photonics

MDPI

Review

Tunable Multiband Microwave Photonic Filters

Mable P. Fok * and **Jia Ge**

Lightwave and Microwave Photonics Laboratory, College of Engineering, The University of Georgia, Athens, GA 30602, USA; jiage@uga.edu

* Correspondence: mfok@uga.edu; Tel.: +1-706-542-2233

Received: 24 October 2017; Accepted: 21 November 2017; Published: 23 November 2017

Abstract: The increasing demand for multifunctional devices, the use of cognitive wireless technology to solve the frequency resource shortage problem, as well as the capabilities and operational flexibility necessary to meet ever-changing environment result in an urgent need of multiband wireless communications. Spectral filter is an essential part of any communication systems, and in the case of multiband wireless communications, tunable multiband RF filters are required for channel selection, noise/interference removal, and RF signal processing. Unfortunately, it is difficult for RF electronics to achieve both tunable and multiband spectral filtering. Recent advancements of microwave photonics have proven itself to be a promising candidate to solve various challenges in RF electronics including spectral filtering, however, the development of multiband microwave photonic filtering still faces lots of difficulties, due to the limited scalability and tunability of existing microwave photonic schemes. In this review paper, we first discuss the challenges that were facing by multiband microwave photonic filter, then we review recent techniques that have been developed to tackle the challenge and lead to promising developments of tunable microwave photonic multiband filters. The successful design and implementation of tunable microwave photonic multiband filter facilitate the vision of dynamic multiband wireless communications and radio frequency signal processing for commercial, defense, and civilian applications.

Keywords: microwave photonics; filters; multiband filters; multiband communications

---

1. Introduction—The Challenges

Due to the increasing demand of heterogeneous wireless network, multi-service systems, and multi-function devices, multiband communications can be found in various wireless radio frequency (RF) systems. The challenge in multiband communications is the dynamic operation of the multiband channel for the proper selection of channels, optimization of system performance, and dynamic adaptation to environmental changes. To facilitate dynamic operation in multiband communications, a tunable and reconfiguration multiband RF filter is needed. However, it is very challenging for RF electronics to achieve RF filters with high passband count or good tuning capability due to the tight design criteria that each frequency band requires, as well as the limited tunability that RF electronics can achieve. Although dual-passband filter could be achieved by cascading two single-band filters, it is not practical to use a bank of single-band RF filter to perform dynamic multiband RF filtering due to the need of high-speed wideband RF switches. Furthermore, to fully utilize the function of the filter in RF signal processing that is beyond conventional channel selection and noise/interference suppression applications, high-passband count filter that is tunable and reconfigurable is highly desired.

Microwave photonics has been a promising candidate for various RF signal processing tasks [1–9], including phase shifting, true time delay, filtering, and analog-to-digital conversion, to name a few. Implementing RF filter with photonic techniques has a number of advantages inherent to photonics—low loss, high bandwidth, tunability/reconfigurability, possibility of parallelism, and immunity to electromagnetic interference. Furthermore, due to the rapid development of radio-over-fiber systems, radar and beamsteering of phased-arrayed antennas, microwave photonic filter naturally fits in nicely which enables the processing of RF signal without the need of high-performance analog-to-digital converters for down conversion. Single passband microwave photonic filters can be implemented using various techniques, including chip-based stimulated Brillouin scattering [10,11], optical comb based filter [12–14], and programmable photonic signal processor chip [10,11,15,16]. Some of the approaches are integratable [17,18] and some are bench-top demonstrations. While development of microwave photonic filter has been a great success, and most of the schemes have been intensively summarized in a number of review papers [5,19,20], there are still room for investigations including integration, tuning speed, noise, and power consumption.

Although microwave photonic techniques for implementing single passband filter are well developed, there are very few successful examples where a multiband microwave photonic filter can be achieved. Most existing microwave photonic filter approaches either lack of the ability to support multiband operations, or the resultant passbands are periodic over a very wide frequency range, limiting its ability to isolate unwanted frequencies within a certain frequency range. By examining the principle of obtaining multiple passbands, the facts that hinder microwave photonic technologies to support multiband filtering capability are the special requirements in the optical source: (i) the optical comb carrier needs to simultaneously consist of multiple interleaving combs with different comb spacings [21], or (ii) the optical comb carrier has to be sampled spectrally [22], or (iii) large number of optical branches (light source or delay elements) are needed [23]. Optical combs are highly periodic in nature, thus, the above optical comb requirements are extremely hard to achieve—which is limited by the scalability, selectivity, and uniformity of most existing microwave photonic filter schemes. Due to these limitations, it is hard to achieve a microwave photonic multiband filter with a large passband number, high selectivity, and good passband uniformity. Needless to say, it is even more challenging to achieve a multiband filter with tuning and reconfiguring capabilities. Table 1 shows a list of multiband RF filter examples with two or more passbands based on various RF electronic and microwave photonic techniques.

Table 1. Comparison of the Tuning Mechanism of the State-of-the-Art Multiband RF Filters.

Reference	Technique	Number of Passbands	Rejection Level (dB)	Tunability/ Reconfigurability	Tuning Mechanism
[24]	LTCC	3	20	Not tunable	-
[25]	Stepped impedance resonator	6	25	Not tunable	-
[26]	Microstrip + trimmer capacitor	4	40	Continuously tunable/Reconfigurable	Adjustable capacitor
[27]	Microstrip + Varactor	2	35	Continuously tunable	Adjustable varactor
[28]	RF-MEMS	2	30	Discretely tunable	MEMS capacitor
[29]	Microstrip + DGS	3	30	Reconfigurable	PIN diode
[30]	(BBS) Broadband optical source	2	20	Continuously tunable	Optical delay line
[22]	BBS + optical switches	3	35	Discretely tunable	Optical switch
[21]	BBS + loop mirror filter	3	35	Reconfigurable	Manual polarization controller
[23]	Phase-shifted FBG	2	25	Continuously tunable	Laser wavelength adjustment
[31]	BBS + modified MZI	2	30	Continuously tunable	Optical delay line
[32]	Stimulated Brillouin Scattering	6	20	Continuously tunable/Reconfigurable	Laser wavelength adjustment
[33,34]	BBS + Lyot loop filter	12	30	Reconfigurable	Polarization controlling
[35]	BBS + SOA incorporated Lyot loop filter	2	40	Reconfigurable	Nonlinear polarization rotation
[36]	BBS + cascaded MZIs	13	35	Continuously tunable and Reconfigurable	Tunable optical delay and Tunable coupler

In this review paper, we will first introduce several microwave photonic approaches to achieve filters with two passbands in Section 2, which helps to understand the scalability issue in microwave photonic approaches. Then, we will examine several breakthroughs in achieving microwave photonic filters with large number of reconfigurable passbands in Section 3. Reconfigurable passbands capability enables the selection of the number of passband among the fix passband frequencies to meet the needs of the system. To enable full control of the multiband filter, continuously tunable multiband filter is essential and will be described in Section 4. Continuously tunable multiband filters enable the center frequency of each passband to be tuned freely across a wide frequency range. Combining both passband reconfigurability and continuous frequency tunability, multiband filters can provide maximum flexibility to satisfy the needs in dynamic microwave system. In the last Section of this review paper, we will discuss various novel applications of tunable multiband filters, especially its potential in dynamic and wideband RF signal processing.

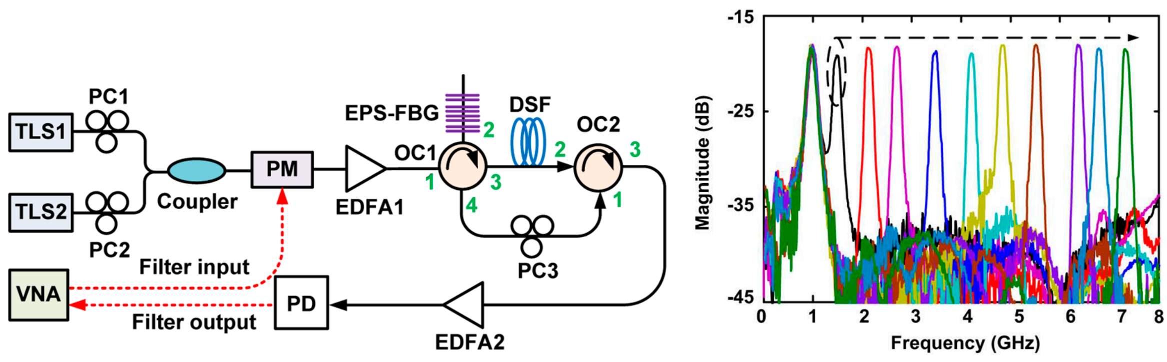
2. Tunable or Reconfigurable Dual-Band Microwave Photonic Filters

While there are a large number of microwave photonic approaches that have successfully demonstrated RF filtering with single passband, most of them are not scalable to achieve RF response with two or more passbands. In this Section, we will introduce several schemes that have successfully achieved microwave photonic filters with two tunable or reconfigurable passbands. By examining the schemes, the challenges of achieving high passband count filters can be clearly displayed.

