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A band-pass microwave photonic filter based on Lyot-Sagnac filter and cascaded optical structures*

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A band-pass microwave photonic filter (MPF) based on Lyot-Sagnac filter and two cascaded optical structures is demonstrated. In the experiment, a stabilized and tunable multi-wavelength optical source is obtained by slicing the broadband optical source (BOS) with a Lyot-Sagnac filter. A standard single-mode fiber (SMF) and a fiber ring resonator are cascaded to improve the mainlobe-to-sidelobe suppression ratio (MSSR) and Q-factor of the filter. The analysis shows that MSSR and Q-factor are improved by reducing the split ratio of the coupler or increasing the length of fiber in fiber ring resonator. The results have significant guidance for MPF design by choosing appropriate devices and parameters. Based on the analyses, a band-pass filter with MSSR of 53.54 dB and Q-factor of 4048 is achieved by choosing the split ratio of 0.01, the length of SMF of 30 km and the length of fiber in fiber ring resonator of 152.27 cm.

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Recently, there have been many papers[1-7] to demonstrate band-pass microwave photonic filter (MPF), such as wavelength conversion based on cross-gain modulation in a semiconductor optical amplifier[1,2], optical phase-modulation to intensity-modulation conversion[3] and stimulated Brillouin scattering (SBS) effect[5]. Normally, a band-pass MPF with high mainlobe-to-sidelobe suppression ratio (MSSR) and high Q-factor is required for different applications. Various filter structures with high MSSR and high Q-factor have been proposed[8-13]. The most common way to suppress the sideband and to improve the MSSR of MPF is apodizating[8] the tap coefficient, such as programming the amplitude and phase of optical carriers by line-by-line pulse shaper[10]. And the most effective way to increase the Q-factor is using two or more incoherent filter structures in cascade[12-14].

In this paper, we present a new negative-coefficient band-pass MPF with cascaded configuration to obtain the high MSSR and high Q-factor simultaneously. The filter is based on a multi-wavelength optical source, a phase modulator (PM) and two cascaded optical structures. And the cascaded optical structures consist of a standard single-mode fiber (SMF) and a fiber ring resonator.

The schematic diagram of the proposed negative-coefficient band-pass MPF with cascaded optical structures is demonstrated in Fig.1.

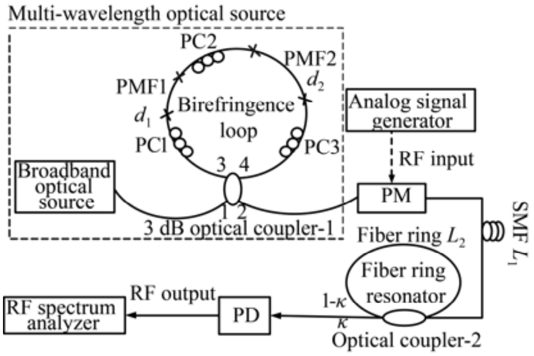

Fig.1 Schematic diagram of negative-coefficient band-pass MPF based on PM and cascaded optical structures

The multi-wavelength optical carriers are obtained by splicing a broadband optical source (BOS) with a Lyot-Sagnac filter. In our experiment, the Lyot-Sagnac filter[15] consists of a 3 dB optical coupler-1 (OC-1), three all-fiber polarization controllers (PCs) and two sections of polarization maintaining fiber (PMF). According to Ref.[15], the polarization state of PCs can control the effective length of PMF in Lyot-Sagnac interferometer and wavelength separation $\Delta\lambda$ of multi-wavelength optical carriers. The transmission T_r and the wavelength spacing $\Delta\lambda$ of the Lyot-Sagnac filter can be expressed as

$$T_r = \cos^2(\frac{2\pi}{\lambda}\Delta n_g \cdot d_{eff}) , \tag{1}$$

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$$\Delta\lambda=\frac{\lambda^2}{\Delta n_{\mathrm{g}}\cdot d_{\mathrm{eff}}}, \tag{2}$$

where d_{eff} is the effective length of PMF in the birefringence loop, and Δn_{g} is the group birefringence index of PMF.

After that, the multi-wavelength optical source is modulated by a PM, and then the light passes through a dispersive medium of 30 km standard SMF. The negative coefficient of MPF is achieved by the PM, which produces a π phase shift between two sidebands[3]. And then, a fiber ring resonator is cascaded to improve the MSSR and the Q-factor due to its advantages of narrow passband and high Q-factor. A photodetector (PD) is used to convert the optical signal into electrical signal, which is then measured by radio frequency (RF) spectrum analyzer (SA).

