A Tunable Photonic Microwave Filter With a Complex Coefficient Using an Optical RF Phase Shifter

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***Abstract*—A novel tunable photonic microwave filter with complex coefficients is proposed and experimentally demonstrated. The complex coefficient is generated using a wideband tunable optical RF phase shifter that consists of two electrooptic intensity modulators. The phase of the RF signal is shifted by simply adjusting the bias voltages applied to the two electrooptic intensity modulators, and the phase shift remains constant over the microwave spectral region of interest. A two-tap photonic microwave filter with one tunable complex coefficient, with a wide and continuous tuning range, is experimentally demonstrated.**

***Index Terms*—Microwave photonics, optical RF phase shifter, photonic microwave filter, radio over fiber (RoF).**

I. Introduction

PHOTONIC microwave filters with the advantageous features such as broad bandwidth, low loss, light weight, large tunability, and immunity to electromagnetic interference have been investigated intensively in the last few years. The processing of microwave signals in the optical domain is of particular interest for applications such as optically controlled phased-array antennas and radio-over-fiber (RoF) systems, since the microwave signals can be processed directly in the optical domain without the need of extra optical-electrical and electrical-optical conversions. In general, a photonic microwave filter is implemented in the optical domain based on a delay line stricture with multiple taps. To avoid optical interferences, most of the proposed filters are operating in the incoherent regime. Photonic microwave filters operating in the incoherent regime can usually have positive coefficients, or special designs have to be incorporated to generate negative coefficients [1]. Based on signal processing theory, a delay line filter with all-positive coefficients can only function as low-pass filters [1]. This results in a severe limitation on the functionalities of the photonic microwave filters. To overcome this limitation, several approaches have been proposed in the last few years to generate negative coefficients and hence to achieve bandpass filtering [1]–[3]. On the other hand, it is also desirable that the photonic microwave filters are tunable. Various techniques have been proposed for the implementation of tunable photonic microwave filters [4]–[7]. The tunability is usually achieved by adjusting the time delay difference. However, the change of the time delay difference would lead to the changes of the free spectral range (FSR), which results in the change of 3-dB bandwidth as well as the entire shape of the filter frequency response. For many applications, it is highly desirable that only the center frequency of the pass-band or stop-band is changed while keeping the shape of the frequency response unchanged. A solution to this problem is to use a photonic microwave filter with complex coefficients.

Two configurations have been recently reported in [8] and [9] for the implementation of tunable microwave filters with complex coefficients. In [8], the complex coefficient was generated in a system using three optical attenuators and two microwave couplers. The use of optical attenuators may achieve only positive coefficients, adjustable from zero to one, which limits the RF phase shift from 0 to 180° or a tunable range of a half FSR [8]. In [9], a tunable photonic microwave filter with complex coefficient that has a tunable range up to one FSR was demonstrated. In the system, the complex coefficient was generated by changing the phase of the microwave signal, which was realized based on a combined use of optical single-sideband modulation (SSB) and stimulated Brillouin scattering (SBS). In [9], to stimulate the SBS, a 20-km single-mode fiber was used, which makes the system bulky. To avoid using a long optical fiber, in this letter we propose a novel tunable photonic microwave filter with a very simple structure. In the proposed filter, the complex coefficient is generated based on a wideband tunable optical RF phase shifter [10], [11], in which the phase of the RF signal can be shifted by simply adjusting the bias voltages applied to two electrooptic intensity modulators (IMs), with the phase shift kept constant over the microwave spectral region of interest. A two-tap photonic microwave filter with one tunable complex coefficient is experimentally demonstrated.

II. Principle

The schematic diagram illustrating the generation of a complex coefficient based on a wideband tunable optical RF phase shifter is shown in Fig. 1. It is a two-tap filter with one tap having a real positive coefficient and the other tap having a complex coefficient. The real positive coefficient is generated using an intensity modulator (IM1) with an input lightwave operating at λ_1. The complex coefficient is generated by the optical RF phase shifter, shown in the dashed-line box of Fig. 1. In the RF phase shifter, two independent light sources both operating at the same

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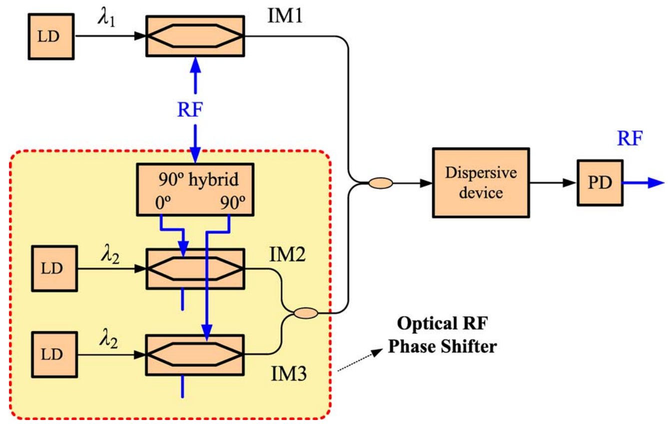

Fig. 1. Generation of complex coefficient based on optical RF phase shifter. LD is laser diode; IM is intensity modulator; and PD is photodetector.

