Tunable and switchable microwave photonic filter using a semiconductor optical amplifier in a Sagnac fiber loop

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A tunable and switchable coherence-free microwave photonic filter configuration is presented. This all-optical structure realizes filters with capability of switching between bandpass and low pass response. It is based on a Sagnac fiber loop interferometer containing a phase modulator and a semiconductor optical amplifier (SOA) with high-birefringence (Hi-Bi) pigtails. The SOA generates a phase difference between the clockwise and counterclockwise propagating waves inside the Sagnac fiber loop interferometer, together with compensating the insertion loss of the Sagnac loop. Measured results confirm the theoretical expressions and demonstrate a robust switchable notch filter response.

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1. Introduction

All-optical processing of microwave and millimeter-wave signals provides advantages such as large time-bandwidth products, insensitivity to electromagnetic interference (EMI) and lightweight [1]-[2]. Considerable number of structures for photonic processing for applications in microwave signal filtering has been proposed over the years [1]-[2]. Most of the conventional incoherent photonic processors can not realize negative coefficient [1]-[4], significantly limiting the variety of obtainable transfer functions. Several methods have been proposed to generate negative coefficient, including cross-intensity modulation of the longitudinal modes in a Fabry-Perot laser [5] and phase modulation based on dispersive medium [6]. Recently, two photonic notch filters based on Sagnac loop with equivalent negative taps have also been proposed [7]-[8]. However, they need the polarization controlled bias nonreciprocal bias unit, and can not provide the compensation of the insertion loss of the Sagnac loop and the tunability. Further, they can not provide the ability to switch between bandpass and low pass response.

We present a novel tunable coherence-free microwave photonic filter. This structure can realize a tunable and switchable response filter which provides conversion between all-optical equivalent negative notch photonic filter and low pass notch filter. It is based on a Sagnac fiber loop interferometer containing a phase modulator and a time delay line. One semiconductor optical amplifier (SOA), with Hi-Bi pigtails, inserts into the Sagnac fiber loop to generate the phase difference between the clockwise and the counter-clockwise propagation waves inside the Sagnac fiber loop, and it can also compensate the insertion loss of Sagnac fiber loop. By tuning the time delay line, which is incoporated in the Saganc fiber loop and has Hi-Bi pigtails, the free spectral range (FSR) of the bandpass or low pass filter can be continuously tunable. Measured results demonstrate a robust notch filter response without phase-induced intensity noise.

2. Experimental configuration and operation principle

The schematic of the new switchable filter is shown in Fig. 1. A DFB laser source is launched into a polarization maintaining (PM) isolator, which absorbs the back reflection from the coupler and has Hi-Bi pigtails. The output of the isolator is coupled into a PM-fiber Sagnac interferometer loop which consists of a 50:50 2×2 PM coupler, a tunable time delay line whose pigtails are Hi-Bi fiber, a phase modulator, and a SOA (COVEGA) with Hi-Bi pigtails. The phase modulator is asymmetrically placed and is driven by an input RF signal, which is located away from the loop centre. The light is spitted equally by the 3 dB Hi-Bi coupler. So half of the light travels in the clockwise (CW) direction, which passes the tunable time delay line and the phase modulator firstly. The other half travels the counter-clockwise (CCW) direction, which is amplified by the SOA firstly to provide the phase difference between the CW and CCW optical signals with phase modulation [9]. After recombination at the coupler, the modulated signal is detected by a photodetector (PD), which is followed by a network analyzer to display the filter transfer characteristic. Since there is no coherence problem in the system, a narrow linewidth of the DFB laser source can be used as the Sagnac fiber loop source. Further, the phase difference can be easily generated by the SOA in the Sagnac fiber loop, and the SOA compensates the insertion loss of the time delay line and the phase modulator.

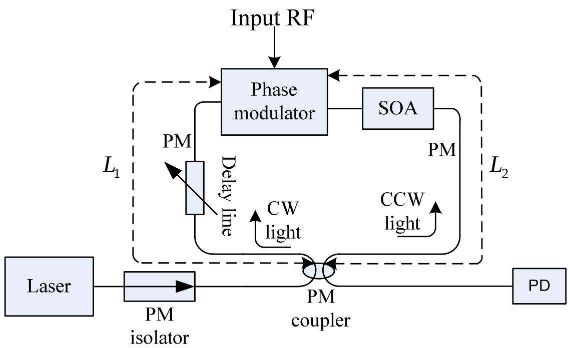

Fig. 1. Experimental setup.