According to Ref.[3], the frequency response of traditional band-pass MPF based on PM and standard SMF is given by

$$H_{\text{PM-SMF}}(f_{\mathrm{RF}})\propto\underbrace{\cos\left(\frac{\pi\bar{D}_m L_1\bar{\lambda}_m^2 f_{\mathrm{RF}}^2}{2}+\frac{\pi}{2}\right)}_{H_1(f_{\mathrm{RF}})}\times$$

$$\underbrace{\sum_{m=1}^{M}P_m\exp[\mathrm{j}2\pi f_{\mathrm{RF}}(m-1)T]}_{H_2(f_{\mathrm{RF}})}, \tag{3}$$

where $\bar{D}_m$ is the average group velocity dispersive (GVD) coefficient of SMF, L_1 is the length of SMF, $\bar{\lambda}_m$ is the average value of wavelength of optical carrier, f_{RF} is the frequency of the RF signal, P_m is the optical power of the multi-wavelength optical source, and $T=\bar{D}_m\cdot L_1\cdot\Delta\lambda$ is the basic delay of the MPF, where $\Delta\lambda$ is the wavelength separation of the multi-wavelength optical source. $H_1(f_{\mathrm{RF}})$ is a cut-off characteristic at the fundamental frequency induced by PM, and $H_2(f_{\mathrm{RF}})$ is a typical transversal periodical frequency response of MPF.

The frequency response of fiber ring resonator[16] can be expressed as

$$H_{\mathrm{ring}}(f_{\mathrm{RF}})=\underbrace{\frac{\kappa}{1-(1-\kappa)\cdot\exp\left(-\frac{\mathrm{j}2\pi f_{\mathrm{RF}}nL_2}{c}\right)}}_{H_3(f_{\mathrm{RF}})}, \tag{4}$$

where c is the optical wave propagation velocity in free space, κ is the split ratio of OC-2, n is the refractive index of fiber, and L_2 is the length of fiber in the fiber ring resonator. Normally, the length of fiber in the fiber ring resonator L_2 is much shorter than the length of SMF L_1. nL_2 for different wavelengths are almost the same, so the fiber ring resonator has the same frequency response at different wavelengths.

According to the cascaded characteristics of optical structures[17], the frequency response of our proposed negative-coefficient band-pass MPF can be expressed as

$$H(f_{\mathrm{RF}})=H_{\text{PM-SMF}}(f_{\mathrm{RF}})\cdot H_{\mathrm{ring}}(f_{\mathrm{RF}})=$$

$$\underbrace{\cos\left(\frac{\pi\bar{D}_m L_1\bar{\lambda}_m^2 f_{\mathrm{RF}}^2}{2}+\frac{\pi}{2}\right)}_{H_1(f_{\mathrm{RF}})}\cdot\underbrace{\sum_{m=1}^{M}P_m\exp[\mathrm{j}2\pi f_{\mathrm{RF}}(m-1)T]\times}_{H_2(f_{\mathrm{RF}})}$$

$$\underbrace{\frac{\kappa}{1-(1-\kappa)\cdot\exp\left(-\frac{\mathrm{j}2\pi f_{\mathrm{RF}}nL_2}{c}\right)}}_{H_3(f_{\mathrm{RF}})}. \tag{5}$$

Whereas, in order to achieve the best filtering capability, the free spectral range (FSR) of cascaded MPF between the two components of optical structures should meet the relationship as

$$FSR=FSR_{\text{PM-SMF}}=q\cdot FSR_{\mathrm{ring}}\qquad(q=1,2,3,\cdots), \tag{6}$$

where $FSR_{\text{PM-SMF}}=1/T=1/(D\cdot L_1\cdot\Delta\lambda)$ is the FSR of traditional MPF filter which is realized by PM and SMF in this paper, and $FSR_{\mathrm{ring}}=c/(nL_2)$ is the FSR of the fiber ring resonator. Based on the above analysis, the length of fiber in the fiber ring resonator can be given by

$$L_2=\frac{c}{n\cdot FSR_{\mathrm{ring}}}=\frac{c}{n\cdot\frac{FSR_{\text{PM-SMF}}}{q}}=$$

