Negative coefficient band-pass microwave photonic filter with improved mainlobe-to-sidelobe suppression ratio by Sagnac interferometer

ZHANG Ai-ling (张爱玲)* **and WU Xiao-jun** (吴晓君)
Tianjin Key Laboratory of Film Electronics and Communication Devices, Communication Devices and Technology Engineering Research Center, Ministry of Education, Tianjin University of Technology, Tianjin 300384, China

(Received 20 December 2012)

A tunable negative coefficient band-pass microwave photonic filter (MPF) with improved mainlobe-to-sidelobe suppression ratio (MSSR) by a Sagnac interferometer (SI) is experimentally demonstrated. The negative coefficient characteristic of MPF is achieved by using the phase modulation technology. The central frequency of the band-pass MPF is tunable continuously by changing the wavelength separation of multi-wavelength optical carriers. A 38-tap negative coefficient band-pass MPF whose MSSR is increased by about 6.371 dB is achieved in experiment by apodizing the tap coefficient with the Sagnac interferometer.
Document code: A **Article ID:** 1673-1905(2013)02-0108-4
DOI 10.1007/s11801-013-2424-9

Microwave photonic filter (MPF) is one of the most important branches in microwave photonic systems, which offers a method to process microwave and radio frequency (RF) signals directly in the optical domain. The advantages of system using photonic components include large bandwidth, low loss, and immunity to electromagnetic interference (EMI)[1,2], and it also overcomes the inherent bottleneck of traditional electronic signal processing systems. The positive coefficients of MPF result in low-pass filters. Aiming at developing band-pass filters, the tap coefficient should be negative or complex.

During the last decade, different configurations were proposed to realize the band-pass MPF, such as differential detection[3], wavelength conversion based on cross-gain saturation modulation in a semiconductor optical amplifier[4], optical phase-modulation to intensity-modulation conversion[5], and all-optical complex coefficient filters[6-8]. To the design of MPF, the tunability and the mainlobe-to-sidelobe suppression ratio (MSSR) are important characteristics. The tunability of the MPF can be realized by changing the wavelength separation of optical source[5-8]. Additionally, the sideband of MPF can be suppressed by converting a designed discrete-time impulse response into a continuous-time impulse response with carrier suppression effect[9]. The most common way to suppress the sideband for improving the MSSR of MPF is to apodize the tap coefficient[10,11] utilizing different modules, such as Gaussian apodization based on fiber Bragg gratings[12] for programming the amplitude and phase of optical carriers by line-by-line pulse shaper[13].

In this paper, we present a simple configuration of a tunable negative coefficient band-pass MPF based on a multi-wavelength optical source, a phase modulator (PM) and a dispersive medium. Tunability of central frequency of the band-pass MPF is implemented by adjusting the wavelength separation of multi-wavelength optical source. In order to improve the MSSR of the band-pass MPF, a Sagnac interferometer (SI) is used to realize the apodization of the multi-wavelength optical source in experiment. The experimental diagram of the tunable negative coefficient band-pass MPF is illustrated in Fig.1.

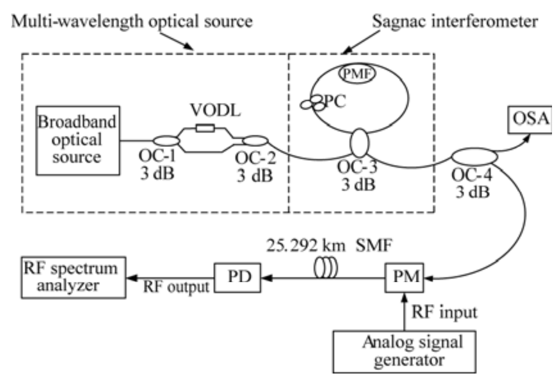

Fig.1 Schematic diagram of experimental setup of the proposed band-pass MPF with Sagnac interferometer

* E-mail: alzhang 99@hotmail.com

The multi-wavelength optical carriers are obtained by splicing a broadband optical source (BOS) by a fiber Mach-Zehnder interferometer (MZI)[14]. A variable optical delay line (VODL) in one arm of the MZI is used to tune the wavelength separation of the multi-wavelength optical carriers. An SI is used to apodize the spectrum of the multi-wavelength optical carriers, which results in reconfiguration of the tap coefficient. The SI is composed of a 3 dB optical coupler (OC), a polarization controller (PC) and a polarization maintaining fiber (PMF). The apodization is realized by changing the state of PC. After that, the apodized multi-wavelength optical source coming out from another port of the 3dB OC-2 is modulated by a PM, and then launched into a standard single-mode fiber (SMF). A photodetector (PD) is used to convert the optical signal into electrical signal, which is then measured by RF spectrum analyzer (SA). In this structure, the negative coefficient characteristic of MPF is achieved by using the phase modulation technology, the central frequency of band-pass MPF is tuned with changing the wavelength separation of the multi-wavelength optical source, and the MSSR is improved by the SI to apodize the tap coefficient of MPF.

