A continuously tunable multi-tap complex-coefficient microwave photonic filter based on a tilted fiber Bragg grating

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Abstract: The coupling coefficients of the cladding-mode resonances of a tilted fiber Bragg grating (TFBG) are linearly increasing or decreasing in different wavelength regions. Based on the Kramers-Kronig relations, when the coupling coefficients are linearly increasing, the phase shifts are linearly increasing correspondingly. This feature is employed, for the first time, for the implementation of a multi-tap continuously tunable microwave photonic filter with complex coefficients by using a TFBG. By locating the optical carriers of single-sideband-modulated signals at the cladding-mode resonances of the TFBG which has linearly increasing depths, linearly increasing phase shifts are introduced to the optical carriers. By beating the optical carriers with the single sidebands, the phase shifts are translated to the microwave signals, and thus complex coefficients with the required linearly increasing phase shifts are generated. The tunability of the complex coefficients is realized by optically pumping the TFBG which is written in an erbium/ytterbium (Er/Yb) co-doped fiber. A proof-of-concept experiment is performed; a three- and four-tap filter with a frequency tunable range of 150 and 120 MHz, respectively, are demonstrated.

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1. Introduction

Microwave photonics (MWP) is a field that studies the interaction between microwave and optical waves for the generation, processing, control and distribution of microwave signals by means of photonics [1–2]. Among the numerous functions, photonic processing of microwave signals is one of the major functions and has been intensively investigated in the last few years [3–4]. The key device for microwave signal processing is microwave filters. It is usually desirable that a microwave filter has a large tunable range, which is hard to fulfill using pure electronic devices. On the other hand, microwave filters based on photonic devices can be implemented with a large tunable range. Numerous techniques have been proposed to implement microwave photonic filters [2–6]. In general, a microwave photonic filter is implemented in the optical domain based on a delay-line structure with a finite impulse response (FIR). To avoid optical interference, which is extremely sensitive to environmental changes, microwave photonic filters are usually designed to operate in the incoherent regime. It is known that an incoherent microwave photonic filter has only positive coefficients which can only function as a low-pass filter, or special designs have to be employed to generate negative or complex coefficients. For many applications, however, band-pass filters are needed. Numerous approaches have been demonstrated for the implementation of microwave photonic FIR filters with negative or complex coefficients [7–13]. In [7], the complex coefficients are achieved by using a phase shifter based on optical single-sideband modulation and stimulated Brillouin scattering. In [8], two electro-optic intensity modulators are used to generate a complex coefficient. In [9], a complex coefficient is implemented based on the slow and fast light effects in a semiconductor optical amplifier (SOA). A tunable microwave photonic FIR filter with a bandwidth of 30 MHz and a tunable range of 8.7 MHz was demonstrated. A tunable two-tap microwave photonic FIR filter was demonstrated based on a phase shifter implemented using a single III-V silicon-on-insulator (SOI) micro-disk resonator [10]. The phase shift in the complex coefficient was tuned by modifying the refractive index through carrier injection. In [11–12], a programmable wavelength processor (WaveShaper) was used to manipulate the amplitude and phase of the tap coefficients to implement a complex coefficient filter. Recently, a tunable three-tap microwave photonic filter based on a single silicon-on-insulator (SOI) microdisk resonator was demonstrated [13]. In this method, the tunability of the phase shifter is achieved by adjustment of the CW laser emission wavelength. A frequency tunable range of 40 MHz was demonstrated. In this technique, the tuning is achieved by tuning the wavelengths of the laser sources, which makes the system complicated and costly.

In this paper, we propose and demonstrate a multi-tap microwave photonic FIR filter with complex coefficients using a single tilted fiber Bragg grating (TFBG). The frequency tunability is achieved by optically pumping the TFBG, thus the wavelengths of the laser sources are maintained fixed. To ensure effective tuning, the TFGB is written in an erbium-ytterbium (Er/Yb) co-doped fiber. Due to the strong light absorption of the co-doped fiber, the refractive index is changed when it is optically pumped by a 980-nm laser diode (LD). It is different from a regular fiber Bragg grating (FBG) which has only a resonance due to the coupling of the counter propagating core-mode, a TFBG has multiple resonances due to the coupling between the code mode and the cladding modes. One interesting feature of a TFBG

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is that the depths of the cladding-mode resonances of a TFBG are linearly increasing in a wavelength region, and thus based on the Kramers-Kronig relations, the phase shifts are linearly increasing. This feature can be perfectly employed to implement a multi-tap complex microwave photonic filter in which the phase shifts of the tap coefficients are linearly increasing. This is the first time, to the best of our knowledge, that this feature is discovered and employed to demonstrate a complex-coefficient microwave photonic filter.

