A tunable microwave photonic filter with complex coefficient based on slicing spectrum and stimulated Brillouin scattering*

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(Received 23 April 2012)

In this paper, we propose a method to realize microwave photonic filter (MPF) with complex coefficient, whose central frequency f_0 and 3 dB bandwidth are tunable. The complex coefficient is realized by multi-wavelength optical source and stimulated Brillouin scattering (SBS). The central frequency of the filter is tuned by adjusting the phase shift caused by SBS without changing its frequency response. The frequency selectivity of filter can be improved through increasing the bandwidth of broadband optical source (BOS) or decreasing wavelength separation to increase the taps of MPF. The mainlobe-to-sidelobe suppression ratio (MSSR) of the filter is affected by the weight of each tap. When the length of fiber is 0.5544 m in birefringence fiber loop mirror (FLM), the MSSR is improved by 18.55 dB compared with that without the weight controlling.

Document code: A **Article ID:** 1673-1905(2012)05-0340-4

DOI 10.1007/s11801-012-2264-z

Microwave photonic signal processing is attractive because of its very low loss, high time-bandwidth product capabilities and immunity to electromagnetic interference (EMI)[1,2]. However, the positive nature of its coefficients can only achieve low-pass filter. In order to realize the band-pass filter, negative coefficient or complex coefficient must be used. For negative coefficient filter, the frequency response is changed when the central frequency is tuned. For complex-coefficient filter with a phase shift of φ which is independent of the radio frequency (RF) of f_{RF}, the frequency response of filter keeps unchanged when the central frequency is tuned[3].

Complex-coefficient microwave photonic filters (MPFs) realized by different all-optical RF phase shift techniques have been reported recently, such as phase-shifted fiber Bragg gratings[3], two intensity modulators[4], a dual-parallel Mach-Zehnder modulator (DPMZM) with a tunable optical bandpass filer (TBPF)[5], a phase modulator with a frequency discriminator[6], semiconductor optical amplifiers (SOAs)[7], silicon-on-insulator (SOI) micro-ring resonators[8] and stimulated Brillouin scattering (SBS)[9-12]. Using these techniques, complex coefficient caused by SBS is easy to be controlled by the pump power of SBS. In this paper, we propose a tunable MPF with complex coefficient also based on SBS. The multiple taps of MPF are realized by splicing a broadband optical source (BOS). The tunability, frequency selectivity and the mainlobe-to-sidelobe suppression ratio (MSSR) of the MPF are analyzed.

According to the frequency shifting property of Fourier transform, in order to tune the central frequency of a filter without changing its basic delay and shape, the frequency response of the filter should satisfy the following relation:

$$\begin{cases} H(\Omega) = \sum\limits_{n=-\infty}^{\infty} h(n)\,\mathrm{e}^{-\mathrm{j}n\Omega T} \\ H(\Omega-\Omega_0) = \sum\limits_{n=-\infty}^{\infty} h(n)\,\mathrm{e}^{-\mathrm{j}n(\Omega-\Omega_0)T} \end{cases} , \qquad (1)$$

where $h(n)$ is the amplitude of the nth tap, and T is the basic delay of the filter. In other words, in order to tune the central frequency of the MPF, a phase shift of $n\Omega_0 T$ should be added on each tap.

The schematic diagram of the proposed tunable MPF with complex coefficient is demonstrated in Fig.1. It consists of three parts: multi-wavelength optical source, the part for processing SBS signal and the part for controlling weight of each tap.

A multi-wavelength optical source is obtained by splic-

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* This work has been supported by the National Natural Science Foundation of China (No.60808004).

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ing a BOS using Mach-Zehnder interferemeter (MZI). Then it is launched into the SBS signal processing part, and then divided into two paths by a 3 dB coupler. The upper path is modulated by an optical single-sideband (OSSB) modulator with $E_{\mathrm{RF}}(t)=\cos(2\pi f_{\mathrm{RF}}t)$. The lower path is modulated by a Mach-Zehnder electro-optic modulator (MZ-EOM) in order to generate a double-sideband suppressed carrier (DSB-SC) signal[13]. A circulator is used to counter-propagate the DSB-SC signal with the OSSB-modulated carrier in standard single-mode fiber (SMF). DSB-SC signal acts as pump wave and Stokes wave of SBS to provide gain and loss for the OSSB signal in SMF. A phase shift φ is only produced on the optical carrier, not on the upper-sideband, due to the narrow bandwidth of the SBS gain. The phase shift only on the optical carrier can be directly translated to the conveyed RF signal, and results in the complex coefficient of MPF.

