**WANG Mu-guang** (王目光)**, **SONG Zi-wei** (宋紫薇), **ZHANG Jing** (张敬), **LI Tang-jun** (李唐军), **and JIAN Shui-sheng** (简水生)

*State Key Laboratory of All Optical Network & Advanced Telecommunication Network of EMC, Institute of Lightwave Technology, Beijing Jiaotong Univesity, Beijing 100044, China*

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A novel approach for the implementation of microwave photonic filter with positive and negative coefficients based on an unbalanced Mach-Zehnder modulator (MZM) is proposed. In the proposed filter, a microwave signal to be filtered is applied to an unbalanced MZM. Thanks to the unbalance between the two arms of the modulator, a π phase shift is obtained by adjusting the wavelength interval between the adjacent wavelengths, which leads to the generation of the positive and negative coefficients. The theoretical fundamentals of the design are described, which show that the required unbalanced MZM in the scheme can be well fabricated by the current technology, and the required other components, including the wavelength multiplexer, are also commercially available devices. An eight-tap microwave photonic filter with positive and negative coefficients is demonstrated. The tunability and reconfigurability of the eight-tap microwave photonic filter are also investigated to verify our approach.

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The implementation of microwave filters in the optical domain has attracted considerable interest over the last two decades due to the inherent advantageous features offered by optics, such as low loss, light weight, broad bandwidth, good reconfigurability and immunity to electromagnetic interference (EMI), and lots of techniques have been proposed and demonstrated[1-3]. Usually, a microwave photonic filter has a delay-line structure with a finite impulse response (FIR). To avoid the optical interferences which are very sensitive to peripheral environmental perturbations, many configurations of filters with only positive coefficients based on incoherent detection have been presented[4]. Based on the theory of signal processing, it is known that the microwave photonic filter operating in the incoherent regime has all-positive coefficients, which leads to the filter only with a function as a low-pass filter. It will severely limit the application range of microwave photonic filters. For many applications, the bandpass filter is needed. So many approaches have been proposed to realize microwave bandpass filters with negative coefficients[5-8]. The first pioneering one[5] is based on the differential photodetection to realize bandpass filtering, which is an optoelectronic hybrid structure in fact.

Subsequently, lots of all-optical approaches have been proposed to achieve microwave photonic filters with negative coefficients. A microwave photonic filter with negative coefficients was demonstrated[6] based on carrier depletion effects in a distributed-feedback laser diode (DFB-LD). Microwave photonic filters with negative coefficients can also be generated[7] based on optical injection locking of a single-mode semiconductor laser. A complementary light source by filtering a broadband light source using cascaded fiber Bragg gratings (FBGs) can also be implemented to realize a microwave photonic filter with negative coefficients[9]. Positive and negative coefficients can also be obtained based on phase-modulation to intensity-modulation (PM-IM) conversion by using a dispersive element, such as linearly chirped FBG (LCFBG)[10] or an optical frequency discriminator, such as Sagnac loop filter[11]. There is a simple way to generate microwave photonic filters with negative coefficients via biasing a pair of identical Mach-Zehnder modulators (MZMs) at the positive and negative slopes to achieve π phase inversion[12]. But in practice, to avoid the amplitude dependence of coefficients on frequency, the characteristics of the two MZMs must be identical. To solve these problems, another approach employing only one MZM was proposed[13,14] based on the wavelength dependence

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** E-mail: mgwang@bjtu.edu.cn

of the half-wave voltage of $V_{\pi}(\lambda)$. It was shown that a $LiNbO_3$ MZM was biased at the positive and negative slopes for two wavelengths at 1550 nm and 1300 nm windows, respectively, which generated microwave photonic filter with a pair of positive and negative coefficients. However, it would lead to a complicated time delay configuration following the MZM, because there is a large dispersion and time delay between 1300 nm and 1550 nm wavebands.

In this paper, we propose and demonstrate a simple approach to implement a microwave photonic filter with positive and negative coefficients based on an unbalanced MZM. Compared with Refs.[13] and [14], the wavelength interval for the taps with positive and negative coefficients can be greatly reduced, and the configuration of the multi-tap microwave photonic filter with negative coefficients can be markedly simplified. An eight-tap microwave photonic filter with positive and negative coefficients is analyzed. The tunability and reconfigurability of the eight-tap microwave photonic filter are also investigated.