For an *N* tap microwave photonic filter, *N* optical phase shifts that are linearly increasing are introduced to *N* optical carriers of *N* single-sideband- (OSSB) modulated signals by placing the optical carriers within the bandwidths of the cladding-mode resonances of the TFBG. The phase shifts are tunable by optically pumping the TFBG by a 980-nm LD. The proposed microwave photonic filter is experimentally demonstrated. A three- and four-tap filter with a frequency tunable range of 150 and 120 MHz, respectively, are demonstrated. The key significance of the approach is that the frequency tuning is done by simply pumping the TFBG, thus the wavelengths of the laser sources are maintained fixed. In addition, since only the phase shifts are tuned, the spectral response of the filter is tuned without changing the shape of the spectral response.

2. Principle

In a TFBG the variation of the refractive index has an angle to the optical axis. The transmission spectrum of a TFBG consists of two different resonances resulted from two different couplings. One is the coupling between the forward and backward core modes and the other is the coupling between the contra-propagating core mode and the cladding modes. Thus, the transmission spectrum of a TFBG contains multiple resonances. The depths of the cladding-mode resonances are linearly increasing and decreasing along the transmission spectrum of a TFBG [14]. Figure 1 shows the transmission spectrum of a TFBG with a tilt angle of 6° and a Bragg wavelength of 1560 nm. As can be seen, the resonance depths are linearly increasing in a wavelength range from 1528 to 1540 nm, and based on the Kramers-Kronig relations, the resulted phase shifts are linearly increasing. This area is shown in a red ellipse in Fig. 1.

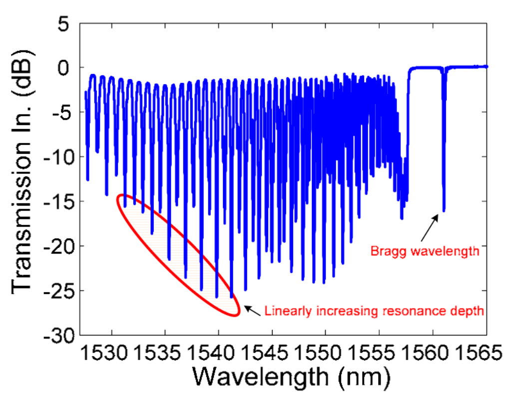

Fig. 1. The transmission spectrum of a TFBG with a tilt angle of 6° and a Bragg wavelength of 1560 nm. The red solid line shows the linear slope of the resonances' depth.

The tunability of a microwave photonic delay-line filter is usually achieved by adjusting the time-delay difference between samples. However, the change of the time-delay difference would lead to the change of the free spectral range (FSR), which would further result in the change of the 3-dB bandwidth as well as the entire shape of the frequency response. For many applications, however, it is highly desirable that only the center frequency of the passband or stopband be changed while maintaining the shape of the frequency response unchanged during the tuning. A solution to this problem is to implement a microwave photonic delay-

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line filter with complex coefficients. An N-tap microwave photonic delay-line filter with complex coefficients should have a transfer function given by [2]

$$\begin{aligned} H(j\omega) &= a_0 + a_1 e^{-j\theta} \cdot e^{-j\omega T} + \ldots + a_{N-1} e^{-j(N-1)\theta} \cdot e^{-j\omega(N-1)T} \\ &= \sum_{n=0}^{N-1} a_n e^{-jn\theta} \cdot e^{-j\omega nT} \end{aligned} \tag{1}$$

where ω is the microwave frequency, a_n is the coefficient of the nth tap, T is the time-delay difference between two adjacent taps and θ is the basic phase shift. To tune the filter while maintaining the shape of the frequency response unchanged, the phase shifts of all the taps should maintain a fixed relationship given by $\left[0, \theta, 2\theta, \cdots, (N-1)\theta\right]$ during tuning [2]. The inherent spectral response of a TFBG enables a simple implementation of a multi-tap microwave photonic filter with complex coefficients.

Recently, we have proposed a technique to implement a continuously tunable phase shifter using an optically pumped TFBG. A phase shift as large as 280° was demonstrated [15]. The TFBG is written in an Er/Yb co-doped fiber and is optically pumped by a 980-nm laser diode. Since the Er/Yb co-doped fiber has a high absorption, the refractive index of the fiber is changed by optically pumping the TFBG [16,17]. Thus, the refractive index along the TFBG is changed by pumping it, which leads to the shift of the resonance wavelengths and consequently the phase shifts are changed.