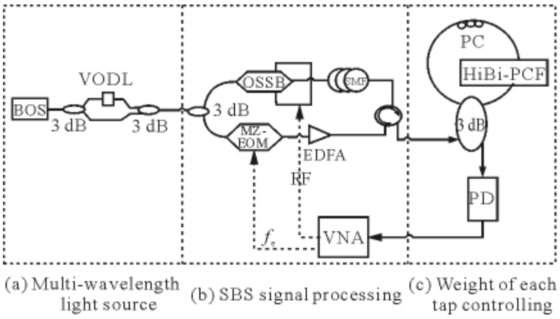


Fig.1 Schematic diagram of the proposed complex-coefficient MPF

When optical source only has a single frequency with electrical field as $E_0(t)=\mathrm{e}^{\mathrm{j}2\pi f_{c0}t}$, the optical field at the output of the OSSB modulator is given by

$$E_{\mathrm{OSSB}}(t)=A_0\,\mathrm{e}^{\mathrm{j}2\pi f_{c0}t}+A_{+1}\,\mathrm{e}^{\mathrm{j}2\pi(f_{c0}+f_{\mathrm{RF}})t}\ ,\tag{2}$$

where A_0 and A_{+1} are the amplitudes of the optical carrier and upper-sideband, respectively.

The optical field at the output of SBS signal processing part is given by

$$E_{\mathrm{out}}(t)=A_0\,\mathrm{e}^{\mathrm{j}\theta_{c0}}\mathrm{e}^{\mathrm{j}\varphi}\mathrm{e}^{\mathrm{j}2\pi f_{c0}t}+A_{+1}\,\mathrm{e}^{\mathrm{j}\theta_{+c1}}\mathrm{e}^{\mathrm{j}2\pi(f_{c0}+f_{\mathrm{RF}})t}\ ,\tag{3}$$

where θ_{c0} and θ_{+c1} are the phase delays of f_0 and f_0+f_{RF} induced by the fiber's dispersion, respectively. The RF signal on the fiber at the output of SBS signal processing part is proportional to

$$E_{\mathrm{RF}}=E_{\mathrm{out}}(t)*E_{\mathrm{out}}^{*}(t)\propto A_0A_{+1}\cdot\cos(2\pi f_{\mathrm{RF}}t+\theta_{+c1}-\theta_{c0}-\varphi)\ ,\tag{4}$$

where we ignore the direct current part, and only consider the RF signal centered at the modulation frequency.

From Eq.(4), the phase-shift modification on the optical carrier is directly translated to the conveyed RF signal, and the phase shift φ is independent of the RF frequency of f_{RF}.

For multi-wavelength optical source, the RF signal on the fiber at the output of SBS signal processing part is written as

$$E_{\mathrm{RF}}(t)\propto\sum_{m=0}^{M-1}P_m\cos(2\pi f_{\mathrm{RF}}t+\theta_{+c1m}-\theta_{c0m}-\varphi_m)\ ,\tag{5}$$

where P_m is the optical power of each carrier, θ_{c0m} and θ_{+c1m} are the phase delays of f_{c0m} and $f_{c0m}+f_{\mathrm{RF}}$ induced by the optical fiber's dispersion, respectively. φ_m is the phase shift caused by SBS on the carrier at f_{c0m}. The phase difference between the carrier and corresponding upper-sideband is expressed by only considering the first three terms of Taylor expansion as

$$\begin{aligned}&\theta_{+c1m}-\theta_{c0m}=\\&\beta_1 2\pi f_{\mathrm{RF}}L+\beta_2(2\pi f_{\mathrm{RF}})^2L/2-m\cdot 2\pi f_{\mathrm{RF}}\cdot T\ ,\end{aligned}\tag{6}$$

where β_1 and β_2 are the first-order dispersion and second-order dispersion of SMF at frequency f_{c0m} (m=0), respectively. $T=D\bullet L\bullet\Delta\lambda$ is the basic delay of the filter, which is proportional to the group velocity dispersive (GVD) coefficient D of SMF, the wavelength separation $\Delta\lambda$ of the multi-wavelength optical source and the length L of SMF.