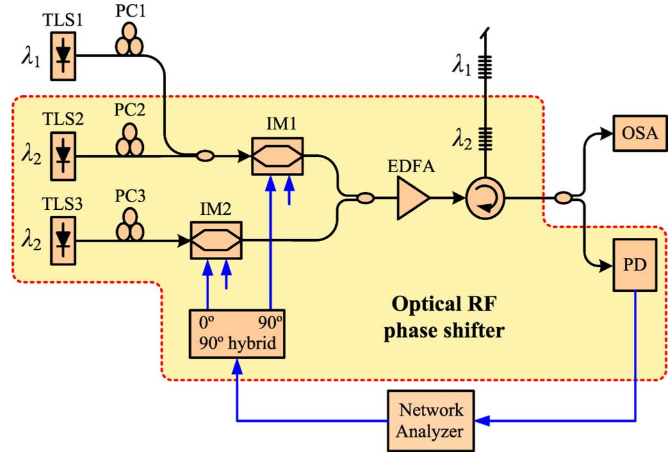

Fig. 2. Experimental setup of proposed filter. TLS is tunable laser source; PC is polarization controller; and OSA is optical spectrum analyzer.

wavelength λ_2, are sent to two intensity modulators (IM2 and IM3), which are modulated by the in-phase and the quadrature components of the microwave signal from a 90° hybrid coupler. The input optical intensities of the two intensity modulators (IM2 and IM3) are I_2 and I_3, and the bias voltages are V_2 and V_3. The output signals from the two IMs are then combined by an optical coupler. Since the two lightwaves are generated by two independent light sources, the optical interference at the optical coupler is minimized, even though they are operating at the same wavelength. If we set $I_2 = I_3 = I$ and $V_3 = V_\pi/2 - V_2$, where V_π is the half-wave voltage of the intensity modulators, the electrical field at the output of a photodetector (PD) is given by [10]

$$E_{\rm RF}(t) \propto J_1(\pi V_m/V_\pi) \cdot I \cdot [\sin(\omega t + \phi + \theta)] \qquad (1)$$

where V_m is the amplitude of the microwave modulating signal, $J_1(\pi V_m/V_\pi)$ is the first-order Bessel function of the first kind, ω is the microwave frequency, ϕ is the initial phase of the microwave signal, and $\theta = \pi V_3/V_\pi$ is the phase shift of the microwave signal introduced by the optical RF phase shifter. As can be seen, the RF phase shift θ is a linear function of the bias voltage V_3, which is independent of the input microwave frequency and can be easily tuned by adjusting the bias voltages. Note that the tuning of the bias voltages would lead to the change of the optical intensities at the outputs of the two IMs, which can be compensated by adjusting the optical powers of the laser sources. To eliminate the frequency-dependent phase shift, the fiber lengths from the outputs of the three IMs to the input of the optical delay line should be controlled to be identical [8].

To introduce a time delay difference between the microwave signal carried by wavelength λ_1 and the phase-shifted microwave signal carried by wavelength λ_2, a dispersive device may be used to introduce a time delay difference, as shown in Fig. 1. The dispersive device can be a length of dispersive fiber. To reduce the size, the dispersive fiber can be replaced by two cascaded fiber Bragg gratings (FBGs) or a single-chirped FBG. The time-delayed microwave signals are then applied to the PD. The transfer function of the filter can be written as

$$H(\omega) = 1 + e^{-j\theta} \cdot e^{-j\omega\Delta\tau} \qquad (2)$$

where $\Delta\tau$ is the time-delay difference between the two time-delayed microwave signals. As can be seen, the filter has two taps with one complex coefficient $e^{-j\theta}$. By tuning the bias voltages applied to IM2 and IM3, the phase shift can be changed, leading to the tuning of the complex coefficient.

Note that the two-tap filter shown in Fig. 1 can be extended to a multi-tap filter by adding more optical RF phase shifters with complex coefficients or more laser sources and intensity modulators with real positive coefficients.

III. Experiment

The proposed system is experimentally investigated. To demonstrate the concept, only a two-tap photonic microwave filter with one complex coefficient, shown in Fig. 2, is tested. To simplify the system, the intensity modulator (IM1) in Fig. 2 is used to perform two functions: 1) to modulate the microwave signal on the optical carrier at λ_1 and 2) to work jointly with IM2 to form an optical RF phase shifter.

