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Novel tunable microwave photonic notch filter using a 3 × 3 coupler based Sagnac loop

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Abstract

We propose a simple and stable structure to realize a tunable negative coefficients microwave photonic notch filter. A 3 × 3 coupler based Sagnac loop interferometer with an asymmetrically placed phase modulator is used to acquire the notches. Our system is simply implemented and with good stability. Theoretical analysis and experimental results are presented and show a good agreement. The structure is proved to be a robust filter with more than 35 dB rejection deep notches.

Keywords: Microwave photonic filter; Notch filter; Sagnac loop; Phase modulator; Optical signal processing

1. Introduction

Microwave photonic filters (MPF) bring significant advantages inherent to photonics such as low loss, large bandwidth, immunity to electromagnetic interference (EMI), tunability and reconfigurability. They can be used in various wireless communications and radar applications. Until now different kinds of MPF have been reported in literatures [1–8], and most of the conventional incoherent MPF [1–3] have positive coefficients of their impulse responses, which exhibit a resonance at baseband. Thus people have been trying different ways to reach negative coefficients. These methods are based on differential detection [4], intensity inversion caused by gain saturation in a semiconductor optical amplifier (SOA) [5], FBG based Sagnac loop [6] and π phase inversion in a Mach–Zehnder modulator [7]. In this paper, we propose a novel tunable negative coefficients photonic notch filter using a 3 × 3 coupler based Sagnac loop. With a broad-band source and a polarization controller, we can achieve stable performance easily. Experimental results and theoretical analysis are presented to verify the proposed configuration and deep notches with more than 35 dB rejection are obtained.

2. Implementation scheme

The proposed MPF topology is shown in Fig. 1. The Sagnac loop consists of two sections of single mode fiber (SMF) with different length L_1 and L_2, a polarization controller (PC) and a phase modulator. Continuous-wave light from a broad-band source is fed into port 2 of the 3 × 3 coupler and split equally into three parts: clockwise (CW) light from port a, counterclockwise (CCW) light from port c and the rest is terminated at port b, respectively. The coupler used here is a fully symmetric one [9], whose *S*-matrix will be given in the following section. The CW light travels through the SMF with length L_1 first, and then passes the PC, phase modulator and SMF with length L_2 in turn. The CCW light passes these components in the opposite order. Because the arrival moments of the CW and the CCW beams at the phase modulator are different, the input RF signal changes, and so does the RF signal induced phase

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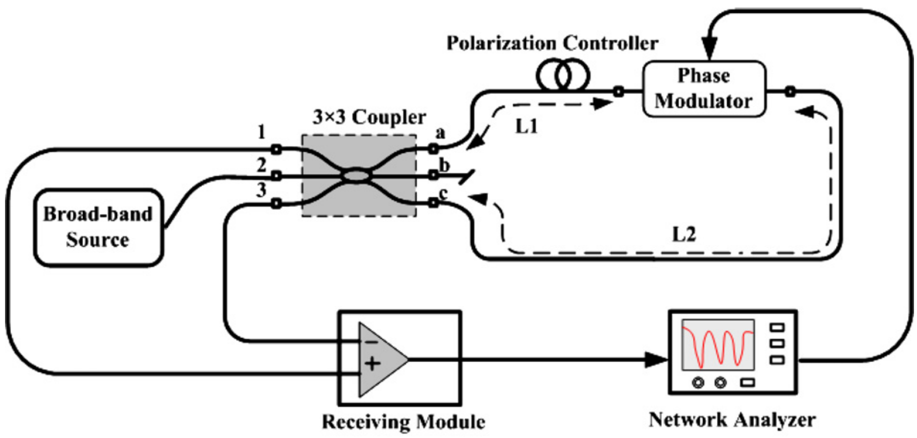

Fig. 1. Topology of negative tap photonic notch filter using a 3 × 3 coupler based Sagnac loop.

modulation upon the two beams. This difference in phase modulation of the two counter-propagating beams will be converted into intensity modulation when these beams recombine at the 3 × 3 coupler to interfere together. Since the fiber used in this scheme is all standard single mode fiber, a polarization controller (PC) is needed to counteract the birefringence in the loop. The optical signals from two output ports (1 and 3) of the 3 × 3 coupler are detected by photodetectors separately, and then are subtracted in the receiving module. Hence, the phase difference induced intensity modulation can be observed. A network analyzer is used to measure the frequency response of the system in the RF regime. Since MPF is used as a device instead of being used for tele-communications, the broadband source does not limit its practical use [10]. Further, our scheme can be easily extended to a tunable MPF by adding a tunable optical fiber delay line into the loop. By tuning the length of the optical fiber delay line, the free spectral range (FSR) of the MPF can be controlled accordingly.

3. Theoretical analysis

According to the structure shown in Fig. 1 along with the transmission matrix of the 3 × 3 fully symmetric coupler [9]

$$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & e^{j\frac{2}{3}\pi} & e^{j\frac{2}{3}\pi} \\ e^{j\frac{2}{3}\pi} & 1 & e^{j\frac{2}{3}\pi} \\ e^{j\frac{2}{3}\pi} & e^{j\frac{2}{3}\pi} & 1 \end{bmatrix}$$

the output RF voltage is given by

$$V = R_0 \times \eta \times (P_1(t) - P_3(t - \Delta t)) \tag{1}$$

where R_0 is the resistor of the receiving circuit, η is the photodiode responsivity, P_1 and P_3 are powers of the two output arms, respectively. Δt is the time difference caused by the length difference of the fibers between the coupler outputs and the photodetectors. Based on the coupler's transmission matrix the items in the bracket can be rewritten as follows:

$$P_1(t) - P_3(t - \Delta t) = \frac{2}{9}DP_0\left[\cos\left(\frac{2}{3}\pi - \varphi(t)\right) - \cos\left(\frac{2}{3}\pi + \varphi(t - \Delta t)\right)\right] \tag{2}$$

In this equation, D is the power transmission coefficient of the loop, P_0 is the power coupled into the Sagnac loop and ϕ is the phase shift difference caused by the asymmetrically placed phase modulator, and it is defined as

$$\begin{aligned}\varphi &= M\sin(\omega_{RF}t) - M\sin\left[\omega_{RF}\left(t - \frac{n(L_1 - L_2)}{c}\right)\right] \\ &= 2M\cos\left(\omega_{RF}\left(t - \frac{\Delta Ln}{2c}\right)\right)\sin\left(\frac{\omega_{RF}\Delta Ln}{2c}\right)\end{aligned} \tag{3}$$

M is modulation coefficient of the phase modulator, i.e. $M = \pi V_{RF}/V_{\pi}$

V_{π} is the phase modulator switching voltage, V_{RF} is the RF signal amplitude, ω_{RF} is the RF signal angular frequency, n is the fiber refractive index and c is the speed of light in vacuum.

To be noted, the switching voltage is different for CW and CCW waves if the frequency is quite high, e.g. several GHz. We make an approximation of their equality here because the phase modulator is operating at several hundreds of MHz in our current scheme. Under such condition, the mismatch of the two sections of output fibers can be neglected as it is easy to control the length of the two fibers at several centimeters scale. Here we assume ϕ is small, and Eq. (1) can be simplified to the following form:

$$V \approx \frac{4\sqrt{3}}{9}DR_0P_0\eta M \times \sin\left(\frac{\omega_{RF}\Delta Ln}{2c}\right)\cos\left(\omega_{RF}\left(t - \frac{\Delta t}{2} - \frac{n\Delta L}{2c}\right)\right) \tag{4}$$

In the experiment the input RF signal should be small enough compared with the switching voltage of the phase