Investigation on microwave photonic filter group delay performance

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Investigation on the group delay performance of microwave photonic filters is presented. Analysis and simulation results show symmetrical distribution on the delayed optical signals in the impulse response is required to obtain a constant group delay performance. Experimental results for both symmetrical and asymmetrical tap distribution microwave photonic notch filters are presented showing the group delay response with $< \pm 25$ ps and around 1 ns ripples, respectively.

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Processing microwave signals in the optical domain has a number of advantages including high reconfigurability, ultra-wide bandwidth, and immunity to electromagnetic interference (EMI)[1]. It also provides new capabilities, such as parallel signal processing comparing to the conventional electronic signal processors[2].

Microwave photonic filters have been a subject of interested in the past 30 years. This is due to their ability to realize a high-resolution response with a widely tunable passband or notch. Various techniques, including delay lines[3–6], remodulation[7], Sagnac loop[8], and stimulated Brillouin scattering[9], have been reported to implement microwave photonic filters. Almost all of the reported microwave photonic filters only focus on the amplitude response performance, such as passband/notch width, rejection level, and skirt selectivity, without considering the phase response. The phase response characteristic of a filter can be described by the group delay performance. Radio frequency (RF)/microwave filters used in applications, such as radar[10] and global navigation satellite system (GNSS)[11], normally require a linear phase response, i.e., a constant group delay performance, in order to avoid the phase distortion. A delay-line-based microwave photonic filter can be designed to have a constant group delay performance. They are realized by generating a number of delayed optical signals, which are referred to as taps. The amplitude, phase, and separation of the taps determine both the filter amplitude and phase response characteristic. Until now, there are only a few reports on investigating microwave photonic filter phase or group delay response[12–14]. In Ref. [12], Bolea *et al.* demonstrated a single bandpass filter, where its electrical group delay has a quasi-linear behavior within the filter passband. Reference [13] presents the design of a non-uniformly spaced microwave photonic filter with a quadratic phase response and Ref. [14] presents a microwave photonic filter in which its phase response can be programmed using a spatial light modulator. However, to the best of our knowledge, there has been no report on the investigation on the requirement of the tap distribution in a microwave photonic filter impulse response in order to obtain a flat group delay response.

The aim of this Letter is to show that a microwave photonic filter with a symmetrical tap distribution impulse response is required to avoid ripples presented in the group delay response. A detailed analysis on microwave photonic filters with different impulse responses is presented. Experimental results of microwave photonic filters with symmetric and asymmetric tap distribution impulse responses demonstrate $< \pm 25$ ps and around 1 ns group delay ripple performance, respectively.

Consider a delay-line-based microwave photonic filter having an impulse response, as shown in Fig. 1(a). The impulse response consists of a number of taps. The impulse response is symmetrical at the tap, having an amplitude a.

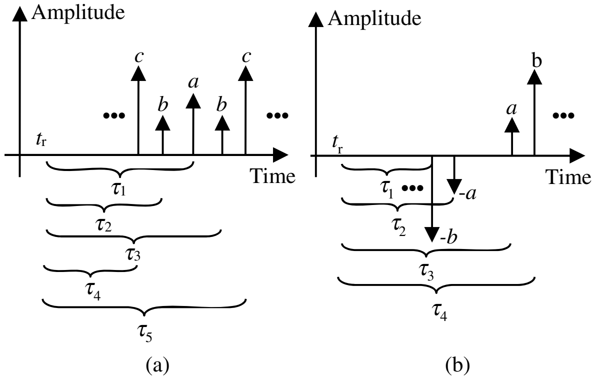

Fig. 1. Impulse response of a microwave photonic filter with (a) all positive taps and (b) positive and negative taps.

This tap is generated after time delay τ_1 from reference time t_r. The taps adjacent to the tap with amplitude a are generated after time delays τ_2 and τ_3 from a reference time t_r, respectively. They have the same amplitude b. Similarly, the taps with an amplitude c are generated at the time delays τ_4 and τ_5. By increasing the number of taps in the pair, as shown above, the impulse response of a microwave photonic filter can be expressed as

$$\begin{aligned} H(t) = {} & a\delta(t-\tau_1) + b\delta(t-\tau_2) + b\delta(t-\tau_3) \\ & + c\delta(t-\tau_4) + c\delta(t-\tau_5) + \cdots, \end{aligned} \tag{1}$$

where $\delta(t)$ represents a delta function. The transfer function of a microwave photonic filter can be obtained by Fourier transforming the impulse response given in Eq. (1) and is given by

$$\begin{aligned} H(\omega) = {} & ae^{-j\omega\tau_1} + be^{-j\omega\tau_2} + be^{-j\omega\tau_3} \\ & + ce^{-j\omega\tau_4} + ce^{-j\omega\tau_5} + \cdots, \end{aligned} \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency. The transfer function given in Eq. (2) can be expressed as

$$\begin{aligned} H(\omega) = {} & ae^{-j\omega\tau_1} + be^{-j\omega\frac{\tau_2+\tau_3}{2}}\left(2\cos\omega\frac{\tau_2-\tau_3}{2}\right) \\ & + ce^{-j\omega\frac{\tau_4+\tau_5}{2}}\left(2\cos\omega\frac{\tau_4-\tau_5}{2}\right) + \cdots. \end{aligned} \tag{3}$$