The first two terms of Eq.(6) are constant phases caused by dispersion of SMF, which are set to zero for simplicity as

$$\theta_{+c1m}-\theta_{c0m}=-\,m\bullet 2\pi f_{\mathrm{RF}}\bullet T\,.\tag{7}$$

Based on Ref.[9], the phase shift caused by SBS can be expressed as

$$\varphi_m=m\bullet\omega_0\bullet T\,,\tag{8}$$

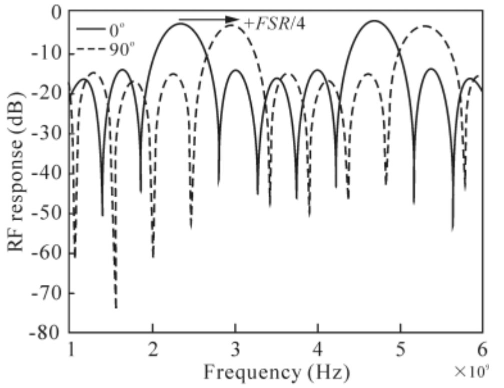
where ω_0 is a parameter depending on the pump power of SBS[9,12]. In Eq.(8), the phase shift at frequency f_{c0m} (m=0) is set to zero for simplicity.

The frequency response of the complex-coefficient MPF can be obtained by substituting Eqs.(7) and (8) into Eq.(5) and conducting Fourier transform on Eq.(5):

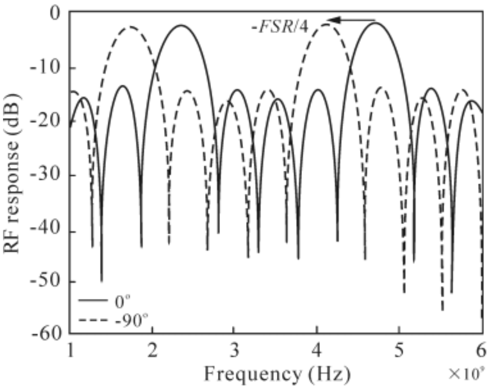
$$H(f_{\mathrm{RF}})\propto\sum_{m=0}^{M-1}P_m\,\mathrm{e}^{-\mathrm{j}m\omega_0T}\,\mathrm{e}^{-\mathrm{j}2\pi f_{\mathrm{RF}}mT}\ .\tag{9}$$

Comparing Eqs.(1) and (8), the phase shift φ_m caused by SBS can tune the central frequency of the MPF, which can be adjusted by the power of BOS and EDFA for a given frequency separation[12]. Using this technique, a tuning range of ±*FSR*/2 of MPF is achieved with the same frequency response when the phase shift is tunable within $\pm180^{\mathrm{o}}$, where *FSR* means the value of free spectral range. The frequency responses of the five-tap complex-coefficient filter with $\pm90^{0}$ phase shift are shown in Fig.2. The parameters used in Fig.2 are λ_1= 1548.1 nm, $\Delta\lambda$ = 1.25 nm, D = 17 ps/(km·nm), and L= 20 km.

In order to improve the filter's selectivity, the filter should



(a) 0° and 90° phase shifts



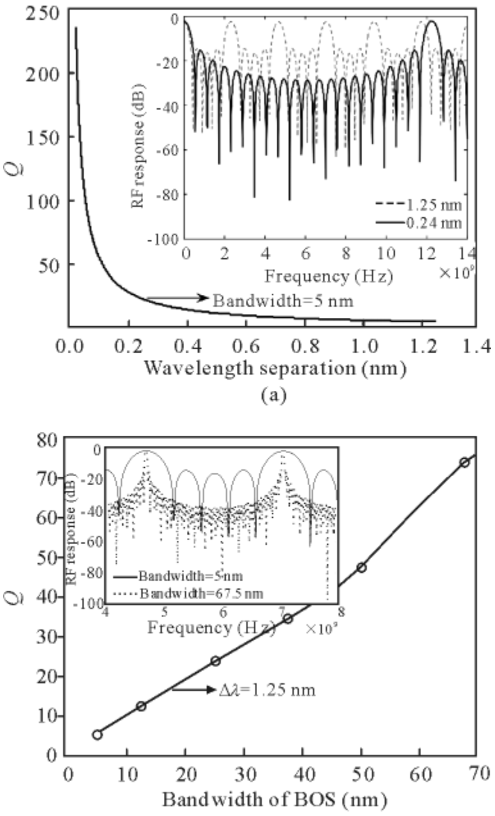
(b) 0° and -90° phase shifts

Fig.2 Tunability of MPF with five complex-coefficient taps

have a greater quality factor Q. Two methods, i.e., reducing the wavelength separation of the multi-wavelength optical source, increasing the operation bandwidth of BOS, can improve the factor Q. Fig.3(a) shows the trends of Q versus the wavelength separation with 5 nm BOS bandwidth, and the inset depicts the frequency response of MPF. When the wavelength separation $\Delta\lambda$ reduces from 1.25 nm to 0.24 nm, the number of taps M of MPF changes from 5 to 21, and the quality factor Q is raised by around 4.256 times. At the same time, the central frequency f_0 is tuned from 2.3529 GHz to 12.2549 GHz, and the 3 dB bandwidth of MPF is also tuned with a small range.

