Continuously tunable and reconfigurable microwave photonic multiband filter based on cascaded MZIs

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Abstract: A tunable and reconfigurable microwave photonic multiband filter with up to 13 simultaneous passbands is presented. All the passband frequencies are continuously tunable over 20 GHz, and the number of simultaneous passbands is highly reconfigurable between 1 to 13.

1. Introduction

Multiband communications have been widely implemented in modern radio frequency (RF) communication systems, where several frequency channels over a wide frequency range are transmitted at the same time to provide multiple functionalities [1]. RF filters with multiple passbands are essential in such systems, the capability to reconfigure the filter passbands is required for dynamic RF systems. Although the need is clear, achieving such an RF filter is challenging, which is due to the lack of tunability in conventional RF electronic devices. For state-of-the-art electronics based RF multiband filters, the maximum number of tunable passband is up to four [2]. Microwave photonics (MWP) have brought several unique features to RF systems, among which the wide operation bandwidth and flexible tunability are critical features for RF filter design [3]. MWP single-pass filters and dual-band filters have been successfully demonstrated with continuously tunable passbands [4], while the number of simultaneous passbands is limited [5]. Recently, the number of simultaneous passbands has been significantly improved to 12 through the use of a two-stage Lyot loop filter [6], however, the 12 passbands are fixed at several preset frequency channels. Due to the fast growing of RF communications, an ideal RF multiband filter --- with a large number of simultaneous passband, wide passband frequency tuning range, and flexible adjusted passband number --- is urgently desired for fulfilling the functionality of multiband RF systems.

In this paper, we present a highly tunable and reconfigurable microwave photonic multiband filter. The number of passbands is adjusted from 1 to 13, while the passband frequencies are continuously tunable from 0 to 20 GHz. The proposed multiband filter is based on the generation of high-order optical frequency combs from three cascaded Mach-Zehnder interferometers (MZI). To the best of our knowledge, this is the first demonstration of a RF multiband filter to achieve a large number of simultaneous passbands with such tunability and reconfigurability.

2. Principle and Experimental Setup

Experimental setup is shown in Fig. 1(a). A broadband light source is spectrally sliced by three cascaded MZIs, and works as a multi-wavelength optical carrier. The RF signal is then modulated onto the comb lines through an electro-optic modulator (EOM), where each comb line contains a copy of the RF input signal. The modulated signal is then launched into dispersion compensating fiber (DCF) such that each of the copies is properly delayed in time. A 4-nm optical Gaussian filter is used to spectrally weight each of the comb lines, essentially weighting the amplitudes of the RF signal copies. The weighted and delayed copies are then added up and converted back to an RF signal through a photo-detector. A finite impulse response RF filter with a bandpass profile can be obtained.

The center frequency of the passband is determined by $\Omega_0 = \frac{2\pi}{\beta_2 L_D \Delta\omega}$, where $\Delta\omega$ is the spacing between each comb lines, β_2 and L_D are the dispersion and the length of the DCF. In order to generate multiple passbands at the same time, an optical frequency comb with multiple comb spacings is required [6]. This is achieved by cascading three MZIs in series and simultanously generating multiple path length differences. In particular, when the light travels through the first MZI, an optical comb with a comb spacing of $\Delta\omega = 2\pi c/nd_1$ is generated, where n is the refractive index of the fiber and d_1 is the length difference between the two branches of a MZI, and c is the speed of light. By cascading a second MZI with a branch length difference of d_2 and adjusting the coupling ratios of the tunable couplers, four length difference combinations can be obtained at the same time, which are d_1, d_2, $d_1 + d_2$, and $d_1 - d_2$. As a result, four different comb spacings are obtained which corresponds to four RF passbands at different frequencies. When three

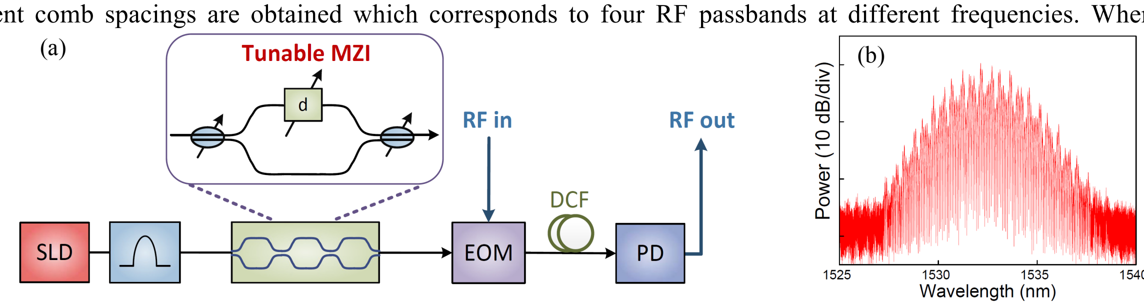

Fig. 1. (a) Experimental setup of the MWP multiband filter based on cascaded MZIs. (b) Measured optical spectrum of the cascaded MZIs.