Since the tap distribution is symmetrical with respect to the tap with an amplitude a in the impulse response, the separation between adjacent taps is the same for all of the taps in the impulse response; hence,

$$\tau_1 = \frac{\tau_2+\tau_3}{2} = \frac{\tau_4+\tau_5}{2} = \cdots. \tag{4}$$

Therefore, Eq. (3) can be rewritten as

$$H(\omega) = \left(a + 2b\cos\omega\tfrac{\tau_2-\tau_3}{2} + 2c\cos\omega\tfrac{\tau_4-\tau_5}{2} + \cdots\right)e^{-j\omega\tau_1}. \tag{5}$$

Equation (5) shows that the phase response of a microwave photonic filter having an impulse response as shown in Fig. 1(a), is

$$\phi(\omega) = -\omega\tau_1, \tag{6}$$

and the amplitude response of the microwave photonic filter is

$$A(\omega) = \left(a + 2b\cos\omega\frac{\tau_2-\tau_3}{2} + 2c\cos\omega\frac{\tau_4-\tau_5}{2} + \cdots\right). \tag{7}$$

Equation (6) shows that the microwave photonic filter has a linear phase response, i.e., the phase changes linearly with the frequency. The group delay of a microwave photonic filter is defined as the negative of the ratio of change in the phase response to change in frequency and is given by

$$GD(\omega) = -\frac{d\phi(\omega)}{d(\omega)} = -\frac{d(-\omega\tau_1)}{d(\omega)} = \tau_1. \tag{8}$$

It can be seen from Eq. (8) that the group delay response is constant with respect to frequency. This shows that a flat group delay response can be obtained when the impulse response has a symmetrical tap distribution. A microwave photonic filter with an asymmetrical impulse response results in ripples in the group delay response. Note that the impulse response shown in Fig. 1(a) has an odd number of taps. In the case of a microwave photonic filter with an impulse response having an even number of taps, the tap at the center of the impulse response needs to be eliminated in order for the impulse response to be symmetrical. A flat group delay response can also be obtained for the taps having the same amplitude but opposite phase in the microwave photonic filter impulse response, as shown in Fig. 1(b). The transfer function of this microwave photonic filter is given by

$$H(\omega) = \left(2a\sin\omega\tfrac{\tau_2-\tau_3}{2} + 2b\sin\omega\frac{\tau_4-\tau_1}{2} + \cdots\right)e^{-j\omega\tau}e^{-j\pi/2}, \tag{9}$$

$$\tau = \frac{\tau_2+\tau_3}{2} = \frac{\tau_1+\tau_4}{2} = \cdots. \tag{10}$$

The linear phase response $\phi(\omega) = -(\omega\tau + \pi/2)$ can be seen from Eq. (9). An investigation on the group delay characteristic of two microwave photonic notch filters with symmetrical and asymmetrical impulse responses was conducted. The reason for choosing notch filters for the microwave photonic filter group delay performance investigation is due to them having a wide passband range so that the group delay characteristic can be observed over a wide frequency range. One of the microwave photonic notch filters has a symmetrical sinc-function tap distribution[15], as shown in Fig. 2(a). The other has an asymmetrical tap distribution, where the amplitude of the first tap (the primary tap) is much higher than that of the subsequent taps, which are referred to as the secondary taps[16]. Its impulse response is shown in Fig. 2(b). Note that the separation between the primary tap and the first secondary tap is half of the separation between all adjacent secondary taps. Both notch filters with the impulse responses, as shown in Figs. 2(a) and 2(b), are finite impulse response (FIR) microwave photonic filters and have the ability to realize an amplitude response with a narrow notch and a wide and flat passband. The notch width is determined by the number of tap pairs for the structure that have an impulse response, as shown in Fig. 2(a). In the case of the primary and secondary tap-distribution-based microwave photonic notch filter, the notch width is determined by the number of secondary taps.

Figure 3 shows the amplitude and the group delay response of the sinc-function tap distribution microwave photonic notch filter with 16-tap pairs and the primary and secondary tap distribution microwave photonic notch

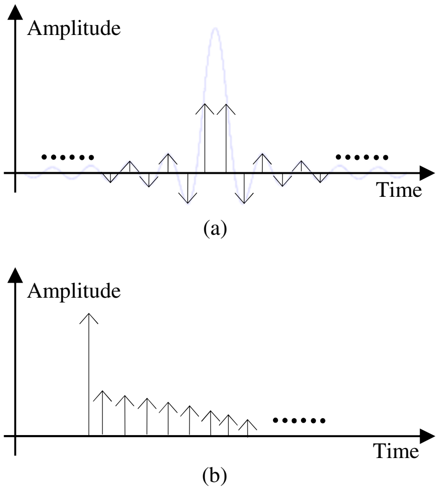

Fig. 2. Microwave photonic notch filter with (a) a sinc-function tap distribution impulse response and (b) a primary and secondary tap distribution impulse response.