Fig.3(b) shows the trends of Q versus the bandwidth of BOS with wavelength separation $\Delta\lambda$=1.25 nm, and the inset is the corresponding frequency response of MPF. When the operation bandwidth of BOS changes from 5 nm to 67.5 nm, the number of taps M of MPF changes from 5 to 55, and the quality factor Q is raised by around 13.125 times. At the same time, 3 dB bandwidth of MPF is reduced from 420 MHz to 32 MHz, and the sidebands of MPF are also restrained a lot. Moreover, the central frequency f_0 and FSR of the MPF remain constant when the bandwidth of BOS is changed.

In order to achieve high MSSR, a high-birefringence fiber loop mirror (FLM) is used to control the weights of taps. The transmission spectrum of the high-birefringence FLM is approximately a periodic function of the wavelength[14] as:



(b)

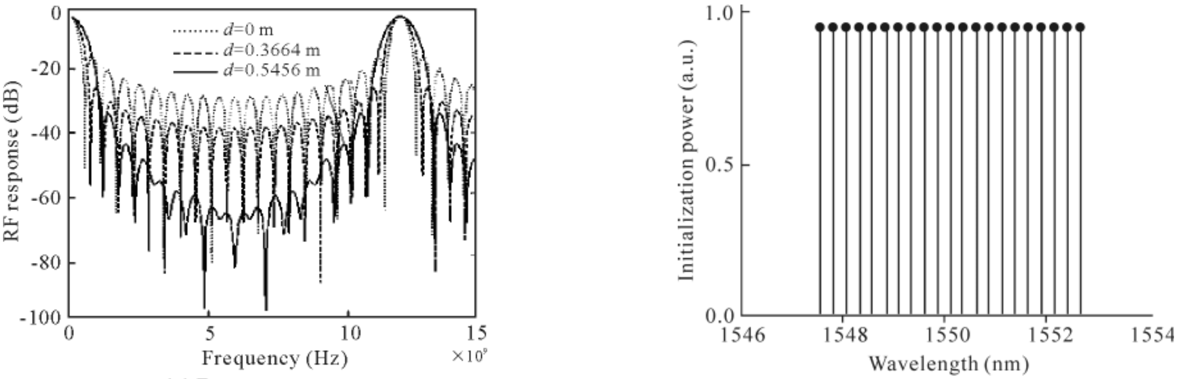
Fig.3 *Q* of MPF versus (a) wavelength separation of carrier with 5 nm bandwidth of BOS and (b) bandwidth of BOS with 1.25 nm wavelength separation of carrier

$$Y = 0.5[1-\cos(\frac{2\pi\Delta n_g d}{\lambda})] \ , \tag{10}$$

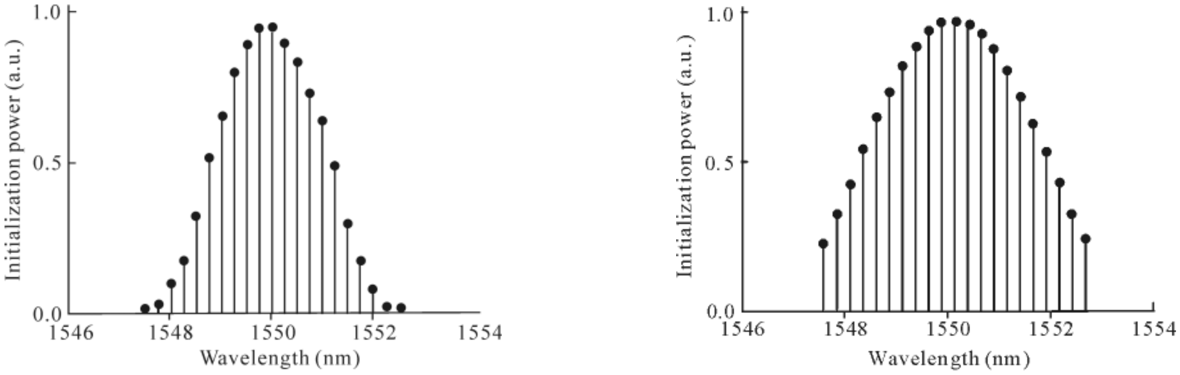
where d is the length of birefringent fiber, and Δn_g=8.65×10^{-4} is the fiber's group birefringence at the wavelength of λ=1550 nm.