The fundamental principle of our proposed microwave photonic filter can be explained by considering the schematic diagram shown in Fig.1. It consists of an array of $N$ laser sources, a wavelength multiplexer (MUX), an unbalanced MZM and a section of dispersion compensation fiber (DCF). The laser sources with $N$ wavelengths are multiplexed by a multiplexer, and then are injected into an unbalanced MZM. The unbalanced MZM is driven by a sinusoidal microwave signal with a tunable angular frequency which is generated by an electrical vector network analyzer (EVNA) and amplified by an electrical amplifier (EA). The polarization controller (PC) is used to adjust the state of polarization (SOP) of the lightwave inputted into the unbalanced MZM. Due to the unbalance between the two arms of the MZM, a π phase shift between the adjacent carriers is obtained by adjusting their wavelength interval, which leads to the generation of the positive and negative coefficients in the meantime. Note that the MZM with bandwidth exceeding 40 GHz and approaching 100 GHz has been reported[15]. A time delay difference is obtained by transmitting the optical signals through a section of DCF as a dispersive element.

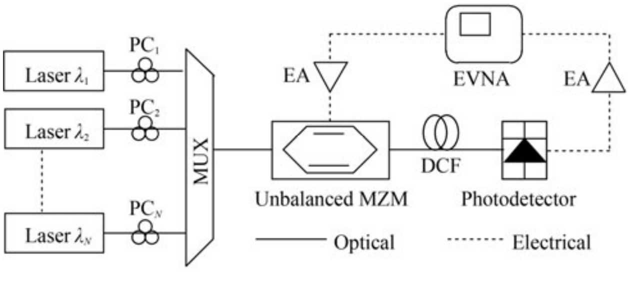


**Fig.1 Schematic diagram of the proposed multi-tap microwave photonic filter**

The transfer function of the unbalanced MZM has different phase shifts at different optical carriers. Considering only one optical source at the wavelength of $\lambda$ is injected into the unbalanced MZM firstly, the normalized optical field at the output of the unbalanced MZM can be expressed as

$$E_{out} = \exp(j\omega t)\times \left[\gamma \exp\left(j\pi\frac{V_m}{V_\pi} + jk\Delta L + j\varphi\right) + (1-\gamma)\exp\left(-j\pi\frac{V_m}{V_\pi}\right)\right], \quad (1)$$

where $\omega$ represents the angular frequency of optical carrier, $\gamma = \left(1+1/\sqrt{\varepsilon_r}\right)/2$ is the splitting (combining) ratio of the input and output Y-branch waveguides, $\varepsilon_r$ is the extinction ratio of the unbalanced MZM, $V_m$ and $V_\pi$ are the external modulation voltage applied on the unbalanced MZM and the half-wave voltage, respectively, $k=2\pi n(\lambda)/\lambda$ and $n(\lambda)$ are the propagation constant and refraction index of the waveguide of the unbalanced MZM, respectively, $\Delta L$ is the length difference between the two arms of the unbalanced MZM, and $\varphi=\pi V_{bias}/V_\pi$ is the phase shift induced by the bias voltage $V_{bias}$. For simplicity, the extinction ratio is assumed to be infinite, i.e., $\varepsilon_r=\infty$, $\gamma=0.5$ and $\varphi=0$. The normalized optical power at the output of the unbalanced MZM can be written as

$$P_{out} = \frac{1}{2}\left[1+\cos\left(2\pi\frac{V_m}{V_\pi}+\theta(\lambda)\right)\right], \quad (2)$$

where $\theta(\lambda)=k\Delta L=2\pi n\Delta L/\lambda$. The transfer function of the unbalanced MZM is a sinusoid function, and can be shifted along the voltage axis by adjusting the wavelength of the optical carrier. Therefore, two complementary signals with counter-phase intensity modulation can be achieved if the phase difference at two different wavelengths satisfies the following condition as

$$\theta(\lambda)=\theta(\lambda_i)-\theta(\lambda_j)=(2l+1)\pi,\ l=0,\ \pm1,\ \cdots. \quad (3)$$

In other words, the unbalanced MZM can be operated with biases at the positive and negative slopes for two wavelengths simultaneously to achieve π phase inversion between two optical signals. Fig.2 shows the results of the two complementary optical signals with counter-phase intensity modulation.

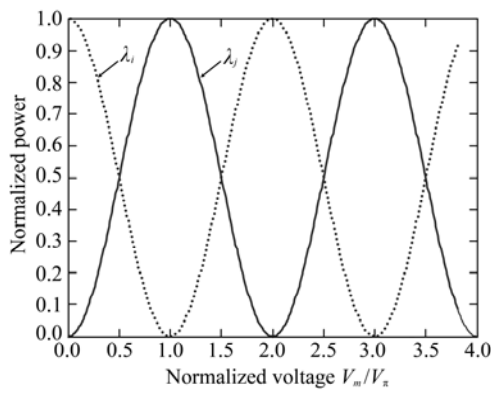


**Fig.2 Transfer functions of the unbalanced MZM at two different wavelengths**

The refractive index of a $LiNbO_3$ unbalanced MZM versus wavelength can be expressed by the Sellmeier equation[16]:

$$n^2(\lambda)-1=\frac{2.6734\lambda^2}{\lambda^2-0.01764}+\frac{1.2290\lambda^2}{\lambda^2-0.05914}+\frac{12.614\lambda^2}{\lambda^2-474.60}. \tag{4}$$

