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# Widely Tunable Microwave Photonic Notch Filter Based on Slow and Fast Light Effects

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**Abstract**—A continuously tunable microwave photonic notch filter at around 30 GHz is experimentally demonstrated and 100% fractional tuning over 360° range is achieved without changing the shape of the spectral response. The tuning mechanism is based on the use of slow and fast light effects in semiconductor optical amplifiers assisted by optical filtering.

**Index Terms**—Coherent population oscillations (CPO), microwave photonics, semiconductor optical amplifier (SOA), slow light.

## I. INTRODUCTION

MICROWAVE photonics has already attracted considerable interest for processing microwave or millimeter-wave signals directly in the optical domain [1]–[3], due to its huge bandwidth, inherent speed, immunity to electromagnetic interference, and low loss. One important application of interest is the microwave photonic notch filter, which has potential for broadband wireless access networks and radar systems. To satisfy the expected bandwidth demand in the coming years, several millimeter-wave frequency bands, such as  $\sim 28$  and  $\sim 40$  GHz, which can provide transfer rates higher than 2 MHz, have already been allocated for these systems [4]. During the past several decades, many approaches to realize tunable notch filters have been proposed [5], e.g., liquid crystal spatial light modulator [6], fiber Bragg gratings (FBGs) [7], arrayed waveguide gratings [8], and optical attenuators [9]. However, all the above techniques result in a simultaneous undesirable variation of the free spectral range (FSR) while the filters are continuously tuned. In [10] and [11], it has been shown that this undesirable effect can be avoided by using microwave photonic phase shifters capable of providing a tunable phase-shift over the full 360° range.

On the other hand, the use of slow and fast light effects based on the physical phenomena of electromagnetically induced transparency and coherent population oscillations (CPO) [12],

[13], to achieve a microwave phase shifter [14]–[18], has received considerable attention lately. In particular, semiconductor-based devices provide advantages such as the possibility of integration, low power consumption, and operation at room temperature. Many results of controlling the microwave phase of sine-modulated optical signals have been demonstrated [16]–[19], which include a  $\sim 120^\circ$  phase shift at the modulation frequency of 4 GHz in two semiconductor optical amplifier-electroabsorber (SOA-EA) pairs [17] and  $\sim 200^\circ$  phase shift at 1 GHz in a 2.5-mm quantum-well SOA [18]. In [19], we reported that optical filtering can exploit the refractive-index dynamics of the SOA to not only largely enhance the phase slow-down effect, but also greatly increase the available bandwidth from a few to tens of gigahertz. Furthermore, by controlling the optical phase difference between the carrier and sidebands of the input optical signal, both  $\sim 120^\circ$  phase delay and  $\sim 170^\circ$  phase advance at 19 GHz can be realized by slow and fast light effects in an SOA assisted by optical filtering [20], [21].

In this letter, we demonstrate for the first time, to the best of our knowledge, 100% fractional tuning over 360° range of a microwave photonic notch filter based on slow and fast light effects in an SOA.

## II. PRINCIPLES OF OPERATION

### A. Microwave Phase Shifter Based on Slow and Fast Light Effects in SOAs

In [19], we have already demonstrated that, for a sinusoidally modulated optical signal at microwave frequency  $\Omega$ , employing an FBG notch filter to suppress the red-shifted sideband after the SOA and before the photodetection can greatly enhance the phase change induced by CPO effects. A  $\sim 150^\circ$  phase delay at the modulation frequency of 19 GHz has been observed and is found to be due to the refractive-index dynamics in the active region of the device. But this is still not enough to achieve a shift of the null frequency of a notch filter by an amount given by the FSR. In [20] and [21], based on a similar setup as used in [19], both  $\sim 120^\circ$  phase delay and  $\sim 170^\circ$  phase advance have been successfully realized by choosing different values for the initial optical phase difference between the carrier and sidebands, which provides a possible way to achieve a  $\sim 360^\circ$  phase shifter.

Fig. 1 shows the basic architecture of the microwave phase shifter. The detailed method to measure the phase shift is similar to that described in [14] and [19]. The RF intensity modulation is imposed on a continuous-wave laser beam using a Mach-Zehnder modulator (MZM). By operating the MZM at the different transmission slopes,  $V_1$  and  $V_2$ ,  $\sim 0^\circ$  or  $\sim 180^\circ$

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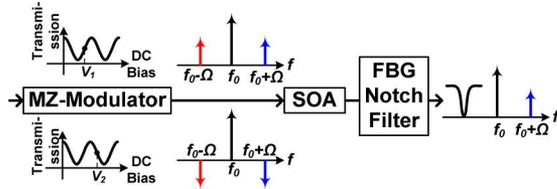


Fig. 1. Schematic of the microwave photonic phase shifter. ( $f_0$ : laser frequency;  $\Omega$ : microwave modulation frequency;  $V_1$  and  $V_2$ : DC bias voltages of the modulator).