MZIs are cascaded, up to 13 different combinations can be obtained and resulting in 13 different passbands, as summarized in Table 1. Fig. 1(b) shows an example of the optical comb generated by the three cascaded MZIs. A tunable optical coupler with adjustable coupling ratio is used to vary the power ratio between the two MZI branches to achieve different extents of interference, such that amplitude of the resultant passband can be adjusted. Furthermore, since the length differences (d_1, d_2 and d_3) can be continously adjusted by tunable delay lines in each MZI, all the resulted passbands are continously tunable in frequency.

Table 1. Passband combinations based on three MZIs

Number	One MZI	Two MZIs	Three MZIs
1			$d_1 - d_2 - d_3$
2		$d_1 - d_2$	$d_1 - d_2$
3			$d_1 - d_2 + d_3$
4			$d_1 - d_3$
5	d_1	d_1	d_1
6			$d_1 + d_3$
7			$d_1 + d_2 - d_3$
8		$d_1 + d_2$	$d_1 + d_2$
9			$d_1 + d_2 + d_3$
10			$d_2 - d_3$
11		d_2	d_2
12			$d_2 + d_3$
13			d_3

3. Results and Discussion

The measured results of different passband combinations are shown in Fig. 2. By adjusting the tunable couplers inside the three MZIs (i.e. enabling/bypassing some of them), the MWP filter is reconfigured to have various simultaneous passbands. A single bandpass filter is shown in Fig. 2(a), which is achieved by setting the tunable couplers inside MZI2 and MZI3 to be 100:0 such that these two interferometers are bypassed. As a result, only one single bandpass filter is generated from MZI1. When MZI1 and MZI2 are enabled, four passbands are observed as shown in Fig. 2(b). The four-passband filter can turn into a three-passband filter by adjusting the tunable delay line in MZI2, such that two of the passbands are tuned to the same frequency and are overlapping with each other, as shown in Fig. 2(c). When all the three MZIs are employed, all of the thirteen passbands listed in Table 1 are obtained. The 13 passbands can be set to be evenly distributed from 0 to 8 GHz with same frequency spacings of 0.6 GHz, as indicated in Fig. 2(f). Alternatively, the passbands can be adjusted to overlap with each other, such that various passbands combinations are achieved, as shown in Fig. 2(d)-2(e). Figure 2(g)-2(h) show continuously tunability that the passbands are tuned to different positions and spread across a 20 GHz frequency range. The frequency tuning range is governed by the adjustable range of the delay lines. In our setup, up to 35 GHz frequency tuning is achieved with the use of a 600 ps delay line. Furthermore, all the passbands show good filter selectivity, with sharp bandpass profiles and over 35 dB sidelobe suppression.

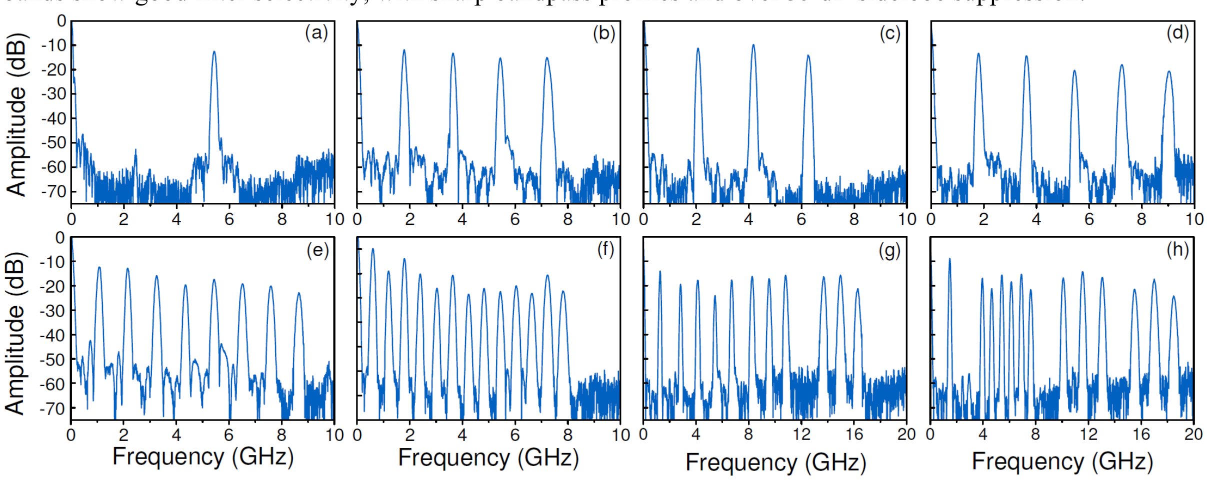

Fig. 2. Measured RF amplitude response of the continuously tunable MWP multiband filter with different passband combinations.

4. Conclusion

A tunable MWP multiband RF filter with up to 13 simultaneous passbands is demonstrated based on three cascaded MZIs. The number of simultaneous passbands is adjustable from 1 to 13, and the passband frequencies are continuously tunable over 20 GHz. Furthermore, the cascaded MZI structure is an excellent candidate for potential integration.

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