To derive the filter transfer function, let us firstly consider that the output signal of narrow linewidth laser, emitting at an angle frequency ω_0, is modulated by an RF signal with a voltage V_{RF} and an angle frequency ω_m. Therefore the output signal of the phase modulator for CW signal in the Sagnac loop results in

$$E_{CW}(t)=\frac{\sqrt{2}}{2}M\sqrt{P_i}\exp\left\{j\left[\omega_0\left(t-T_1-T_2\right)\right]+jm_1\cos\left[\omega_m\left(t-T_2\right)\right]\right\} \quad (1)$$

where $T_1=nL_1/c$, $T_2=nL_2/c$, $m_1=\pi V_{RF}/V_{\pi,for}$ is the modulation index in CW direction, $V_{\pi,for}$ is half-wave voltage for forward direction of the phase modulator, n is the fiber effective refractive index, and c is the speed of light, M is the amplitude factor, P_i is the laser output power, and M is a signal amplitude factor, which includes the insertion loss of the time delay line and the phase modulator as well as the gain of the SOA. The corresponding electric field of the light wave for CCW signal can be given by

$$E_{CCW}(t)=\frac{\sqrt{2}}{2}M\sqrt{P_i}\exp\left\{j\left[\omega_0\left(t-T_1-T_2\right)+\pi/2+\phi\right]+jm_2\cos\left[\omega_m\left(t-T_1\right)\right]\right\} \quad (2)$$

where $m_2=\pi V_{RF}/V_{\pi,rev}$ is the modulation index in CCW direction, the and reverse $V_{\pi,rev}$ is half-wave voltage for reverse direction of the phase modulator. The $\pi/2$ phase shift is due to the Hi-Bi coupler and ϕ is the nonlinear phase difference because of the SOA. The nonlinear phase difference ϕ and gain ratio $\varepsilon=g_{cw}/g_{ccw}$ for the two different directions of the SOA are coupled by the linewidth enhancement factor α of the SOA [10]:

$$\phi=-\frac{\alpha}{2}\ln\left(\frac{g_{cw}}{g_{ccw}}\right)=-\frac{\alpha}{2}\ln\left(\varepsilon\right) \quad (3)$$

Here $g_{cw}(t)$ and $g_{ccw}(t)$ are the SOA amplitude gains in the two different directions. Further, since the CW light is modulated by the phase modulator in the forward direction, whereas the CCW light is modulated in the back-forward direction. The modulated half-wave voltage relationship for the forward $V_{\pi,for}$ and reverse $V_{\pi,rev}$ traveling waves is related to the signal transit time (τ_x) in the phase modulator [11].

$$V_{\pi,rev}=V_{\pi,for}\frac{\omega_m\tau_x}{\sin\left(\omega_m\tau_x\right)} \quad (4)$$

Then the output field of the Sagnac fiber loop can be noted as

$$E(t)=\frac{1}{2}M\sqrt{P_i}\begin{Bmatrix}\exp\left\{j\left[\omega_0\left(t-T_1-T_2\right)\right]+jm_1\cos\left[\omega_m\left(t-T_2\right)\right]\right\}\\+\exp\left\{j\left[\omega_0\left(t-T_1-T_2\right)+\pi+\phi\right]+jm_2\cos\left[\omega_m\left(t-T_1\right)\right]\right\}\end{Bmatrix} \quad (5)$$

Then the conjugation of Eq. (5) can be expressed as

$$E^*(t)=\frac{1}{2}M\sqrt{P_i}\begin{Bmatrix}\exp\left\{-j\left[\omega_0\left(t-T_1-T_2\right)\right]-jm_1\cos\left[\omega_m\left(t-T_2\right)\right]\right\}\\+\exp\left\{-j\left[\omega_0\left(t-T_1-T_2\right)+\pi+\phi\right]-jm_2\cos\left[\omega_m\left(t-T_1\right)\right]\right\}\end{Bmatrix} \quad (6)$$