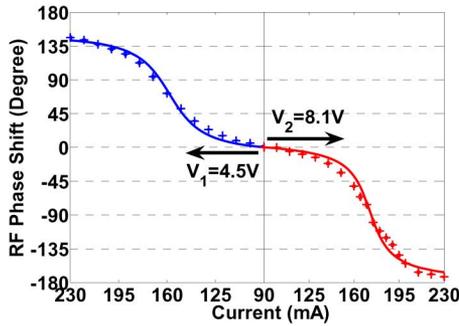


Fig. 2. Phase shifts as a function of injection current of the SOA when the modulator is biased at  $V_1 = 4.5$  V (blue curves in the left part) and  $V_2 = 8.1$  V (red curves in the right part). The “+” markers show experimental results and the solid lines are numerical simulations. (The modulation frequency is sweeping between 29.75 and 30.25 GHz.)

phase difference between the carrier and sidebands can be obtained.

Fig. 2 illustrates the phase shifts induced by slow and fast light effects through changing the injection current of the SOA for two different operating bias voltages of the modulator. For these two cases, the reference phase is chosen at the injection current of 90 mA, and the input optical power into the SOA is fixed at 9 dBm. The laser wavelength is 1552.7 nm. When the MZM is operated at the positive slope ( $V_1 = 4.5$  V), about  $150^\circ$  phase delay at 30 GHz is achieved, as shown in the left part of Fig. 2. On the other hand, about  $170^\circ$  phase advance, shown in the right part of Fig. 2, is obtained for the negative slope ( $V_2 = 8.1$  V). Fig. 2 also shows that the phase sensitivity is different over the whole tuning range,  $\sim 12^\circ$  phase shift due to a 5-mA current change at the injection current of around 170 mA and  $\sim 2^\circ$  phase shift due to the same current change at around 90 or 230 mA. The solid lines are numerical results, calculated using a four-wave mixing model appropriate for semiconductor waveguides [14], [18], and show good agreement with the experimental results. In [19], we have already shown that the optical filtering technique can increase the bandwidth of the phase shifter to at least 15 GHz, which means that this proposed microwave phase shifter can provide  $\sim 360^\circ$  phase shift at other microwave frequency bands. The lower microwave frequency is limited to several gigahertz by the bandwidth of the optical FBG notch filter, which is employed to block the red-shifted sideband.

### B. Experimental Setup

Fig. 3 describes the experimental scheme. The filter itself is a simple Mach–Zehnder interferometer composed of two arms, one of which incorporates the microwave phase shifter, shown

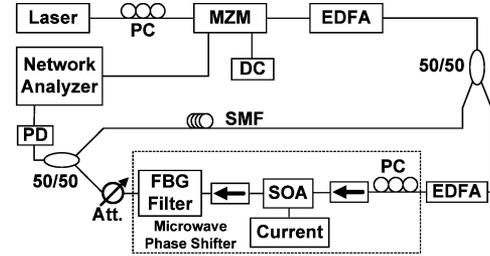
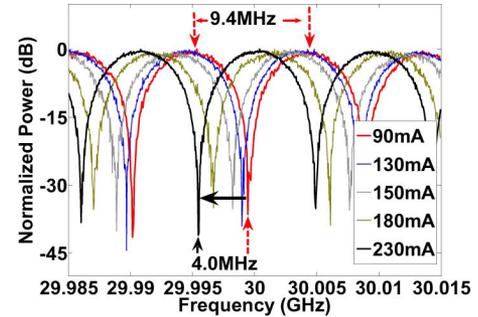
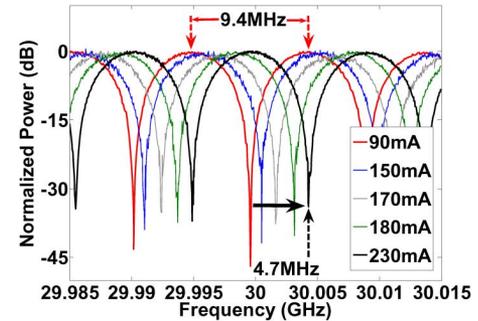


Fig. 3. Experimental setup of a tunable two-tap microwave photonic notch filter. (Att.: tunable attenuator; PC: polarization controller.)