2.1. Independently Tunable Dual-Passband Filter Based on Phase Modulator and an Equivalent Phase-Shifted Fiber Bragg Grating

This approach demonstrates a microwave photonic filter with two independently tunable passbands, based on phase-modulation to intensity-modulation (PM-IM) conversion using a phase modulator and an equivalent phase-shifted fiber Bragg grating (EPS-FBG) [23]. The EPS-FBG is a unique device where equivalent phase shifts are introduced to both of the ±1st channels, such that notches in each of the two channels are resulted. Therefore, two passbands are obtained during PM-IM conversion in the EPS-FBG. Central frequency of each passband is determined by the wavelength difference between the notch and the optical carrier. Therefore, passband frequency of each passband is tunable through the control of the optical carrier wavelength. The resultant dual passband filter has a 3-dB bandwidth of 167.3 MHz and 143.3 MHz for the 1st and 2nd passbands. The passband frequency tuning ranges of the 1st and 2nd passbands are 5.4 and 7.4 GHz, respectively.

Figure 1a illustrates the experimental setup of the EPS-FBG scheme for achieving a dual-passband microwave photonic filter [23]. Two optical carriers generated from two tunable laser sources are modulated by the input RF signal at a phase modulator. To measure the RF frequency response of the filter, frequency sweeping sinusoidal RF signal generated by a vector network analyzer (VNA) is used as the RF input. Wavelengths of the two optical carriers are selected such that the desired passband frequencies can be generated. The two phase-modulated signals are amplified and are launched to an EPS-FBG via an optical circulator. Due to the alignment between the EPS-FBG notches and one of sideband in the phase-modulated signals, one sideband of each of the phase-modulated signal is removed by the notch, resulting in PM-IM conversion.



(**a**) (**b**)

Figure 1. (**a**) Schematic diagram of the proposed dual-passband microwave photonic filter (with the courtesy of Dr. J. P. Yao). TLS(1,2): tunable laser source; PC(1–3): polarization controller; PM: phase modulator; EDFA(1,2): erbium-doped fiber amplifier; EPS-FBG: equivalent phase-shifted fiber Bragg grating; OC(1,2): optical circulator; DSF: dispersion-shifted fiber; PD: photodetector; VNA: vector network analyzer. (**b**) RF frequency response of the resultant dual-passband filter (with the courtesy of Dr. J. P. Yao)—the 1st passband is kept unchanged while the 2nd passband is tuned.

To improve the spurious-free dynamic range and noise figure of the microwave photonic filter, a stimulated Brillouin scattering (SBS)-assisted filter is used to suppress the power of the optical carriers. The SBS-assisted filter consists of two optical circulators, dispersion-shifted fiber and a polarization controller (PC3). Frequency response of the dual-passband filter is obtained by detecting the optical signal using a photodetector and is measured by a VNA. Figure 1b [23] shows the measured frequency response of the dual-passband filter with the 1st passband kept unchanged while the 2nd passband is tuning from 1.5 to 7.4 GHz by varying the wavelength of the tunable laser (TLS2). The filter has a sidelobe suppression ratio of 20 dB and the 3-dB bandwidth of each passband is between 143.3 MHz and 167.3 MHz. The number of passbands in this scheme depending on the number of tunable laser as well as the number of matched and phase shifted notches in the EPS-FBG. Therefore, to achieve a high passband count multiband filter, a large number of tunable lasers and precise fabrication of the EPS-FBG are required.

2.2. Reconfigurable Dual-Passband Filter Based on a Modified Mach-Zehnder Interferometer

To eliminate the use of multiple laser sources while enabling dual-passband operation in microwave photonic filters, a scheme that uses a broadband light source and a modified Mach-Zehnder interferometer (MZI) has been proposed [31]. As shown in Figure 2a, a broadband light from a superluminescent diode is spectrally sliced by a modified MZI to generate the multi-wavelength optical carrier. The RF input signal is modulated onto the multi-wavelength optical carrier via an intensity modulator. The modulated signal is passed to a 25-km standard single mode fiber for dispersion, which is then amplified and detected by a photodetector. The resultant RF response is measured by a network analyzer.

The modified MZI has a dual-pass structure, which consists of two optical couplers, a polarization controller PC2, and an optical delay line. The polarization controller is used to optimized the extinction ratio of the optical comb generated by the modified MZI, while the optical delay line is for adjusting the comb spacing ($\Delta\lambda$) of the optical comb, governed by

$$\Delta\lambda = \lambda^2/n\Delta L, \tag{1}$$

where n is the refractive index of the fiber and ΔL is the path difference between the two MZI branches. By controlling the polarization rotation of PC1 and PC2, the resultant comb spacing from the modified MZI can be switched from $\Delta\lambda$ to $2\Delta\lambda$, as well as two interleaving combs that consists of both $\Delta\lambda$ and

2Δλ. The demonstrated architecture is based on finite impulse response (FIR), therefore, the time delay difference between each optical tap is set to be the same through the use of dispersion in the standard single mode fiber. After photodetection, the resultant RF response will consist of passbands at frequencies that meet the following requirement:

$$\Omega = 2\pi/(\beta_2 L_D \Delta\omega), \quad (2)$$

where β_2 and L_D are the group velocity dispersion and length of the dispersive medium, and $\Delta\omega$ is the frequency spacing between each optical taps.

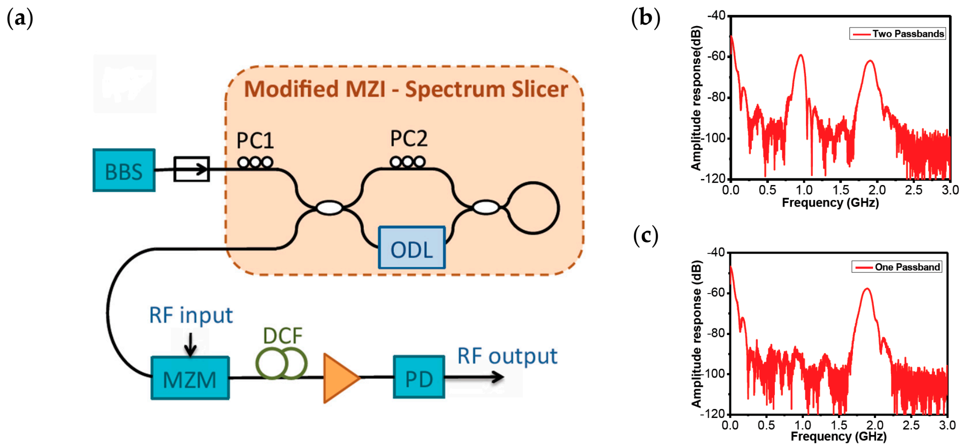


Figure 2. (**a**) Schematic diagram of the reconfigurable and tunable dual-band microwave photonic filter. BBS: broadband optical source; MZM: Mach-Zehnder modulator; PD: photodiode; PC(1,2): polarization controller; ODL: variable optical delay line. (**b**) Resultant dual-passband filter with two passbands (adapted from [31] with the courtesy of Dr. H. Fu). (**c**) Reconfigured microwave photonic filter with just one passband (with the courtesy of Dr. H. Fu).

Therefore, by controlling the path difference between the two MZI branches (ΔL) using the tunable optical delay line, the center frequencies of both the passbands can be tuned at the same time. Furthermore, the two resultant passbands are switchable through the controlling of the polarization controllers PC1 and PC2. Figure 2b,c show the resultant RF response of the dual-passband microwave photonic filter with dual passband and single passband at 2 GHz, respectively. The sidelobe suppression ratio is over 30 dB.