Since the frequency range of the filter is less than 300 MHz, $m_1 \approx m_2=m$. Then the spectrum of the optical power incident on the photodector for detection is

$$I\left(\omega_m\right)=\frac{1}{2}M^2P_i\cos\left\{\phi+\pi-2m\sin\left[\frac{\omega_m\left(T_2-T_1\right)}{2}\right]\sin\left[\omega_m\left(t-\frac{T_1+T_2}{2}\right)\right]\right\} \quad (7)$$

Under small modulation index condition, using a Bessel series expansion to obtain the fundamental frequency response, Eq. (7) can be represented as

$$I\left(\omega_m\right)=\frac{1}{2}mM^2P_i\cos\left[\phi+\pi+\frac{\omega_m\left(T_2-T_1\right)}{2}\right]\sin\left[\omega_m\left(t-\frac{T_1+T_2}{2}\right)\right] \quad (8)$$

When $\phi=\pi/2$, the amplitude response of Eq.(8) can be noted as

$$I\left(\omega_m\right)\propto\sin\left[\frac{\omega_m\left(T_2-T_1\right)}{2}\right] \quad (9)$$

Eq.(9) shows the response of the filter is bandpass. Meanwhile, if $\phi=\pi$, amplitude response of the electrical current is

$$I\left(\omega_m\right)\propto\cos\left[\frac{\omega_m\left(T_2-T_1\right)}{2}\right] \quad (10)$$

Eq.(10) describes that the response of the filter is lowpass. Further, the FSR is dependent on the time differences between the CW and CCW light, which can be expressed as

$$\Delta T = T_2 - T_1 = \frac{n\left(L_1 - L_2\right)}{c} \tag{11}$$

3. Experimental results and discussion

The operation and the characteristics of the tunable and switchable filter can be verified by the experimental results.The DFB laser source (Anritsu DFB 108875) has a maximum power of 14.26 dBm with a linewidth of 100 kHz. The SOA (COVAGA) has Hi-Bi pigtails at both input and output ports, and the input RF signal power is 0 dBm. The maximum current of the SOA is 500 mA with 0.8 dB polarization dependent gain (PDG). By tuning the drive current of the SOA, the phase difference induced by the SOA can be continuously tunable in the Sagnac fiber loop. When its value reaches $\pi/2$, it generates bandpass response, as shown in Eq.(9). However, when its values is π, as given by Eq.(10), the filter response is low pass.

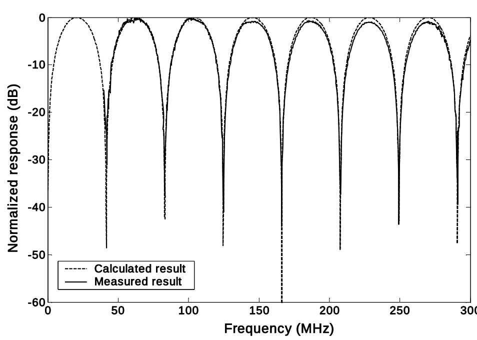

Fig. 2. Measured and calculated response of the bandpass filter without tuning the time delay line

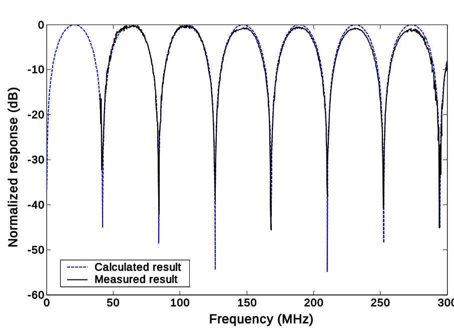

Fig. 3. Measured and calculated response of the bandpass filter when the time delay is tuned to 300 ps.

In the experiment, the path difference $L_2 - L_1$ for the single drive MZ modulator located in the Sagnac loop is 4.81 m. This corresponds to a filter with FSR of 41.55 MHz. The input laser power is 14.26 dBm and the drive current of the SOA is 164.8 mA. The measured bandpass response is shown in Fig.2, together with the calculated result. Excellent agreement can be seen. The lowest measurement frequency of the calculated result is limited by the network minimum measurable frequency (40 MHz). However, since the response is periodic with a period of 41.55 MHz, extrapolating the results shows that the filter response is bandpass. The tunability of the bandpass filter can be realized by tuning the time delay line with Hi-Bi pigtails, whose tuning range is between 0 ps to 300 ps. Fig. 3 shows the measured bandpass response when the time delay is tuned to the maximum value, 300 ps, which corresponds to an FSR of 42.08 MHz. The agreement between the measured result and the calculated result is also very good, and no phase induced intensity noise is observed at the output port.