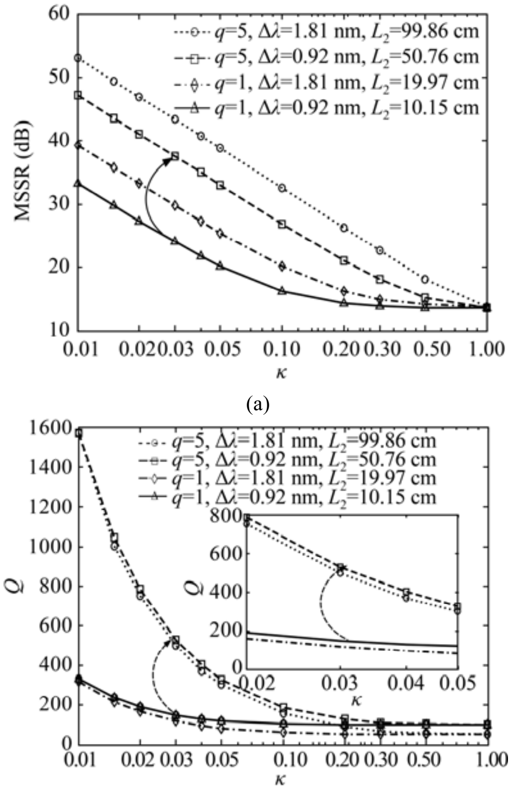
$$\frac{q\cdot c\cdot D\cdot L_1\cdot\Delta\lambda}{n},\qquad(q=1,2,3\cdots). \tag{7}$$

In order to improve the frequency selectivity of MPF, the filter should have a greater MSSR and a greater Q-factor. In the configuration, we use the cascaded characteristic of optical structure to improve the selectivity of MPF.

According to Eq.(5) we can get the frequency response of the cascaded MPF, and then calculate the relationships of MSSR and Q-factor with κ as shown in Fig.2, where the inset is the partially enlarged version.

From Fig.2, MSSR and Q-factor of the cascaded band-pass MPF are both improved by reducing the split ratio κ of OC-2. From Fig.2(a), the growth trend of MSSR of cascaded band-pass MPF is related to the length of fiber in fiber ring resonator L_2. When longer L_2 is selected, MSSR is increased faster by reducing κ. When $L_2=0$ which means $\kappa=1$, the filter's MSSR is the smallest at 13.536 dB, which has no relation to the wavelength separation $\Delta\lambda$. When $L_2=99.86$ cm, MSSR is raised from 13.536 dB to 52.992 dB by reducing κ from 1.00 to 0.01. From Fig.2(b), the growth trend of Q-factor is related to q (q is proportional to the ratio of the fiber length L_2 and the wavelength separation $\Delta\lambda$). The Q-factor is increased faster by reducing κ for larger q. When $\kappa=1$, the Q-factor of the filter is also the smallest. The smallest Q-factor is 51.987 for $\Delta\lambda=1.81$ nm, and is 101.682 for $\Delta\lambda=0.92$ nm. When $\Delta\lambda=1.81$ nm and $q=5$, the Q-factor is increased from 51.987 to 1567.754 by reducing κ from 1.00 to 0.01.

From Fig.2, we also conclude that when the split ratio κ of OC-2 is fixed, MSSR and Q-factor of the cascaded band-pass MPF are both improved by increasing the fiber length in the fiber ring resonator L_2. Such as, when the split ratio κ=0.03 and the wavelength separation $\Delta\lambda$=0.92 nm are fixed, with the increase of fiber ring length L_2 from 10.15 cm to 50.76 cm, MSSR of the cascaded band-pass MPF is raised from 24.039 dB to 37.535 dB, and Q-factor is improved from 150.182 to 529.703, which are shown in Fig.2(a) and (b).



(a)

(b)

Fig.2 The relationships of (a) MSSR and (b) Q-factor with split ratio *κ*

In order to achieve high MSSR and large Q-factor, smaller κ and longer L_2 should be considered. By choosing κ=0.01, L_1=30 km and L_2=152.27 cm, a band-pass filter with MSSR of 53.54 dB and Q-factor of 4048 is achieved, whose RF response is shown in Fig.3.