(a)



(b)

Fig. 4. Tunable RF response of the notch filter obtained by changing the injection current of the SOA, when the modulator is biased at (a)  $V_1 = 4.5$  V and (b)  $V_2 = 8.1$  V.

in the dotted-line box, which is made up of an SOA followed by an FBG notch filter. The erbium-doped fiber amplifier is used to adjust the SOA input optical power to 9 dBm, in order to ensure that the SOA operates in the saturation regime. After the microwave phase shifter, a tunable attenuator provides amplitude balance between the two arms to compensate  $\sim 10$ -dB power change of the output signal after the SOA [19].

Tuning of the null frequency can be achieved by changing the injection current of the SOA. Through switching between the two operating stages ( $V_1 = 4.5$  V and  $V_2 = 8.1$  V) of the MZM, a  $330^\circ$  phase shift, which is the sum of an  $\sim 150^\circ$  phase delay and  $\sim 170^\circ$  phase advance, is expected. Note that the switching between the two different operating points of the MZM will not change the spectral shape of the filter.

### III. EXPERIMENTAL RESULTS

Fig. 4 shows the measured filter responses for different currents. The FSR is 9.4 MHz, corresponding to 22-m optical fiber length difference between the two arms. The notch rejection is

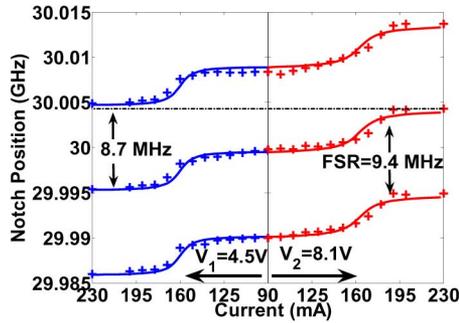


Fig. 5. Measured notch frequency versus injection current of the SOA, when the modulator is biased at  $V_1 = 4.5$  V, (the blue curves in the left part) and  $V_2 = 8.1$  V (the red curves in the right part). The “+” markers and the solid lines are experimental and numerical results, respectively.

always larger than 30 dB over the entire tuning range. The spectral response at the SOA injection current of 90 mA is chosen as the reference for both operating stages of the MZM.

For  $V_1 = 4.5$  V, as shown in Fig. 4(a), the null frequency experiences a shift of 4.0 MHz towards lower frequencies as the current increases from 90 to 230 mA, which corresponds to almost +50% fractional tuning range. Similarly, Fig. 4(b) shows that if the MZM is operated at the negative slope  $V_2 = 8.1$  V, a 4.7-MHz shift in the other direction, corresponding to the -50% fractional tuning range, is obtained by changing the current from 90 to 230 mA. Note that the two initial frequency responses at 90 mA in Fig. 4(a) and (b) have the same position as well as the same shape. Fig. 5 demonstrates that through switching between the two operation points of the MZM, the notch positions of the microwave photonic notch filter can be continuously tuned over 8.7 MHz, without changing the spectral shape of the response, by changing the injection current of the SOA. The solid lines are simulation results. Because the phase shifts shown in Fig. 2 are measured over a bandwidth of 500 MHz, this almost 100% fractional tuning range will be maintained for even larger filter FSRs, which can be achieved by decreasing the time difference between two arms. Notice, however, that for the time difference on the order of or smaller than the coherence time of the laser, optical interference effects have to be taken into account [5].

#### IV. CONCLUSION AND OUTLOOK

We have presented a novel scheme to achieve a widely tunable microwave photonic notch filter, which is based on slow and fast light effects in SOAs and can realize 100% fractional tuning range at 30 GHz. The experimental results agree well with numerical results and show the potential for the application of this technique in the new generation of mobile broadband systems operating in the millimeter-wave frequency range. The advantages of the proposed scheme are large tuning range, wide choice of frequency bands, low control voltage, and fast reconfiguration in the order of a few nanoseconds or several hundreds of picoseconds, which is only determined by the switching time of the SOA because the switching of the bias points of the MZM could be avoided by using a specially designed MZM. Furthermore, the tunable attenuator used to balance the power between

the two arms could be replaced by an EA, rendering the entire setup promising for future integrated devices.

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