2.3. Tunable Dual-Passband Filter Based on Broadband Light Source and Optical Delay Branches

To enable independent control of the passband frequencies while eliminating the use of large number of laser source, another approach is demonstrated using a broadband light source from an erbium doped fiber amplifier, as shown in Figure 3 [30]. The broadband light source is first shaped by a rectangular optical filter with 3-dB bandwidth of 3.6 nm and center wavelength of 1551.25 nm, which is then passed to a 1:3 coupler to obtain three copies of the light source. One of the copy is launched to a phase modulator where the RF input signal is modulated onto the light source, while the other two copies are launched to two separate optical delay lines with delays of t_1 and t_2 for time adjustment and two optical attenuators for weight adjustment. All the branches are combined again at a 3:1 coupler and are launched to a dispersion compensating fiber with a group velocity dispersion of −989 ps/nm. A photodetector is used to convert the optical signal back to RF signal and is measured by a vector network analyzer. The beating between the modulated copy and the copy with t_1 delay results in one passband, while the beating between the modulated copy and the copy with t_2 delay results in the second passband. The resultant frequency of the RF passbands is governed by the time delay between the modulated branch and the delayed branch.

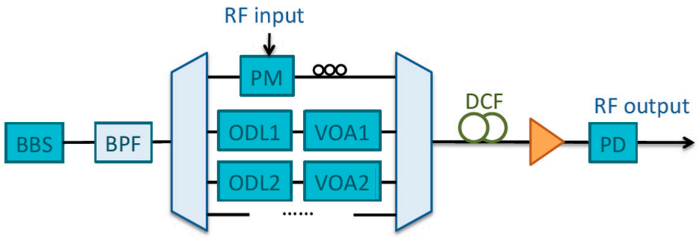


Figure 3. Schematic diagram of the microwave photonic filter with independently tunable passbands (with the courtesy of Dr. Y. Jiang). BBS: broadband optical source, BPF: optical filter, ODL(1,2): optical delay line, VOA(1,2): variable optical attenuator, PM: phase modulator, DCF: dispersion compensating fiber, PD: photodetector.

Passband frequency of each of the two passbands can be tuned by adjusting the optical delays t_1 and t_2, respectively. The optical delay line has a maximum tuning range of 600 ps which potentially allows the passband frequency to be tuned over 30 GHz. In the demonstration, both the first and second passbands can be tuned from 4 GHz to 30 GHz by varying t_1 and t_2 by 200 ps. Although the 600 ps delay range in the optical delay line enables a much larger frequency tuning in the passband, the passband magnitude decreases significantly as the passband frequency increases, limited by the bandwidth of the phase modulator, photodetector, and the dispersion slope of the dispersion compensating fiber. The resultant passband has a 3-dB bandwidth of 250 MHz, however, the magnitude of sidelobe are relatively high—about 13 dB below the passband. In principle, the number of passband can be increased by adding more copies of the broadband light source; however, extra sets of optical delay lines and optical attenuators are needed for each passband, limiting its scalability. Furthermore, carrier suppression effect will severely affect the passband magnitude and shape, which prohibited the scheme to support multiple passband operation.

2.4. Reconfigurable Dual-Passband Filter Based on a Lyot Loop Filter

Although having the ability to tune the passband frequency and reconfigure its passband on and off according to the desired channel selection are important, it is equally critical for a microwave photonic filter scheme to be scalable—have the potential to achieve high passband count, and have high bandpass selectivity. To achieve passband reconfiguring capability and high passband count, a tunable Lyot loop filter based reconfigurable microwave photonic multiband filter has been experimentally demonstrated [33,34]. Through polarization control, the Lyot loop filter can be adjusted to have four different spectral characteristics using just a single piece of birefringent fiber, which is used to slice the broadband optical source and generate the desired optical comb according to the selected passband frequency. With the Lyot loop filter, a reconfigurable microwave photonic bandpass filter with four operating states, i.e., single-bandpass filter with two different frequencies, dual-bandpass filter, and all-block RF filter, is achieved. Due to the large number of optical comb lines generated by the Lyot loop filter from the broadband light source, the microwave photonic filter has sharp RF spectral profile and high bandpass selectivity of 46-dB sidelobe suppression.

Figure 4a shows the experimental setup of the Lyot loop filter based reconfigurable microwave photonic dual-passband filter. A broadband light source (BBS) is reshaped by a Gaussian profile optical filter to apodize the amplitude of the resultant multi-wavelength optical carrier such that a Gaussian bandpass frequency response in RF domain can be obtained. Then, a Lyot comb filter is used to spectrally slice the Gaussian BBS into a multi-wavelength optical carrier. The RF input signal is modulated onto the multi-wavelength optical carrier through a phase modulator. A piece of dispersion compensating fiber (DCF) is used to provide linear delay for different carrier wavelengths (filter taps), and then the modulated signal is fed into a photodetector and converted back to a RF signal. In the experiment, signal from a network analyzer is used as the RF input for measuring frequency response of the microwave photonic filter.

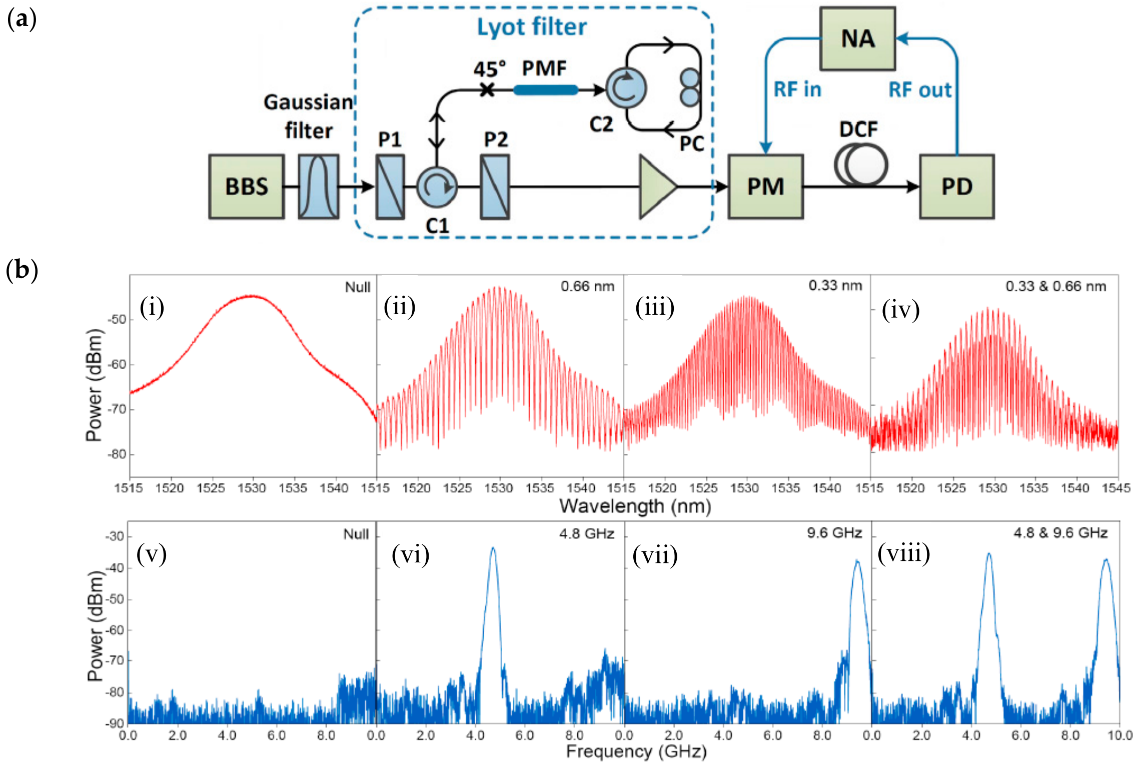


Figure 4. (**a**) Experimental setup of the Lyot loop filter based frequency band selectable dual-band bandpass filter. BBS: broadband source; P1, P2: polarizers; C1, C2: circulators; PC: polarization controller; PMF: birefringent fiber; PM: phase modulator; DCF: dispersion compensating fiber; PD: photodetector; NA: network analyzer. (**b**) (**i–iv**) Multi-wavelength optical carriers with different comb spacings and combinations; (**v–viii**) Resultant frequency responses of the microwave photonic dual-band filter.