According to Ref.[15], for a small modulation index, the frequency response of tunable band-pass MPF based on PM and standard SMF is given by:

$$H(f_{\mathrm{RF}}) \propto \cos\left(\frac{\pi \bar{D}_n f_{\mathrm{RF}}^2 L \bar{\lambda}_n^2}{c} + \frac{\pi}{2}\right) \times \sum_{n=1}^{N} P_n \exp[\mathrm{j}2\pi f_{\mathrm{RF}}(n-1)T], \quad (1)$$

where the first item represented by $H_1(f_{\mathrm{RF}})$ is a cut-off characteristic in the fundamental frequency which is induced by PM and fiber dispersion, and the second item represented by $H_2(f_{\mathrm{RF}})$ is a typical transversal periodical frequency response of MPF, which is determined by the wavelength separation of optical source and the total dispersion of SMF. N is the number of filter coefficients, c is the speed of light in vacuum, $\bar{\lambda}_n$ is the mean value of wavelengths of optical carriers, and f_{RF} is the frequency of the RF signal. $T = \bar{D}_n \cdot L \cdot \Delta\lambda$ is the basic delay of the MPF, which is proportional to the mean group velocity dispersive (GVD) coefficient $\bar{D}_n$ of SMF, the wavelength separation $\Delta\lambda$ of the multi-wavelength optical source and the length L of SMF. P_n is the optical power of the multi-wavelength optical source.

According to the apodization filtering technique, the MSSR of filter can be improved by changing the tap weighting coefficient of P_n. In Eq.(1), the envelope of optical power of each carrier P_n is modulated by the transmission spectrum T_r of Sagnac interferometer[16], which can be expressed as

$$T_r = \frac{1}{2}[1 - \cos(\frac{2\pi \Delta n_{\mathrm{g}} d}{\lambda})], \quad (2)$$

where Δn_{g} is the group birefringence index of PMF, and d is the length of PMF.

In our experiment, a BOS (EXFO FLS-2300B ASE SOURE) is used, whose bandwidth range is from 1520 nm to 1615 nm. The length of PMF in the SI is d=5.0 cm, and the group birefringence index is $\Delta n_g = 0.0005$. The spectra of multi-wavelength optical carriers before and after the SI are shown in Fig.2. A 25.292 km SMF-28 is employed as the dispersion delay device, and the fiber shows a chromatic dispersion of D=17.9 ps/(km·nm) at 1568 nm.

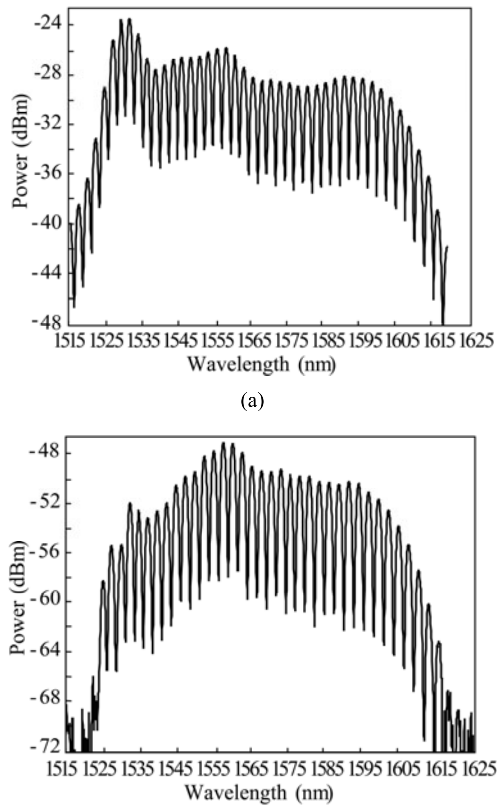

Fig.2 Spectra of multi-wavelength optical source based on slicing spectrum technique (a) before and (b) after Sagnac interferometer with $\Delta\lambda$ =2.560 nm

From Fig.2, the shape of the sliced multi-wavelength optical source is changed, and the tap coefficient of MPF is apodized when the SI is inserted. Moreover, when the spectrum of the sliced source is changed by varying the state of PC, the tap weighting coefficient of P_n can be varied in another way by changing the state of PC.