As shown in Fig.4(a), highly birefringent photonic crystal fibers (HiBi-PCFs) with different lengths are used to realize the taps controlling of 21-tap complex-coefficient MPF. Fig.4(b), (c) and (d) show the spectra of multi-wavelength optical source after the FLM with different lengths of HiBi-PCF, which correspond to weight of taps' distribution of MPF. Here the bandwidth of BOS is from 1547 nm to 1552 nm. The filter's MSSR is raised from -15.39 dB to -33.94 dB when the length of HiBi-PCF changes from d = 0 m to d = 0.5544 m. From Fig.4(a), the 3 dB bandwidth of filter is affected by the spectra of FLM. In practice, according the specific requirements of the MPF, we can use different fiber lengths (for different d) or different fiber properties (for different Δn_g) to achieve a compromise between 3 dB bandwidth and the filer's MSSR to get good performance of the complex-coefficient MPF.

In summary, a tunable MPF with complex coefficient is proposed by combining the sliced broadband source and SBS interaction. From the analysis and simulation, the filter's



(a) Frequency response   (b) d=0 m



(c) d=0.5456 m   (d) d=0.3664 m

Fig.4 Frequency response of the MPF in FLM and spectra of multi-wavelength optical source after FLM with different lengths of HiBi-PCF

coefficient becomes complex by introducing a phase shift caused by SBS. The filter is tunable by changing the pump power of SBS without changing its frequency response. The frequency selectivity of the filter can be improved by increasing the bandwidth of BOS or decreasing the wavelength separation of carriers. The MSSR of the filter is increased by introducing an FLM to change the weight of each tap.

References

[1] Yitang Dai and Jianping Yao, IEEE Transactions on Microwave Theory and Techniques **58**, 3279 (2010).

[2] YANG Xu-sheng, HUANG Xu-guang, XIE Jin-ling and ZHU Jia-hu, Journal of Optoelectronics • Laser **22**, 706 (2011). (in Chinese)

[3] M. Sagues, R. Garcia-Olcina, A. Loayssa, S. Sales and J. Capmany, Multiple-Tap Complex-Coefficient Incoherent Microwave Photonics Filters using Phose-Shifted Fiber Bragg Gratings, European Conference and Ehxibition of Optical Communication (ECOC), 1 (2007).

[4] Yu Yan and Jianping Yao, IEEE Photon. Technol. Lett. **19**, 1472 (2007).

[5] Wei Li, Ninghua Zhu and Li Xian Wang, IEEE Photonics Journal **3**, 462 (2011).

[6] Xiang Li, Jianji Dong, Yuan Yu and Xinliang Zhang, IEEE Photon. Technol. Lett. **23**, 308 (2011).

[7] W. Xue, S. Sales, J. Mork and J. Capmany, IEEE Photon. Technol. Lett. **21**, 167 (2009).

[8] Minhao Pu, Liu Liu, Weiqi Xue, Yunhong Ding, Lars H. Frandsen, Haiyan Ou, Kresten Yvind and Jorn M. Hvam, IEEE Photon. Technol. Lett. **22**, 869 (2010).

[9] Alayn Loayssa, José Capmany, Mikel Sagues and José Mora, IEEE Photon. Technol. Lett. **18**, 1744 (2006).

[10] YIN Jing-chan, XIAO Xiao-sheng and YANG Chang-xi, Journal of Optoelectronics • Laser **21**, 786 (2010). (in Chinese)

[11] Alayn Loayssa and Francisco Javier Lahoz, IEEE Photon. Technol. Lett. **18**, 208 (2006).

[12] Mikel Sagues, Alayn Loayssa and José Capmany, IEEE Photon. Technol. Lett. **19**, 1194 (2007).

[13] A. Loayssa, R. Hernandez, D. Benito and S. Galech, Opt. Lett. **29**, 638 (2004).

[14] J. E. Roman, M. Y. Frankel and R. D. Esman, Opt. Lett. **23**, 939 (1998).

[15] Chun-Liu Zhao, Xiufeng Yang, Chao Lu, Wei Jin and M. S. Demokan, IEEE Photon. Technol. Lett. **16**, 2353 (2004).