The most important component here that governs passband switching is the Lyot loop filter—a modified version of a standard Lyot filter that allows light to propagate through the birefringent fiber (PMF) twice bi-directionally through the optical circulator (C2) [37]. A phase difference ($\Delta\varphi$) of

$$\Delta\varphi = 2\pi B L_B/\lambda, \tag{3}$$

is obtained between the fast and slow axis when the light pass through the PMF at 45° with respect to the axis, where B and L_B are the birefringence and length of the PMF. By allowing the light propagates twice bi-directionally in the birefringent fiber through the circulator C2 and adjusting the polarization controller (PC) to let the light rotate to a different polarization angle of 0°, 45° or 90°, an accumulated phase difference of $2\Delta\varphi$, $\Delta\varphi$, and 0 can be obtained, corresponding to a piece of PMF with an equivalent length (L_e) of $2L$, L and 0, respectively. Different L_e results in different comb spacings in the optical carrier, which in turn governs the passband frequency. The passband frequency of the microwave photonic filter (Ω) is governed by

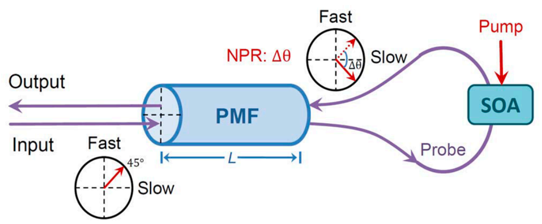
$$\begin{aligned} \Omega &= 2\pi/\beta_2 L_D \Delta\omega \\ &= B L_e/\beta_2 L_D C, \end{aligned} \tag{4}$$

where L_e is the equivalent length of the birefringent fiber, $\Delta\omega$ is the comb spacing of optical carrier, and C is the speed of light. Since both β_2 and L_D are fixed in the experiment, the resultant passband frequency can be tuned by controlling the optical comb spacing of the carrier, which is tunable by adjusting the PC in the Lyot loop filter. To obtain dual-passband operation, the polarization rotation angle in the Lyot loop filter is set to a value between 45° and 0°, such that two optical combs with two different comb spacings are interleaving with each other, resulting in two passbands. Figure 4b shows the four different comb spacings and combinations of the optical carrier, with Figure 4b(iv) shows two interleaving combs with different comb spacings. Figure 4b(v–viii) show the corresponding microwave photonic filter response, that corresponds to (i) a all-block filter, (ii,iii) single passband filter, and (iv) dual-passband filter. All the passbands show sharp filter profile and consistent spectral performance, with sidelobe suppression of 46 dB and 3-dB bandwidth of 200 MHz. The use of Lyot loop filter to generate the multi-wavelength optical carrier is highly cascadable. With another stage of the Lyot loop filter or an additional piece of PMF, a total of 12 passbands can be obtained, which will be described in Section 3.2.

2.5. Ultrafast Passband Reconfiguration Based Nonlinear Polarization Rotation

Although all the approaches described above enable passband tuning or reconfiguration, the tuning mechanisms are based on slow thermal or mechanical tuning of laser wavelength, manual tuning of delay line, or manual tuning of polarization state. In a dynamic RF environment, it is desired to have a fast tuning speed to switch the passband or tune the passband frequency. With the Lyot loop filter based approach described in Section 2.4, ultrafast passband reconfiguration can be achieved with nonlinear polarization rotation in a semiconductor optical amplifier (SOA), where gigahertz reconfiguration speed between different states have been achieved through the control of the optical pump power to the SOA. Figure 5a shows the modified Lyot loop filter with the polarization controller replaced by an optically pumped SOA.

(**a**)



(**b**)

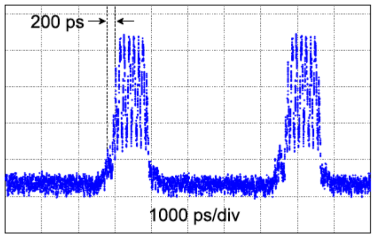


Figure 5. (**a**) Operation principle of the optically controlled Lyot loop filter. The pump laser and the SOA work as an optically controlled polarization controller through ultrafast nonlinear polarization rotation effect. (**b**) Tuning speed measurement of the optically controlled microwave photonic dual-band filter. The filter is switching between the all-block and single-band states.

Instead of manually adjusting the polarization rotation angles, the SOA together with the pump laser work as an optically controlled polarization controller inside the Lyot loop filter. The effective birefringence of the SOA changes as the optical pump power changes, such that the broadband signal experiences different polarization rotation angles after propagating through the SOA [38]. Power of the optical pump can be adjusted through an electro-optic intensity modulator, where a polarization rotation range up to 180° can be achieved [39]. Figure 5b shows an experimental measurement of the switching time of the SOA based dual-passband filter. The passband as well as the input RF signal at 6.8 GHz are being switched on and off by changing the optical pump power. A switching rise time of less than 200 ps is obtained, proving the ultrafast passband switching capability of the microwave photonic dual-passband filter.

3. Passband Reconfigurable Multiband Microwave Photonic Filters

As shown in Section 2, most microwave photonic filter approaches are not scalable—requiring an individual sets of laser source, delay element, or optical comb generator for each spectral passband, which is not practical for achieving high passband count multiband microwave photonic filters. Recently, there are breakthroughs in achieving passband reconfigurable multiband microwave photonic filters with more than two passbands—which open the possibility of realizing dynamic multiband RF communications. In this section, we will introduce the successful examples of passband reconfigurable multiband microwave photonic filters.

3.1. Three-Passband Microwave Photonic Filter

High-order loop mirror filter that consists of more than one piece of high-birefringent fiber has been used for generating optical comb filters with unique comb profiles for various signal processing tasks [40–42]. With careful design, the high-order comb profile can be used as a spectral slicer for generating multi-wavelength optical carrier with multiple interleaved combs. Figure 6a shows the architecture of a high-order loop mirror filter with two segments of high-birefringent fiber [21], where the resultant comb profile is adjustable by the polarization controller in between the two pieces of high-birefringent fibers. The number of passband in the microwave photonic filter depends on the number of interleaving optical comb (with different comb spacings) in the high-order loop mirror filter. With two pieces of high-birefringent fiber with length of L_1 and L_2, a maximum of three interleaving comb spacings that are governed by L_1, L_2, and $L_1 + L_2$ are resulted.

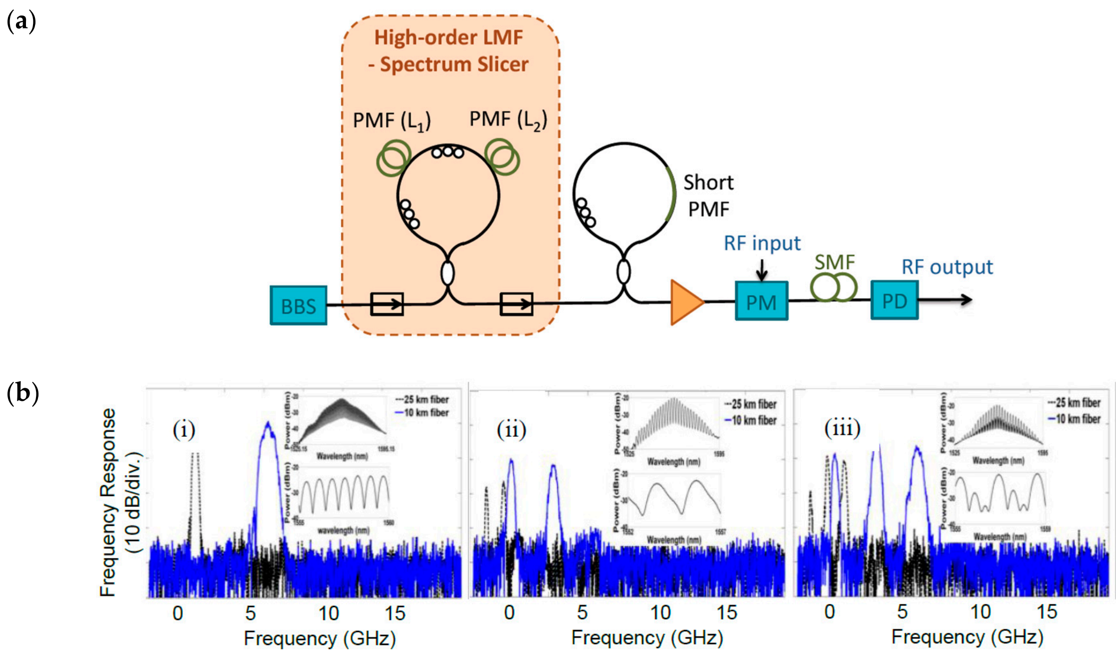


Figure 6. (**a**) Experimental setup of the loop mirror (LMF) based three-passband microwave photonic filter. BBS: broadband light source; PMF: high-birefringent fiber; PM: phase modulator; SMF: standard single mode fiber; PD: photodetector. (**b**) Resultant filter response with reconfigurable passbands (with the courtesy of Dr. Y. Jiang): (**i**) one passband, (**ii**) two passbands, (**iii**) three passbands.