The free spectral range (FSR) of MPF can be tuned by adjusting the wavelength separation of the multi-wavelength optical source, and the relation is $FSR = 1/T = 1/(D \cdot L \cdot \Delta\lambda)$. In order to tune the frequency response of MPF, we change the phase caused by VODL in MZI by applying different voltages on it. When the voltage applied on VODL changes from +17 V to -17 V, the wavelength separation $\Delta\lambda$ increases from 2.560 nm to 2.625 nm. And then, the corresponding frequency responses of the band-pass MPF without Sagnac interferometer for different wavelength separations are shown in Fig.3. Experimental and theoretical results show good agreement. In simulation, carrier power P_n is set up based on the experimental results of multi-wavelength optical source, where the carrier power P_n of wavelength separation of $\Delta\lambda$=2.560 nm is shown in Fig.2(a).

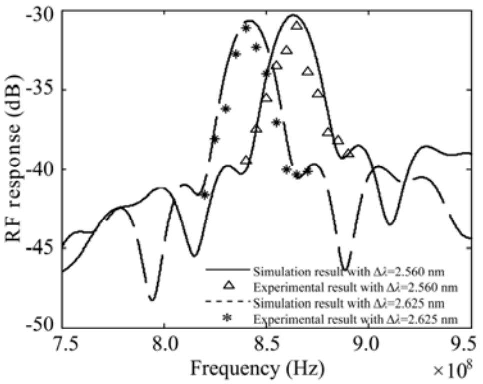

Fig.3 Experimental and simulation tunabilities of band-pass MPF without Sagnac interferometer for $\Delta\lambda$ = 2.560 nm and $\Delta\lambda$ =2.625 nm

From Fig.3, the central frequency of band-pass MPF changes from 865 MHz to 840 MHz when the wavelength separation of the multi-wavelength optical source is tuned from 2.560 nm to 2.625 nm, which is consistent with the simulation results.

Here, the tunability is mainly limited by the variation range of wavelength separation. If the wavelength separation $\Delta\lambda$ varies from 2.560 nm to 0.150 nm, the central frequency f_0 of MPF can be tuned from 865 MHz to 14.72 GHz, which is shown in Fig.4. The inset is the simulation result of corresponding frequency response of MPF with constant carrier power P_n without Sagnac interferometer. The chromatic dispersion D=17.9 ps/(km·nm) and the length of SMF L=25.292 km are used in simulation.

For improving the MSSR of the filter, an SI is used to shape the sliced multi-wavelength optical source. The wavelength separation of multi-wavelength source is set as $\Delta\lambda$=2.560 nm, and the amplitude of incident RF signal is set as -3 dBm. The frequency response of the band-pass MPF is measured from 780 MHz to 950 MHz with 5 MHz frequency step. The experimental and simulation frequency responses of the 38-tap negative coefficient band-pass MPF without and with the SI are shown in Fig.5.

It can be seen that by using an SI to shape the optical power of each carrier, the sidelobe suppression of 15.295 dB is achieved compared with the sidelobe suppression of 8.498 dB without SI. The experimental results show that the MSSR is increased by about 6.371 dB, which agrees with the simulation results. The limitation of MSSR is due to the apodization effect of multi-wavelength optical carriers. When the apodized multi-wavelength optical carriers' envelope is a quasi-Gaussian type with the variance σ=20, a 38-tap MPF with the wavelength separation of $\Delta\lambda$=2.560 nm can be obtained and with 43.512 dB MSSR. A little offset of the experiment results compared with the simulation results is thought to be caused by the transmission loss, connection loss, and the responsivity of PD. In the experiment, we also find that the performance of MPF with an SI is more stable.