The output from a tunable laser source (TLS1) at a wavelength of $\lambda_1 = 1546.29$ nm is injected into IM1 through an optical coupler. In the optical RF phase shifter, two lightwaves from two independent tunable laser sources (TLS2 and TLS3), both at the same wavelength of $\lambda_2 = 1549.68$ nm, are sent to IM1 and IM2. The polarization controllers (PC1, PC2, and PC3) connected between the tunable laser sources and the intensity modulators are used to align the polarization directions of the lightwaves with the principle axes of the intensity modulators, to minimize the polarization-dependent loss. The microwave signal generated by a vector network analyzer (VNA) is applied to the two IMs via a 90° hybrid coupler, with the in-phase and the quadrature components to drive IM2 and IM1, respectively. The microwave signal carried by wavelength λ_1 and the phase-shifted microwave signal carried by λ_2 are combined at a 3-dB coupler and amplified by an erbium-doped fiber amplifier (EDFA), then time delayed by two cascaded FBGs with a time-delay difference determined by the physical separation of the two FBGs.

We first investigate the phase-shift property of the optical RF phase shifter, which is shown in the dashed-line box of Fig. 2.

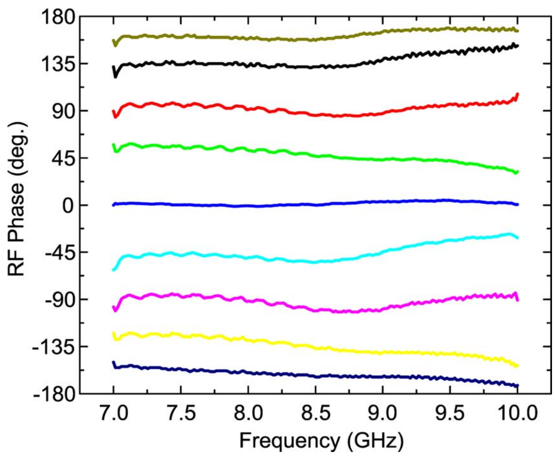

Fig. 3. Measured phase shift for different bias voltages. Phase shift is independent of microwave frequency.

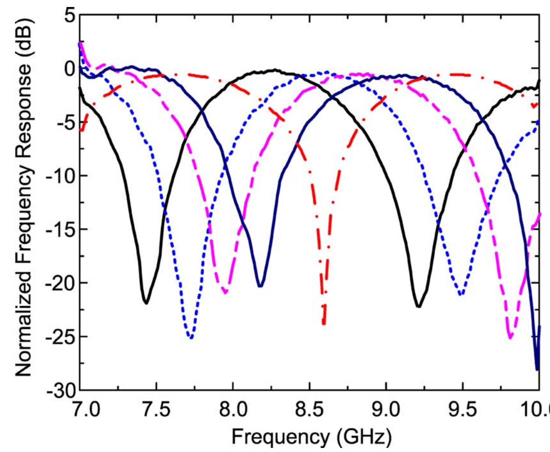

Fig. 4. Measured frequency response of two-tap photonic microwave filter with one complex coefficient.

In this case, TLS1 is disconnected. By sweeping the microwave frequency, we obtain the phase shift of the recovered microwave signal, which is measured by the VNA. As can be seen from Fig. 3, the phase shift of the microwave signal is from -180° to 180° by adjusting the bias voltages applied to the two IMs. The tuning range of the bias voltages is $0 \sim 12$ V, determined by the half-wave voltage of the IMs. The phase shift is independent of the microwave frequency. Therefore, it is possible to use this RF phase shifter to generate the complex coefficient in the photonic microwave filter with a tunable range of one FSR. The phase shift ripples are caused by the measurement errors and the nonideal phase and amplitude response of the 90° hybrid coupler. The nonuniformity of the phase shifts over the frequency band is a result from the nonidentical fiber lengths. Using the photonic integrated circuits technology, the phase errors can be controlled to be smaller than 3° [10].

Then, we reconnect TLS1. The system now becomes a two-tap microwave filter with one complex coefficient. The physical separation between the two FBGs is 5.5 cm, which corresponds to a time-delay difference of 550 ps or an FSR of 1.8 GHz. To measure the frequency response, we scan the frequency of the microwave signal generated by the VNA while maintaining a constant microwave power. Fig. 4 shows the frequency responses of the two-tap microwave filter with the bias voltages adjusted at different values. The tunability of the frequency response is demonstrated. It is different from the tuning of the time delay difference of a delay line filter, where the shape and the 3-dB bandwidth of the frequency response are changed. In the proposed system, since only the microwave phase is changed, the shape and the 3-dB bandwidth of the filter response remain unchanged.

We should note that if the two FBGs are replaced by a chirped FBG, the time-delay difference between the two taps can also be easily changed by simply tuning the wavelength of TLS1. This property provides an additional flexibility to the filter design.

IV. Conclusion

A novel photonic microwave filter with complex coefficient was proposed and experimentally demonstrated. The complex coefficient was generated using a wideband tunable optical RF phase shifter. By simply adjusting the bias voltages applied to the two intensity modulators, the filter response could be continuously tuned. Since the tuning was performed by adjusting the phase shift of the microwave signal, the shape of the filter response and the 3-dB bandwidth were maintained unchanged. This property is important since we can design a microwave filter that is tunable while maintaining an optimized frequency response. Another advantage of the proposed filter is that it has a very simple structure, which has the potential to be integrated using the photonic integrated circuits technology.

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