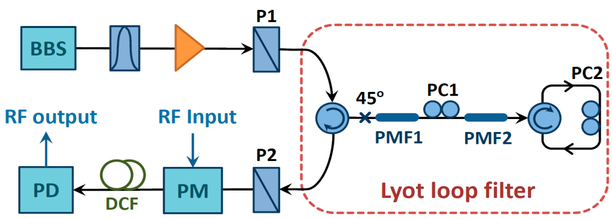
In the experiment shown in Figure 6a, a broadband light source covers the C and L bands is used. The broadband light source is spectrally sliced by the first loop mirror filter that consists of two pieces of high-birefringent fiber, creating the optical carriers (taps) that are needed to generate the RF passbands. The two pieces of high-birefringent fibers are 6 m and 3 m in length. The spectrally sliced optical source is then reshaped by another loop mirror filter that has an 8-cm high birefringent fiber, resulting in a Gaussian-like profile with 3-dB bandwidth of 6 nm. The multi-wavelength optical carrier is then modulated by the input RF signal via an electro-optic phase modulator. Time delay is introduced to each of the optical carrier using the dispersion in a 25-km standard single mode fiber. The modulated optical signal is launched to a 12-GHz photodetector and the RF response is measured by a vector network analyzer. By properly setting the polarization rotation angles in the spectral slicing loop mirror filter, a maximum of three interleaving optical combs with different comb spacings are resulted, in other words, three passbands in the microwave photonic filter are resulted. Figure 6b shows the measured RF response of the multiband microwave photonic filter with three reconfigurable passbands. By manually adjusting the polarization setting in the loop mirror filter, the microwave photonic filter can have one, two, or three passbands at the specified frequency—governed by the length of the high-birefringent fiber. The black curve and blue curve corresponds to the measured results with the use of a 25 km and 10 km single mode fiber for dispersion, respectively. A narrower passband is resulted with a longer piece of single mode fiber, i.e., larger dispersion results in larger time delay between each taps. With the high-order loop mirror filter approach, three reconfigurable passbands are resulted with the use of two pieces of birefringent fiber of different lengths.

3.2. High Passband Count Reconfigurable Microwave Photonic Filter

To further increase the passband count in reconfigurable microwave photonic filter, the dual-passband microwave photonic filter based on a Lyot loop filter presented in Section 2.4 shows a promising solution towards the goal. The unique dual-pass structure of the Lyot loop filter enables a single piece of birefringent fiber to be used twice to provide addition phase control of the multi-wavelength optical carrier—the optical comb. Lyot loop filter that consists of one piece of birefringent fiber can results in two interleaving optical combs with different comb spacings, i.e., two RF passbands; while two pieces of birefringent fiber results in twelve interleaving optical combs with different comb spacings, i.e., twelve possible RF passbands, as shown in Figure 7a. The twelve RF passbands microwave photonic filter can be achieved either using two cascaded Lyot loop filters each has one piece of birefringent fiber [34], or using one Lyot loop filter with two pieces of birefringent fiber [33], as shown in Figure 7b.

Number	Length Combination	Equivalent PMF length (L_e, m)	Comb spacing ($\Delta\omega$, pm)	MWP Filter passband (Ω_0, GHz)
1	L_1	11	336.19	1.3
2	$2L_1$	22	168.09	2.6
3	$\|2L_1-L_2\|$	33	112.06	4.0
4	$\|L_1-L_2\|$	44	84.04	5.4
5	L_2	55	67.24	6.7
6	L_1+L_2	66	56.03	8.1
7	$2L_1+L_2$	77	48.02	9.5
8	$\|2L_1-2L_2\|$	88	42.02	10.9
9	$\|L_1-2L_2\|$	99	37.35	12.2
10	$2L_2$	110	33.62	13.6
11	L_1+2L_2	121	30.56	14.9
12	$2L_1+2L_2$	132	28.01	16.2

(**a**)



(**b**)

Figure 7. (**a**) Twelve possible combinations of the high-order Lyot loop filter based microwave photonic multiband filter (L_1 = 11 m, L_2 = 55 m). (**b**) Experimental setup of the reconfigurable microwave photonic multiband filter with twelve passbands based on a high-order Lyot loop filter [33]. BBS: broadband optical source; P1, P2: polarizers; PC1, PC2: polarization controllers; PMF1, PMF2: polarization maintaining fibers; PM: optical phase modulator; DCF: dispersion compensating fiber; PD: photodetector.

In this approach, the key for enabling multiband RF filtering is the high-order Lyot loop filter that consists of two pieces of birefringent fiber, as illustrated in the dashed box in Figure 7b. When light propagates through a birefringent fiber with an incident angle of 45° with respect to the fast axis, a phase difference of $\Delta\varphi = 2\pi B L_B/\lambda$ is obtained between the fast and slow axis, where B and L_B are the birefringence and length of the birefringent fiber, respectively. Depending on the polarization angle between the two pieces of birefringent fiber, PMF1 and PMF2, controlled by polarization controller PC1, the resultant effective length of the birefringent fiber could be different. If PMF1 and PMF2 are aligned, then the length adds up; if PMF1 and PMF2 are orthogonal, the length subtracts; if PMF1 is aligned at 45° with PMF2, then PMF2 is "invisible". Since light propagates through the two PMFs twice bi-directionally through the circulator-PC based loop at the far end, there are virtually four pieces of birefringent fiber that the light has to pass through with different incident angles, adjustable by PC1 and PC2. Thus, with two pieces of PMFs, up to twelve different equivalent lengths can be obtained with equivalent length $L_e = |mL_1 + nL_2|$, where m, n = 0, 1, or 2, as shown in Figure 7a. The equivalent length of the PMF determines the comb spacing of the multi-wavelength optical carrier as well as the passband frequency of the microwave photonic filter. To generate multiple passbands in the multiband microwave photonic filter, multiple optical combs with various comb spacings have to co-exist in the Lyot loop filter, resulting in interleaving combs. This can be achieved by setting the polarization rotation angle at the circular-PC loop at the far end to a value between 0° and 45°, resulting in a higher order filter with multiple interleaving combs. Furthermore, all the passbands can be switched off by always aligning the light to the fast axis of the birefringent fiber inside the whole Lyot loop filter, such that no phase difference is introduced and the microwave photonic filter can work as an all-block filter.

RF response of the 12-passband microwave photonic filter is measured with a network analyzer, as shown in Figure 8. By adjusting the polarization controllers inside the high-order Lyot loop filter, various passband combinations can be achieved. In Figure 8a, one single passband at 5.4 GHz is observed with the microwave photonic filter working in a single-band state, while in Figure 8b two passbands at 8.1 GHz and 16.2 GHz are recorded with the microwave photonic filter working as a dual-band filter. Figure 8c–f show the measured results of multiple passbands, the passband numbers are adjusted through polarization control, so that the microwave photonic filter simultaneously can have 3, 5, 7, and 12 passbands, respectively. All 12 passband frequencies calculated in Figure 7a are observed at the same time in Figure 8f, which are evenly distributed between 1.3 GHz and 16.2 GHz. The 12 passbands are equally separated with a frequency spacing of 1.3 GHz. This Lyot loop filter based microwave photonic filter is highly scalable, 61 passbands can be achieved with three pieces of birefringent fiber in the high-order Lyot loop filter.