As can be seen, according to Eqs.(2)–(4) and using the two wavelengths of the optical carriers, we can easily obtain the required length difference between two arms of the unbalanced MZM, which is expressed as

$$\Delta L=\frac{(2l+1)\lambda_i\lambda_j}{2\left[n(\lambda_i)\lambda_j-n(\lambda_j)\lambda_i\right]}=\frac{(2l+1)\pi c}{n(\lambda_i)\omega_i-n(\lambda_j)\omega_j}, \tag{5}$$

where $c$ is the light speed in the vacuum, and $\omega_{i,j}$ are the corresponding angle frequencies of the optical carriers $\lambda_{i,j}$. For instance, it can be calculated that $\Delta L$ is about 680 μm for a given wavelength spacing of 0.8 nm. Such a $\Delta L$ about a few hundred micrometers can be easily achieved by adjusting the half angle of input and output Y-branches very slightly[17]. Note that the relationship between the length difference $\Delta L$ and wavelengths of optical carriers is not unique because of the integral number of $l$. Fig.3 shows the relationship of the phase difference and the wavelength in the C-band relative to the wavelength of 1530 nm when the $\Delta L$ is 680 μm. It is easy to see that the phase difference between 1550.12 nm and 1549.32 nm is π.

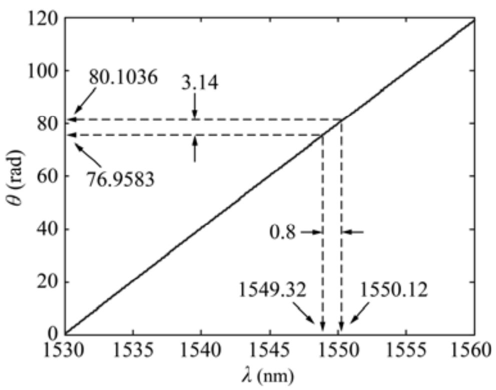


**Fig.3 Relationship between phase difference and wavelength in the C-band when $\Delta L$ is 680 μm**

The eight-tap microwave photonic filters are numerically analyzed. Note that a roll of DCF with length of 2 km serves as the wavelength-dependent optical time delay line, whose dispersion parameter $D$ is –170 ps·nm$^{-1}$·km$^{-1}$ at 1550 nm. First, eight lightwaves from one laser array module with wavelengths of 1540.52 nm, 1541.32 nm, 1542.12 nm, 1542.92 nm, 1543.72 nm, 1544.52 nm, 1545.32 nm and 1546.12 nm are sent to the unbalanced MZM through a multiplexer and PC. The eight lightwaves have 0.8 nm (100 GHz) spacing which corresponds to the time delay difference of 272 ps and a free spectral range (FSR) of 3.7 GHz. Since the wavelengths of the adjacent carriers are located at the points with opposite slopes, negative and positive coefficients are obtained. Fig.4(a) shows the numerical simulation result of frequency response with coefficients of [1, -1, 1, -1, 1, -1, 1, -1]. As can be seen, a high sidelobe at the baseband is depressed compared with Fig.4(b), whose coefficients are [1, 1, 1, 1, 1, 1, 1, 1] and wavelengths of the outputs from the laser array are tuned to be 1540.52 nm, 1542.12 nm, 1543.72 nm, 1545.32 nm, 1546.92 nm, 1548.52 nm, 1550.12 nm and 1551.72 nm with spacing of 1.6 nm (200 GHz), respectively.