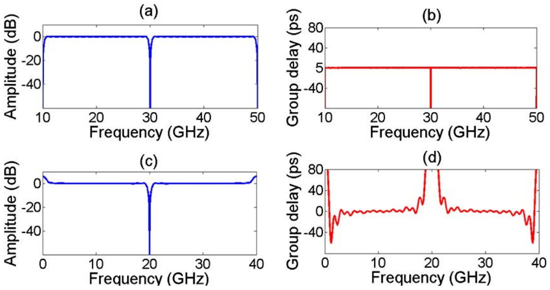

Fig. 3. (a) and (c) Simulated amplitude response and (b) and (d) group delay response of the sinc-function tap distribution and the primary and secondary tap distribution microwave photonic notch filter.

filter with 16 secondary taps. The time delays of the two notch filters are designed so that there is a 20 GHz passband adjacent to the notch. The simulation results show that the two notch filters have a similar amplitude response, which consists of a narrow notch and a wide and flat passband. However, their group delay responses are different. No group delay ripple is presented in the sinc-function tap distribution notch filter. On the other hand, the primary and secondary tap distribution notch filter has ±35 ps group delay ripples at the passband. This shows that not all FIR microwave photonic filters have a constant group delay response. The taps in the impulse response need to be symmetrical in order to eliminate ripples in the group delay response.

The two notch filters with symmetrical and asymmetrical impulse responses were set up experimentally. The optical source was a Fabry–Perot (FP) laser operated at a 1550 nm wavelength, which had a number of different-wavelength lasing modes. The lasing modes from the FP laser were phase modulated by an RF signal. The amplitude and phase of the different-wavelength phase modulated optical signals were controlled by a Fourier-domain optical processor. This was followed by a length of single mode fiber to introduce different delays to the different-wavelength phase modulated optical signals. The output was detected by a photodetector. A detailed discussion on the experimental setups can be found in Refs. [15,16]. The sinc-function tap-distribution-based microwave photonic notch filter was designed to have four-tap pairs and a 0.43 ns time delay. The primary and secondary tap-distribution-based microwave photonic notch filter had six secondary taps and a time delay of 0.214 ns.

The amplitude and group delay responses of the two microwave photonic notch filters were measured by a vector network analyzer and are shown in Fig. 4. It can be seen from Figs. 4(a) and 4(c) that both notch filters have a high-resolution notch filter response with a −3 dB notch width of 110 and 80 MHz, respectively. Figures 4(b) and 4(d) show the measured group delay responses of the two notch filters. The sinc-function tap-distribution-based microwave photonic notch filter has a group delay ripple of < ± 25 ps. These small group delay ripples are mainly due to imperfect symmetrical tap distribution in the impulse response. The ripples in the group delay response can be suppressed by improving the symmetricity of the impulse response. Around 1 ns ripples in the primary and secondary tap-distribution-based microwave photonic notch filter group delay response can be seen in Fig. 4(d). The experimental results show that the two notch filters have a very different group delay performance even though they have a similar amplitude response with a narrow notch and a wide and flat passband. The results verify that a microwave photonic filter with an asymmetric tap distribution in the impulse response has group delay ripples, which cause a phase distortion problem. The amplitude and group delay responses of the two notch filters are simulated and are shown in dotted lines in Fig. 4, using the experimental parameter values, such as the tap amplitude and time delay. The simulation results were obtained by assuming that the tap time delays have a ±0.15% deviation from the desired value. An excellent agreement between measured and simulated responses can be seen.

In conclusion, the requirement for a microwave photonic filter to have a constant group delay with respect to

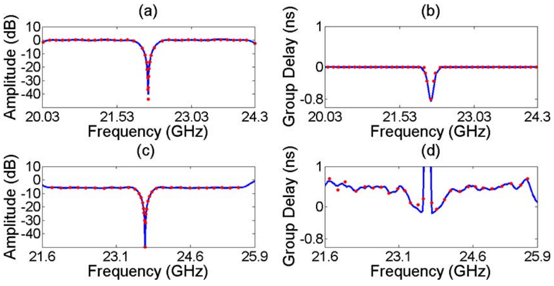

Fig. 4. (a) and (c) Measured (solid lines) and simulated (dotted lines) amplitude response and (b) and (d) group delay response of the sinc-function tap distribution and the primary and secondary tap distribution microwave photonic notch filter.

frequency is presented. Analysis and simulation results show that not all microwave photonic filters with FIRs have a flat group delay response. An FIR microwave photonic filter also needs to have a symmetrical tap distribution in order to avoid group delay ripples. Experiments of two microwave photonic notch filters with a symmetrical and an asymmetrical tap distribution impulse response are set up to verify the concept, and an excellent agreement between the theory and measurements is shown.

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