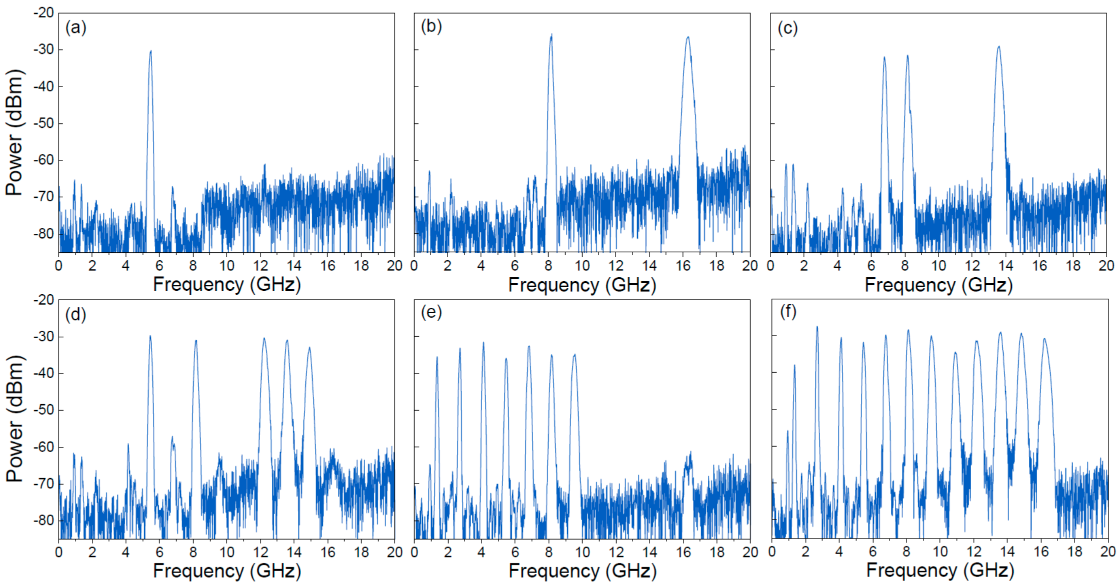


Figure 8. Measured frequency spectra of the reconfigurable microwave photonic multiband filter with different passband combinations [33]. (**a**) One single passband at 5.4 GHz. (**b**) Two passbands at 8.1 GHz and 16.2 GHz. (**c**) Three passbands at 6.7 GHz, 8.1 GHz and 13.6 GHz. (**d**) Five passbands at 5.4 GHz, 8.1 GHz, 12.2 GHz, 13.6 GHz, and 14.9 GHz. (**e**) Seven passbands from 1.3 GHz to 9.5 GHz. (**f**) Twelve passbands from 1.3 GHz to 16.2 GHz (All twelve passbands shown in Figure 7a).

4. Passband Tunable and Reconfigurable Multiband Microwave Photonic Filters

Various schemes to achieve wavelength reconfigurable multiband microwave photonic filters have been presented in Section 3, where the possible filter passbands are set at specific preset frequency channels. Due to the fast growing of RF communications, there is a need to tune the transmission frequency dynamically outside certain preset channels to meet the system functionality requirement. Therefore, it is necessary to develop an RF multiband filter with a large number of simultaneous passband, wide and continuous passband frequency tuning range, and flexible reconfigurable passband number. Examining the existing passband reconfigurable approaches, the factor that limits the capability to continuously tune the passband frequency is the inability of continuous adjustment of the optical comb spacing. The comb spacing is determined by the birefringence and length of the birefringent fiber, which is fixed by the physical parameter of the fiber used in the filter. While it is possible to tune the birefringence using electro-optics approach [37], the amount of birefringence tuning is too small to be observed in the resultant passband frequency. Although Lyot loop filter offers great scalability to achieve high passband count multiband microwave photonic filters, an alternative way to generate a continuously tunable interleaving optical comb is needed to enable continuous passband frequency tuning in multiband microwave photonic filters. In this Section, we will introduce two different approaches that have been successfully demonstrated to achieve microwave photonic filters with both passband frequency tunable and reconfigurable capabilities. The two approaches are: (i) Tailoring of the Brillouin gain in chalcogenide chip using arbitrary waveform generation, and (ii) Cascading tunable Mach-Zehnder interferometer for interleaving FIR filter taps generation.

4.1. Multiband Filter Based on Tailoring of the Brillouin Gain in Chalcogenide Chip Using Aribitary Waveform Generation

This stimulated Brillouin scattering (SBS) approach is based on a single passband microwave photonic filter as described in Figure 9a [32]. The input RF signal is modulated onto an optical carrier using a phase modulator, such that two sidebands with a phase difference of π separated from the RF carrier frequency is resulted. The phase-modulated signal is then launched to a chalcogenide chip with high SBS gain, where the output after the chalcogenide chip is detected by a photodetector. A SBS pump is also launched to the chalcogenide chip for controlling the SBS gain. When the SBS pump is turned off, there is no effect on the input phase modulated signal, therefore, due to the π phase difference of the two sidebands, they will destructively interfere at the photodetector and result in a DC signal. When the SBS pump is turned on, SBS gain at a frequency of ~7.6 GHz away from the pump is induced in the chalcogenide chip. The frequency components that experience SBS gain will not be cancel out due to the significantly larger power at those specific frequencies, while the rest of the frequency will be destructively interfered. Therefore, only the portion that align with the SBS gain will pass through the filter, resulting in a bandpass filter with a ~30 MHz bandwidth and a Loretzian shape. Both the bandwidth and filter shape are determined by the material properties of the SBS medium, i.e., chalcogenide chip. To modify the SBS gain profile and enable multiband filtering, an arbitrary waveform with multiple frequency components are used to spectrally modulate the SBS pump. If the SBS pump has a wide spectral width, a bandpass filter with wide passband is resulted. Therefore, a SBS pump with multiple frequency components is created that consists of multiple SBS gain peaks in the spectrum, as a result, multiple passbands can be obtained at the RF response of the multiband microwave photonic filter. Figure 9b,c show the measured RF response of the SBS based multiband microwave photonic filter, the passband frequency is continuously tunable through the control of spectral shape of the SBS pump. Four spectral lines in the SBS pump result in four passbands, while six spectral lines in the SBS pump result in six passbands.

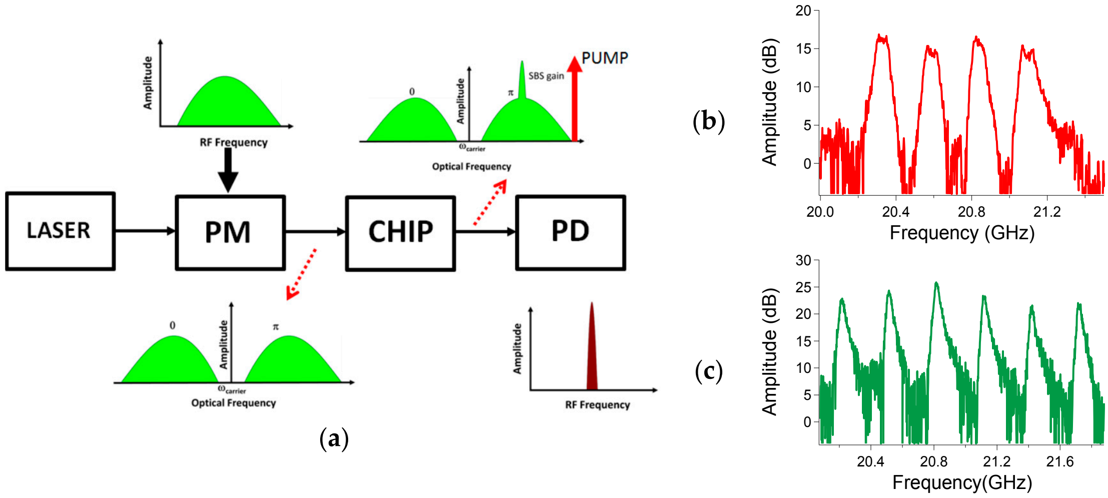


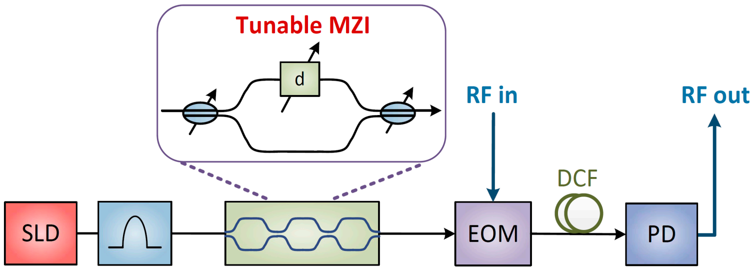
Figure 9. (**a**) Experimental setup of the SBS based multiband microwave phonic filter (courtesy of Dr. A. Choudhary). PM: phase modulator; CHIP: chalcogenide chip; PD: photodetector; AWG: arbitrary waveform generator. (**b**,**c**) Measured RF response with four and six passbands each separated by 250 MHz and 300 MHz, respectively (with the courtesy of Dr. A. Choudhary).