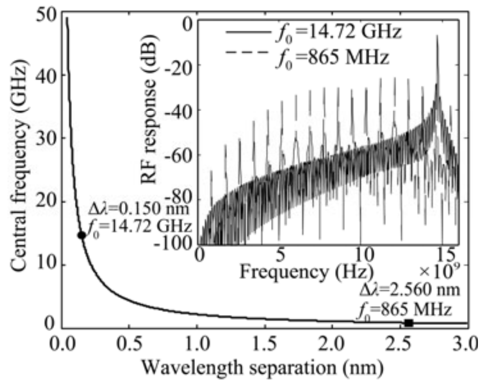

Fig.4 Central frequency of band-pass MPF versus the wavelength separation of the multi-wavelength optical source

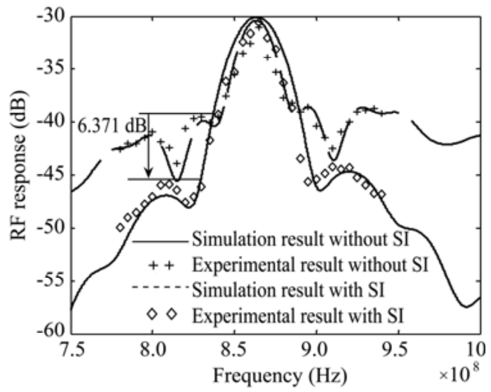

Fig.5 Experimental and simulation frequency responses of MPF without and with Sagnac interferometer

In summary, a 38-tap tunable negative coefficient band-pass MPF with improved MSSR by a Sagnac interferometer is demonstrated experimentally in this paper. The central frequency of the band-pass MPF is tunable from 840 MHz to 865 MHz by changing the wavelength separation from 2.625 nm to 2.560 nm. A wider tuning range can be achieved by expanding the changing range of wavelength separation. In addition, the MSSR is increased by about 6.371 dB by apodizing the tap coefficient with Sagnac interferometer. The method of using Sagnac interferometer to shape the taps of MPF is simple, especially for MPF with lots of optical carriers.

References

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

[2] J. Zhou, S. N. Fu, F. Luan, J. H. Wong, S. Aditya, P. P. Shum and K. E. K. Lee, J. Lightwave Technol. **29**, 3381 (2011).

[3] M. Bolea, J. Mora, B. Ortega and J. Capmany, Multiband Ultrawideband Pulse Generation based on a Tunable Single Band-Pass Photonic Filter and Differential Detection, International Topical Meeting on Microwave Photonics, 1 (2009).

[4] E. Xu, X. L. Zhang, L. Zhou, Y. Zhang, Y. Yu, X. Li and D. X. Huang, J. Lightwave Technol. **28**, 2358 (2010).

[5] Y. Yan, R. Blais and J. P. Yao, J. Lightwave Technol. **25**, 3283 (2007).

[6] M. Sagues, A. Loayssa and J. Capmany, IEEE Photon. Technol. Lett. **19**, 1194 (2007).

[7] M. Pu, L. Liu, W. Xue, Y. Ding, L. H. Frandsen, H. Ou, K. Yvind and J.M. Hvam, IEEE Photon. Technol. Lett. **22**, 869 (2010).

[8] JIANG Hong-wei and WU Yuan-da, Journal of Optoelectronics·Laser **22**, 813 (2011). (in Chinese)

[9] T. X. H. Huang, X. K. Yi and R. A. Minasian, Opt. Express **19**, 6231 (2011).

[10] X. Xu and R. M. Narayanan, IEEE Trans. Antennas Propagat. **49**, 1836 (2001).

[11] E. Hamidi, V. Supradeepa, M. Song, R. Wu, C. M. Long, D. E. Leaird and A. M. Weiner, Achieving Arbitrary Passband Profiles and High Stopband Attenuation in Microwave Photonic Filters, IEEE MTT-S, 1 (2011).

[12] M. Popov, P. Fonjallaz and O. Gunnarsson, IEEE Photon. Technol. Lett. **17**, 663 (2005).

[13] M. Song, C. M. Long, R. Wu, D. Seo, D. E. Leaird and A. M. Weiner, IEEE Photon. Technol. Lett. **23**, 1618 (2011).

[14] J. Mora, B. Ortega, A. Díez, J. L. Cruz, M. V. Andrés, J. Capmany and D. Pastor, J. Lightwave Technol. **24**, 2500 (2006).

[15] F. Zeng and J. P. Yao, J. Lightwave Technol. **23**, 1721 (2005).

[16] H.-M.Kim, T.-H. Kim, B. Kim and Y. Chung, IEEE Photon. Technol. Lett. **22**, 1539 (2010).