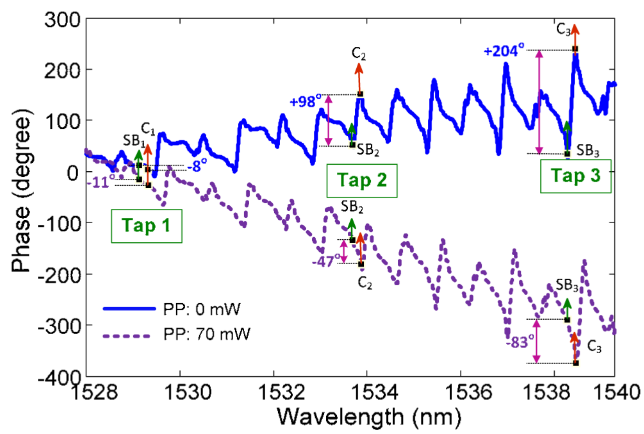

Fig. 2. The phase responses of the TFBG and the placement of the wavelengths of the optical carriers for a three-tap filter at two pumping power levels of 0 and 70 mW. C_1, C_2 and C_3 represent the three carriers, and SB_1, SB_2 and SB_3 represent the three sidebands.

Figure 2 shows the phase responses in the wavelength range of 1528-1540 nm. The placement of the wavelengths of the optical carriers for a three-tap filter at a pumping power of 0 and 70 mW is shown. As can be seen at the pumping power of 0 mW, the phase shifts of + 204°, + 98°, and −11° are introduced to tap 3, 2, and 1, respectively, which corresponds to a basic phase shift of $\theta = +109^0$ in (1). By changing the pumping power to 70 mW, the phase shifts of −83°, −47°, and −11° are introduced to tap 3, 2, and 1, respectively, which corresponds to a basic phase shift of $\theta = -36^0$. Thus, by placing the tap wavelengths in the TFBG resonances as Fig. 1, the filter spectral response can be shifted by tuning the pumping power from 0 to 70 mW.

3. Experiment

Figure 3 shows the experimental setup of the proposed tunable microwave photonic delay-line filter. For an N-tap filter, N wavelengths are generated, which are sent to Mach-Zehnder

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modulator (MZM). The wavelengths of the light waves are selected to be in the bandwidths of the TFBG cladding-mode resonances with linearly increasing depths such that the phase shifts satisfy the relationship given in (1). A microwave signal generated by a vector network analyzer (VNA, Agilent E8364A) is applied to the MZM via the RF port to modulate the light waves. The MZM is biased at the quadrature point and a WaveShaper (Finisar 4000S Multiport Optical Processor) is used to suppress one of the two sidebands to obtain OSSB-modulated signals. The OSSB-modulated optical signals are sent to the TFBG through a wavelength division multiplexing (WDM) coupler. The fiber used to fabricate the TFBG is a photosensitive Er/Yb co-doped fiber (EY 305, Coractive). The TFBG is pumped by a 980-nm LD. The optical signals at the output of the TFBG are sent to a length of dispersive fiber (a single-mode fiber in the experiment) to introduce time delays. An EDFA is used to compensate for the insertion losses. The time-delayed optical signals are detected by a 45-GHz photodetector. The detected signals are sent back to the VNA to measure the frequency response of the filter.

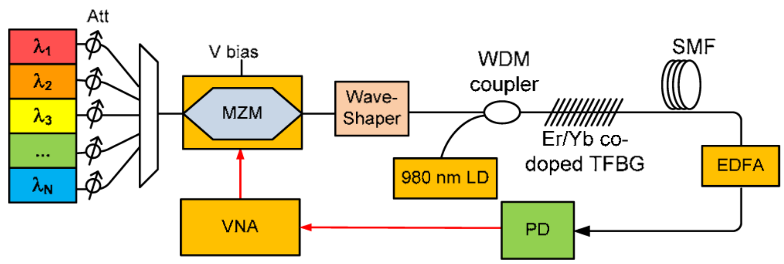

Fig. 3. Experimental setup of the proposed multi-tap microwave photonic filter with complex coefficients. Att: optical attenuator, MZM: Mach–Zehnder modulator, LD: laser diode, WDM: 980/1550 nm wavelength division multiplexer, SMF: single mode fiber, EDFA: erbium-doped fiber amplifier, PD: photodetector, VNA: vector network analyzer.

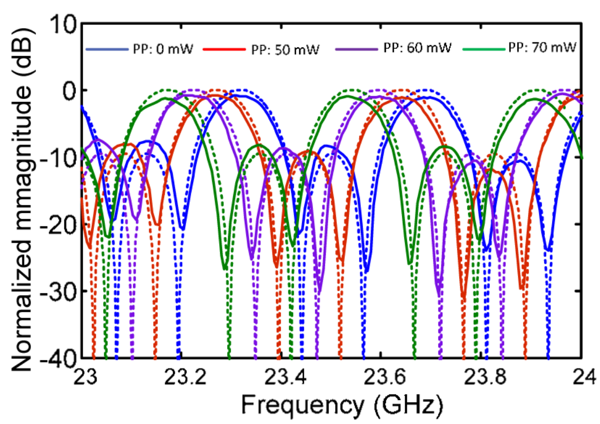

Fig. 4. Frequency response of the three-tap microwave photonic filter with complex coefficients at different pumping power levels (solid lines). The dashed lines show the simulated frequency response corresponding to a basic phase shift of + 105°, + 58°, + 10^0 and −36°. PP: pumping power.