4.2. Multiband Filter Based on Cascading Tunable Mach-Zehnder Interferometers for Interleaving FIR Filter Taps Generation

According to the interferometric optical comb filter based microwave photonic filter we introduced in the previous sections, highly reconfigurable and tunable multiband filter can be achieved by cascading tunable interferometric optical filters. An alternate interferometric optical comb filter—Mach-Zehnder Interferometer (MZI) has been a well-known type of interferometric filter due to its potential for integration—integrated MZI modulator and phase decoder have been commercially made. It is not a favorable interferometric filter in a non-integrated fiber based structure due to its sensitivity to environment change—compare with Lyot loop filter and loop mirror filter, because it has two physically separated interferometric branches. One major limitation in using birefringence based interferometric filter, i.e., Lyot loop filter and loop mirror filter, in microwave photonic filter is the inability to continuously tune the optical comb, resulting in the inability in continuously tuning of the microwave photonic filter passband frequency. Unlike in birefringence based interferometric filter, the comb spacing resulted in a MZI is governed by the path difference between the two MZI branches, which could be continuously tuned using a tunable delay line. Therefore, MZI is a promising candidate to solve the continuous passband frequency tuning challenge in microwave photonic filter.

The basic structure of the passband tunable multiband microwave photonic filter is similar as the passband reconfigurable microwave photonic filter described in Section 3.2, however, the Lyot loop filter is now replaced by a cascaded MZI, as shown in Figure 10a [36]. The cascaded MZI consists of three MZIs in series, where the comb spacing of each MZI is defined as $\Delta\omega = 2\pi c/nd_1$, where n is the refractive index of the fiber, d_1 is the length difference between the two branches in a MZI, and c is the speed of light. Each MZI consists of a tunable optical coupler at the input, as well as a tunable delay line in one of its branches. Therefore, comb spacing of the MZI can be tuned by the tunable delay line, and can be enable/disable by the tunable optical coupler. With one MZI, only one comb spacing that is governed by d_1 can be obtained. By cascading a second MZI with a 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, i.e., d_1, d_2, $d_1 + d_2$, and $d_1 - d_2$. Therefore, two cascaded MZIs results in a microwave photonic filter with four tunable passbands. In the experiment, three cascaded MZIs are used, which lead to 13 different combinations of length difference combinations, as shown in Figure 10b. Since d_1, d_2, and d_3 are all tunable using the tunable delay lines in the MZIs, frequency of the resulting 13 passbands are all continuously tunable. It is worth noticing that frequency of some of the passbands are related to others, according to Figure 10b, the effort on the improvement of design is ongoing to achieve independently controllable and adaptable passbands.

(**a**)



(**b**)

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

Figure 10. (**a**) Experimental setup of the cascaded tunable multiband microwave photonic filter [36]. SLD: Superluminescent diode; MZI: Mach-Zehnder interferometer; EOM: electro-optic modulator; DCF: dispersion compensating fiber; PD: photodetector. (**b**) 13 possible combinations of the cascaded MZI based microwave photonic multiband filter.

With the use of the tunable coupler in the MZIs, the microwave photonic filter can be reconfigured to have various number of simultaneous passband—passband reconfigurable, by enabling or bypassing some of the MZI. Figure 11 shows several examples of the passband reconfiguring and tuning capability of the multiband microwave photonic filter. A single bandpass filter is shown in Figure 11a, which is achieved by setting the tunable couplers inside MZI 2 and MZI 3 to be 100:0 such that these two interferometers are bypassed, i.e., only MZI 1 is contributing to the optical comb with one comb spacing. Four passbands are observed if MZI 1 and MZI 2 are enabled, as shown in Figure 11b, which matches well with the prediction in Figure 10b. By controlling the tunable delay line in MZI 2, two of the passbands can be tuned to the same frequency and results in a three passband multiband filter, as shown in Figure 11c. When all the three MZIs are enabled, a maximum of 13 passbands are observed in the multiband filter, as shown in Figure 11f, with the passbands match with the prediction in Figure 10b. Various combinations can be achieved with the same principle using the delay line and coupler. A maximum of 35 GHz frequency tuning range can be achieved with the use of a 600 ps delay line.

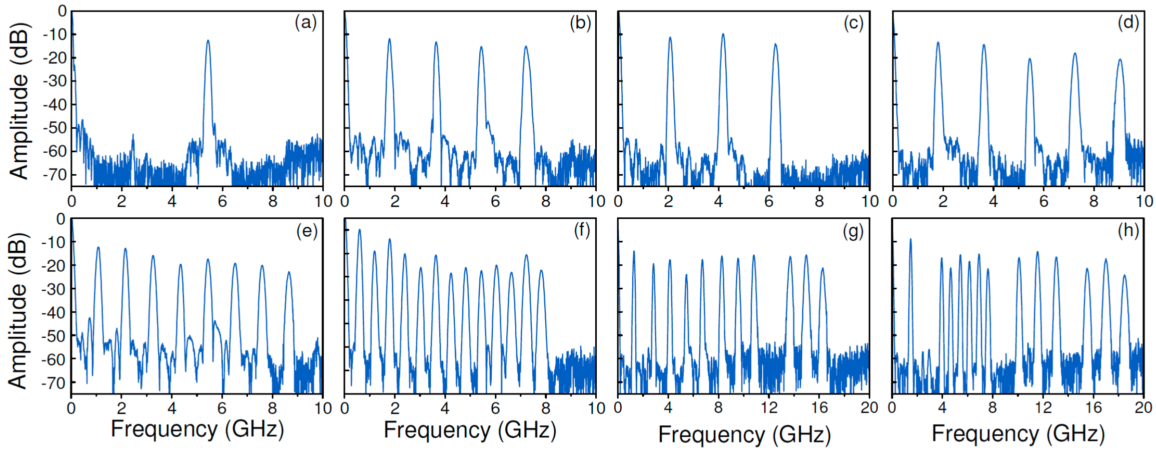


Figure 11. Measured frequency spectra of the tunable and reconfigurable microwave photonic multiband filter with different passband combinations [36]. (**a**) One single passband. (**b**–**d**) Three to five passbands. (**e**) Eight passbands. (**f**) Thirteen passbands with evenly distributed frequency spacing. (**g**) Eleven passbands. (**h**) Thirteen passbands with uneven frequency spacings.

5. Applications of Tunable Multiband Microwave Photonic Filters

Although single passband microwave photonic filters are well developed, their applications in RF signal processing are limited to spectral filtering. It is impossible to provide more sophisticated signal processing functions with just a single passband. Multiband microwave photonic filters are originally designed for channel selection and noise removal in multiband RF communications. With the development of passband tunable and passband reconfigurable high-passband count multiband filter, it is possible to dynamically process a wide range of RF spectrum, which opens up a large variety of applications for processing wideband microwave signals. Here, we are introducing two applications of the multiband microwave photonic filter, based on the passband tunable and reconfigurable filter described in Section 4.2, including RF spectral equalization, RF pulse and spectral shaping.

5.1. RF Equalizer

In microwave systems, a common challenge in obtaining consistent performance over a wide frequency range is the non-uniform gain and loss in RF components and RF channels at different frequencies. The consequence is significant deterioration of signal quality and narrow band system operation. The situation is even worse in a dynamic system, where the frequency dependent gain and loss could change over time, making it very challenging to compensate the variation. To solve this problem, a broadband and reconfigurable RF equalizer is required to compensate and balance the frequency dependent gain and loss. However, existing RF equalizer are mainly based on tunable attenuators, bandpass filter, or their combination, resulting in very limited spectral function and limited tuning capability—only linear and parabolic compensating curves can be obtained. Furthermore, the only adjustable parameters are the attenuation coefficient and the compensating slope for a very limited range. Without physically replacing the hardware, it is impossible to achieve a wide range of equalization function with tunability.

With the multiband microwave photonic filter described in Section 4.2, a comprehensive photonic based RF equalizer with highly reconfigurable functionalities can be achieved for the first time. Various compensation functions are demonstrated, including positive/negative linear slopes with variable slope steepness, tunable parabolic and inverted parabolic responses, bandpass filter with variable filter profiles, and multiple-peak spectral shaping. The microwave photonic RF equalizer has variable number of spectral control points, customizable frequency control, and dynamic amplitude control to achieve wideband and flexible RF equalization functions.

Figure 12 shows several measured sample spectral functions that the proposed RF equalizer can achieved. With minor adjustment in the RF equalizer, spectral functions including tunable low pass filter, tunable single passband filter, triangular function, parabolic function with tunable width, inverted parabolic function with tunable width, tunable negative slope, tunable positive slope, multiple parabolic function, multiple inverted parabolic function, tunable attenuation floor, to name a few.