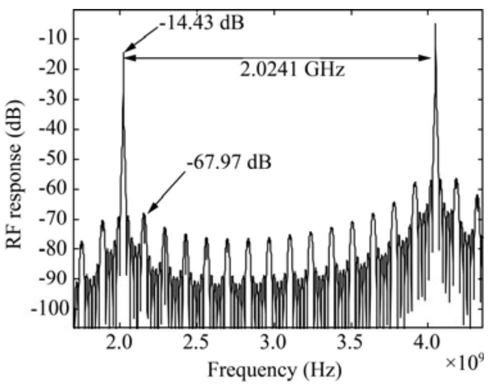
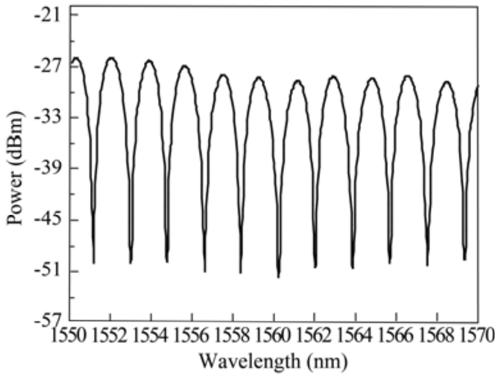


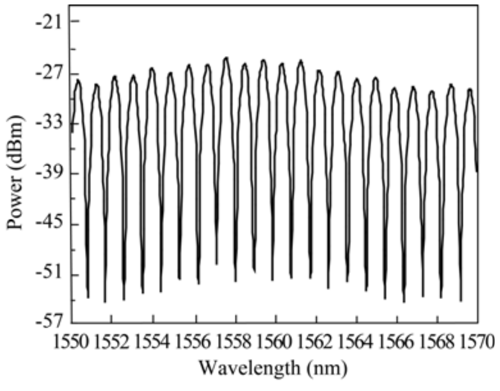
Fig.3 The simulation result of the band-pass filter with *κ*=0.01, *L*₁=30 km and *L*₂=152.27 cm

In addition, a stabilized and tunable multi-wavelength optical source is achieved by splicing BOS with Lyot-Sagnac filter in experiment. Therefore, the central frequency of the filter can be tuned by adjusting the wavelength separation $\Delta\lambda$.

In our experiment, a BOS (EXFO FLS-2300B ASE source) is used, whose bandwidth range is from 1520 nm to 1615 nm. Fig.4 shows the measured output spectra of the multi-wavelength optical carriers after the Lyot-Sagnac filter in the range from 1550 nm to 1570 nm. In the proposed scheme shown as Fig.1, the 2-element Lyot-Sagnac filter has only two valid rotation angles of +45° and –45°[15]. Therefore, the effective lengths of PMF d_{eff} in the birefringence loop are $\Delta n_1 d_1+\Delta n_2 d_2$ and $|\Delta n_1 d_1-\Delta n_2 d_2|$, respectively. In the experiment, d_1=1 m and d_2=3 m are the lengths of PMFs with the same birefringence index of $\Delta n_g=\Delta n_1=\Delta n_2=6.698\times10^{-4}$, respectively.



(a) d_{eff}=2 m ($\Delta\lambda$=1.81 nm)



(b) d_{eff} =4 m ($\Delta\lambda$=0.92 nm)

Fig.4 Output spectra of multi-wavelength optical source by splicing BOS with Lyot-Sagnac filter

According to the multi-wavelength optical source in Fig.4, the frequency response of the cascaded MPF with κ=0.01 is shown in Fig.5. In the simulation analysis, the chromatic dispersion D=17.9 ps/(km·nm) and the length of SMF L_1=30 km are used.

From Fig.5, the central frequency of the cascaded MPF changes from 1.0288 GHz to 2.0241 GHz when the wavelength separation of the multi-wavelength optical source is changed from 1.81 nm to 0.92 nm, i.e., L_2 is changed from 99.86 cm to 50.76 cm.

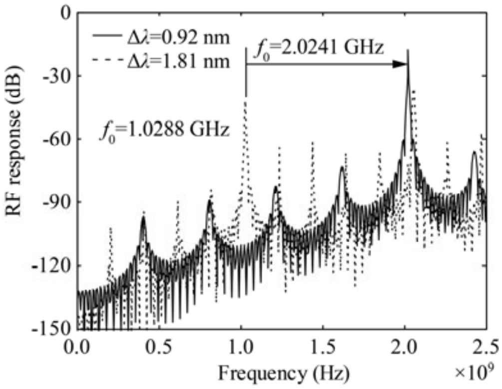


Fig.5 The frequency response of the cascaded MPF when κ=0.01

In summary, a negative-coefficient band-pass MPF is proposed in this paper by combining a Lyot-Sagnac filter and two cascaded optical filter structures. Due to the cascaded optical structures, MSSR and Q-factor, which represent the frequency selectivity of filter, are both improved by reducing the split ratio κ of OC-2 or increasing the length of fiber in fiber ring resonator L_2. Furthermore, the central frequency of the filter can be changed by adjusting the wavelength separation of the optical source and the length of L_2.

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