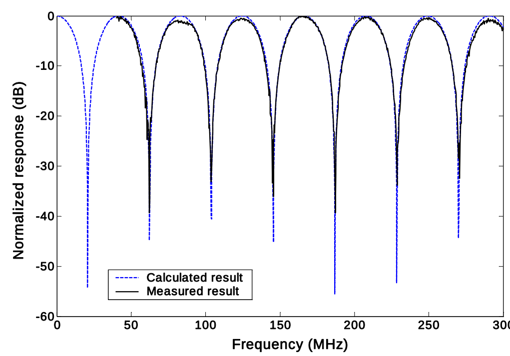

Fig. 4. Measured and calculated response of the low pass filter without tuning the time delay line

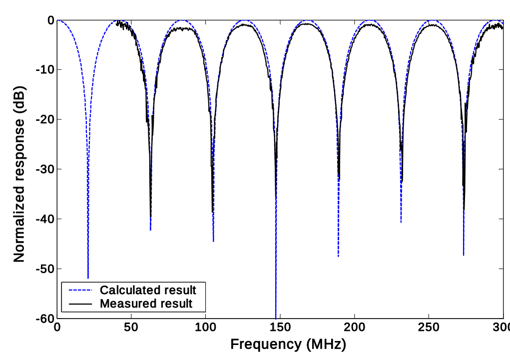

Fig. 5. Measured and calculated response of the low pass filter when the time delay is tuned to 300 ps.

However, when the input laser power is 14.26 dBm, and the drive current of the SOA is 233.5 mA, the filter response is low pass rather than bandpass. The measured low pass response is shown in Fig.4, together with the calculated result. Excellent agreement can also be seen. The lowest measurement frequency of the measured result is also limited by the network minimum measurable frequency (40 MHz). However, since the response is periodic with a period of 41.55 MHz, extrapolating the results shows that the filter response is low pass. Fig.5 shows the measured low pass response when the time delay is tuned to a value of 300 ps, which corresponds to an FSR of 42.08 MHz. The agreement between the measured results and calculated results is also good.

4. Conclusions

A novel tunable and switchable coherence-free photonic filter has been presented. This structure can realize a tunable filter with capability of switching between bandpass response and low pass response. It is based on a Sagnac fiber loop interferometer containing a phase modulator. One SOA inserts into the Sagnac fiber loop to generate the phase difference between the clockwise and the counter-clockwise propagation waves inside the Sagnac loop, and it can also compensate the insertion loss of Sagnac fiber loop. By tuning the time delay line, which is incoporated in the Saganc fiber loop and has Hi-Bi pigtails, the FSR of the bandpass and low pass filter can be continuously tunable. Measured results demonstrate a robust notch filter response without phase-induced intensity noise.

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Reference

[1] J. Capmany, B. Ortega, D. Pastor, S. Sales, J. Lightwave Technol. **23**, 702 2005.
[2] R. A. Minasian, Trans. Microw. Theory Technol., **54**, 832 (2006).
[3] A. J. Seeds, Trans. Microw. Theory Technol. **50**(3), 877 (2002).
[4] W. Zhang, J. A. R. Williams, I. Bennion, Electron. Lett. **35**, 2133 (1999).
[5] X. Wang, K. T. Chan, Lett. **36**, 2001 (2000).
[6] J. Wang, J. P. Yao, Photon. Technol Lett. **17**, 1737 (2005).
[7] E. H. W. Chan, R. A. Minasian, Photon. Technol Lett., **17**, 1740 (2005).
[8] E. H. W. Chan, R. A. Minasian, Photon. Technol Lett., **18** .1252 (2006).
[9] G. P. Agrawal, N. A. Olsson, J. Quantum Electronics, **35**, 2297 (1989).
[10] M. Eiselt, W. Pieper, H. G. Weber, J. Lightwave Technol., **13**, 2099 (1995).
[11] M. Y. Frankel, R. D. Esman, J. Lightwave Technol., **16**(5), 859 (1998).

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