A three-tap microwave photonic filter with three complex coefficients is first demonstrated. In the experiment, the magnitudes of the tap coefficients, a_n, are controlled by adjusting the optical attenuator in each tap. The FSR of the filter is controlled by the length of the single-mode fiber and the wavelength spacing between adjacent taps. The length of the SMF is 35 km and the wavelength spacing is 4.58 nm, thus the time delay difference between two adjacent taps is 2700 ps, corresponding to an FSR of 370 MHz. Figure 4 shows the

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frequency response of a three-tap filter at different pumping power levels from 0 to 70 mW (solid lines). For comparison, the simulated frequency responses are also shown in Fig. 4 as dashed lines. A good agreement is observed. As can be seen in Fig. 4, by changing the pumping power from 0 to 70 mW, the spectral response is shifted by 150 MHz, corresponding to a tunability of 40%. Note that since the phase relationship is always maintained during the pumping, the spectral shape of the spectral response is maintained unchanged. The refractive index change due to optical pumping is in the range of 1-20 μs [16], and the response time of the 980-nm LD is about 15 μs. Thus, by changing the pumping power, the change in the filter response can be achieved in 16-35 μs.

A four-tap microwave photonic filter with four complex coefficients is then demonstrated. The spectral response is shown as solid lines in Fig. 5. The length of the SMF is 53 km and the wavelength spacing is 3 nm, thus the time delay difference between two adjacent taps is still 2700 ps, corresponding again to an FSR of 370 MHz. By changing the pumping power from 0 to 70 mW, the basic phase shift θ in (1) is changed from –30° to + 90°, the spectral response is shifted by 120 MHz, corresponding to a tunability of 33%. For comparison, the simulated frequency responses are also shown in Fig. 5 as dashed lines. Again, a good agreement is reached between the experimental and the simulated results. Since the phase relationship is always maintained during the pumping, the spectral shape is maintained unchanged during the tuning process. It should be noted that since the Er/Yb co-doped fiber is pumped by the 980-nm LD, it works like an optical amplifier. The gain provided by the pumped Er/Yb co-doped fiber is about 2 dB at a pumping power of 90 mW. This optical amplifier would introduce an ASE noise to the filter. However, since the ASE noise is filtered by the TFBG, the impact of the ASE noise to the microwave photonic filter is low.

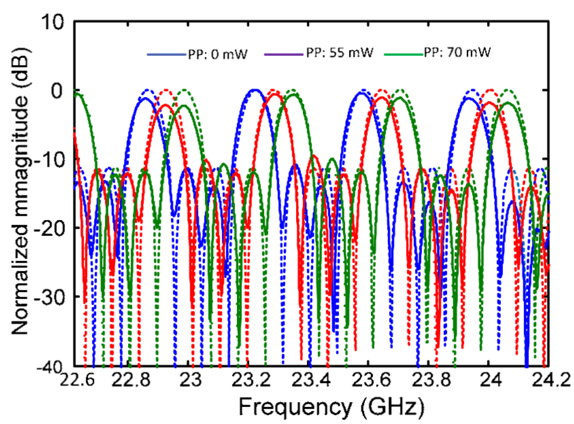

Fig. 5. Frequency response of the four-tap microwave photonic filter with complex coefficients at different pumping power levels (solid lines). The dashed lines show the simulated frequency response corresponding to a basic phase shift of –30°, + 36°, and + 90°. PP: pumping power.

4. Conclusion

A frequency-tunable multi-tap microwave photonic filter with complex coefficients based on a TFBG in an Er/Yb co-doped fiber was proposed and experimentally demonstrated. It was discovered that the resonance depths in the transmission spectrum of a TFBG are linearly increasing, thus the phase shifts are linearly increasing correspondingly. This feature ensures that the phase relationship in the tap coefficients is met if the optical carriers are placed in the resonances in this wavelength region. The tunability of the filter was achieved by pumping the TFBG by a 980-nm LD and the TFBG was written in an Er/Yb co-doped fiber. An experiment was performed. A three- and four-tap microwave photonic filter with a fractional tuning range of 40% and 33% was achieved, respectively. During the tuning, the shape of the spectral response was maintained unchanged.

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By designing a TFBG with stronger coupling coefficients and larger wavelength region with increasing or decreasing coupling coefficients, a microwave filter with more taps and lager tunable range could be implemented.

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