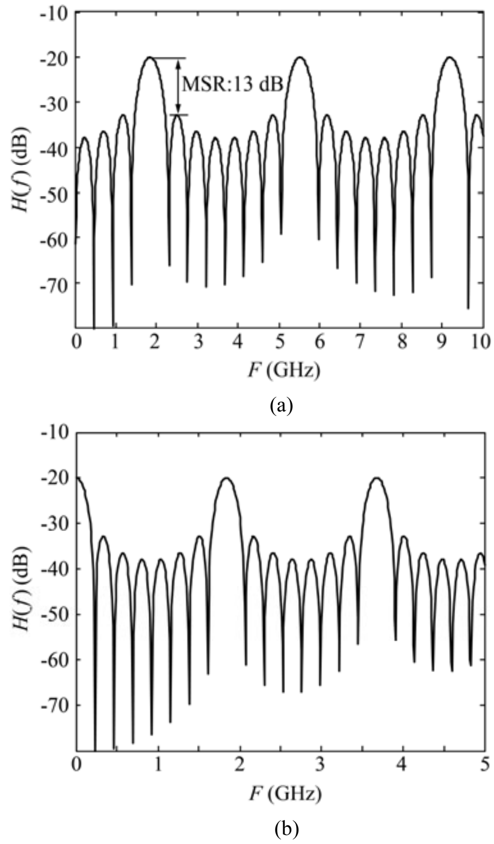


**Fig.4 Frequency responses of the eight-tap filters with (a) wavelength spacing of 0.8 nm and coefficients of [1, -1, 1, -1, 1, -1, 1, -1] and (b) wavelength spacing of 1.6 nm and coefficients of [1, 1, 1, 1, 1, 1, 1, 1]**

Second, the tunability of the proposed microwave filter is also demonstrated. When the eight wavelengths are 15540.52 nm, 1542.92 nm, 1545.32 nm, 1547.72 nm, 1550.12 nm, 1552.52 nm, 1554.92 nm and 1557.32 nm with 2.4 nm (300 GHz) spacing, a filter with negative coefficients is still obtained. But the time delay difference between two adjacent taps is larger. Therefore, the FSR of the filter is decreased. As shown in Fig.5, the FSR of the microwave filter with coefficients of [1, -1, 1, -1, 1, -1, 1, -1] decreases from 3.7 GHz to 1.2 GHz, compared with the FSR shown in Fig.4(a). Note that the tunability of the microwave photonic filter can also be performed by tuning the total dispersion of the DCF.

Finally, to investigate the reconfigurability of the filter, a window function is applied to make the coefficients be [0.35, -0.5, 0.75, -1, 1, -0.75, 0.5, -0.35] by controlling the output optical power of the LD arrays at each wavelength.

The frequency response of the filter after windowing is shown in Fig.6. Compared with the uniform coefficients, it can be seen that after windowing, the mainlobe-to-sidelobe ratio (MSR) of the microwave photonic filter with coefficients of [0.35, -0.5, 0.75, -1, 1, -0.75, 0.5, -0.35] increases from 13 dB to 23 dB, and an apparent improvement of MSR is obtained.

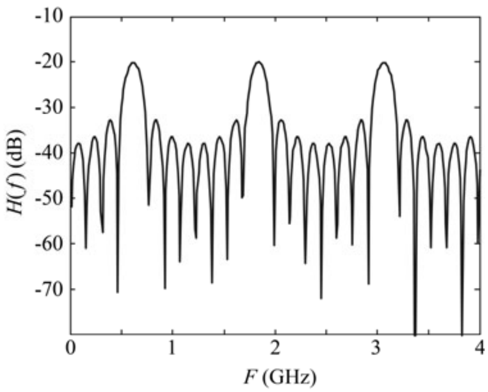


**Fig.5 Frequency response of an eight-tap filter with wavelength spacing of 2.4 nm and coefficients of [1, -1, 1, -1, 1, -1, 1, -1]**

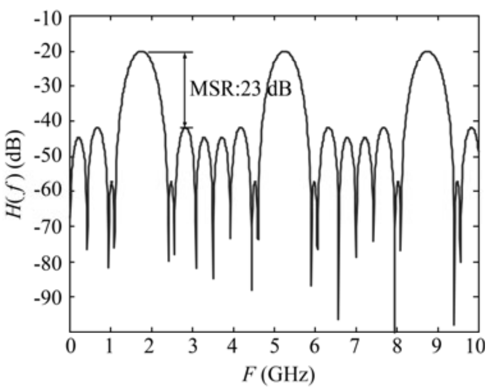


**Fig.6 Frequency response of an eight-tap filter with wavelength spacing of 0.8 nm and coefficients of [0.35, -0.5, 0.75, -1, 1, -0.75, 0.5, -0.35]**

We propose and demonstrate a novel approach for the implementation of microwave photonic filter with positive and negative coefficients based on an unbalanced MZM. Thanks to the unbalance between the two arms of the modulator, a $\pi$ phase shift is obtained by adjusting the wavelength interval between the adjacent optical carriers. It is shown that the required unbalanced MZM in the scheme can be well fabricated based on the existing techniques. An eight-tap microwave photonic filter with positive and negative coefficients is demonstrated. The tunability and reconfigurability are also investigated to verify our approach. By changing the wavelength spacing, an eight-tap filter with all-positive coefficients is achieved. By applying a window function to the coefficients of the eight-tap filter through adjusting the optical power of the lightwaves from the LD array, an eight-tap filter with an increased MSR is realized.

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