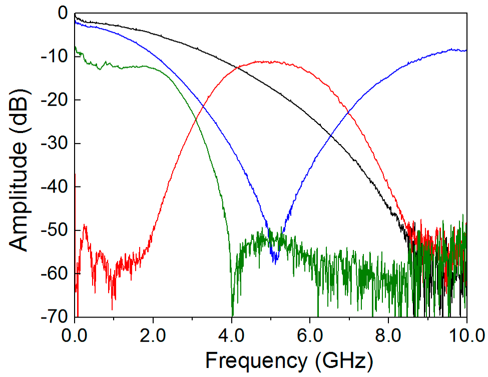


Figure 12. Measured RF equalization functions obtained by the multiband filter based RF equalizer.

5.2. Pulse Shaping and Spectral Shaping

Due to the wide operation bandwidth and customizable spectral profile of the multiband filter, the tunable multiband filter introduced in Section 4.2 can be used to manipulate a wide range of frequency component for spectral shaping and arbitrary pulse shaping. The idea has been tested using a 125 Mbit/s square pulse train as the original pulse input, as shown in Figure 13a, which is then launched to the multiband filter for pulse shaping. The square pulse train has a wide spectrum and can be manipulated by configuring the multiband filter to obtain different spectral profiles. First, a low-pass filter function with Gaussian profile is used, where high frequency components above 1 GHz are removed. The multiband filter turns the square pulse into a Gaussian pulse, as shown in Figure 13b. Then, the multiband filter is adjusted to have four spectral control points such that a saw-tooth function is obtained as the filter's RF response. By passing the square pulse into the multiband filter, it is manipulated by the saw-tooth spectral filter and turned into a triangular pulse, as shown in Figure 13c.

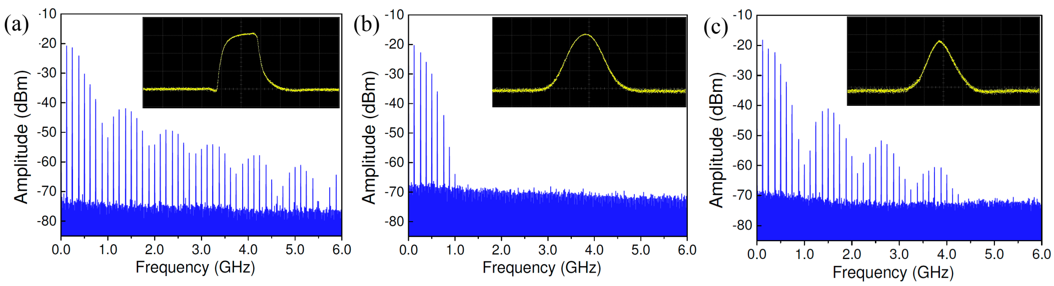


Figure 13. Demonstration of the pulse shaping function based on the proposed RF equalizer. (**a**) RF spectrum of a square-like pulse that to be reshaped. (**b**) Reshaped into a Gaussian pulse through the low-pass equalization function. (**c**) Reshaped into a triangular pulse trough the saw-tooth equalization function. Insets: Waveforms of the corresponding pulses in time domain.

The resolution and precision of spectral shaping depend on the number of passbands in the multiband filter, as well as the capability to preciously control the amplitude of each optical comb line. Currently, the multiband filter is configured to have 4 passbands which gives the spectral shaper 4 control points for adjusting both the frequency and amplitude of the signal. It is worth noticing that an additional stage of interferometer would increase the number of passband to 13, as illustrated in Figure 11.

6. Discussion and Conclusions

This paper reviews the recent development of tunable and reconfigurable multiband microwave photonic filters that can potentially enable dynamic multiband and advanced RF communication systems. Multiband filter is an essential component in multiband RF communications for channelization, desired channel selection, as well as noise and interference suppression. Commercially available single passband tunable filter usually has a high extinction ratio of over 40 dB and a 3-dB bandwidth of a few percentage of the operating frequency, i.e., 3-dB bandwidth of tens of MHz for filter with center frequency of 1 GHz. The supported tunable frequency range is usually within 2 GHz. Although single passband tunable filter is well developed, it is hard to find commercially available dual-band or multi-band tunable filter. The desired number of passband depending on the applications that the system is targeting for—number of functions and how flexible it is to adapt to the environment. A large number of passband is preferred if the multiband filter is used for other novel applications, such as equalization, spectral shaping, or pulse shaping. In terms of research development, a number of electronics based multiband RF filter are summarized in Table 1, which either has low extinction ratio of less than 30 dB, or without tuning/reconfiguring capability, or has small number of passband, or having asymmetric/inconsistence passband profiles. While it is desired to have multiband tunable RF filter with similar performance as their single band counterpart, it has always been a challenge for RF electronics to achieve high-passband count multiband filter that is highly tunable and reconfigurable, due to the tight design criteria to meet the needs of all the desired passbands and the limited tuning ability in electronics. Microwave photonic technique is a promising candidate to solve many of the challenges in RF electronics and lots of single passband microwave photonic filters have been developed, however, the development of tunable and reconfigurable multiband microwave photonic filters is not trivial. Multiband microwave photonic filter requires the use of a large number of optical carriers, with unique spacing and delay that matches with the design of the multiband filter. This cannot be achieved with conventional microwave photonic filter approaches that require large number of optical branches with individual delay and weight components or periodic optical comb carriers that has no capability to obtain unique comb spacings, to tune, and to adjust.

Recent advancements in microwave photonic filters have shown that it is possible to achieve high-passband count multiband microwave photonic filter with as many as 13 passbands, and each passbands have the capability of continuous frequency tuning and individual passband on/off switching—reconfigurability. To achieve high-passband count filtering, one can tailor the SBS gain spectrum to achieve multiband microwave photonic filter with as much as 6 passbands within 1.5 GHz range. On the other hand, high order interferometer can be used to spectrally slice a broadband light source to create the unique interleaving optical comb that consists of various comb spacing. With a high-order loop mirror filter, three-passband filter is achieved with reconfigurable passbands using two pieces of birefringent fiber. With a high-order Lyot loop filter, twelve-passband filter with reconfigurable passband is achieved with two pieces of birefringent fiber. With three-cascaded Mach-Zehnder interferometer, thirteen-passband filter with both passband frequency tuning and passband reconfigurable capabilities is achieved.

The rapid development of tunable multiband microwave photonic filters opens up lots of possibilities in the field of emerging microwave technologies, from enabling dynamic multiband communications to wideband spectral shaping. Looking forward, practical aspects of the microwave photonic multiband filters, including SWaP (size, weight, and power), dynamic range, independently control and adaptation, noise performance, have to be optimized and enhanced to facilitate their practical implementation to existing and future microwave systems.

7. Patent

Fok, M.P.; Ge, J. Continuously Tunable and Highly Reconfigurable Multiband RF Filter. U.S. Patent filed, S/N: 62/376,576, 18 August 2017.

Acknowledgments: The research work is supported by research grant from National Foundation, grant numbers ECCS 1653525 and CMMI 1400100.

Author Contributions: J. Ge and M. P. Fok conceived and designed the experiments; J. Ge performed the experiments; J. Ge and M. P. Fok analyzed the data; M. P. Fok and J. Ge wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yao, J. Microwave photonics. *J. Lightw. Technol.* **2009**, *27*, 314–335. [CrossRef]
2. Capmany, J.; Novak, D. Microwave photonics combines two worlds. *Nat. Photonics* **2007**, *1*, 319–330. [CrossRef]
3. Loayssa, A.; Lahoz, F.J. Broad-band RF photonic phase shifter based on stimulated Brillouin scattering and single-sideband modulation. *IEEE Photonics Technol. Lett.* **2006**, *18*, 208–210. [CrossRef]
4. Chin, S.; Thévenaz, L.; Sancho, J.; Sales, S.; Capmany, J.; Berger, P.; Bourderionnet, J.; Dolfi, D. Broadband true time delay for microwave signal processing, using slow light based on stimulated Brillouin scattering in optical fibers. *Opt. Express* **2010**, *18*, 22599–22613. [CrossRef] [PubMed]
5. Yao, J. Photonics to the rescue: A fresh look at microwave photonic filters. *IEEE Microw. Mag.* **2015**, *16*, 46–60. [CrossRef]
6. Han, Y.; Jalali, B. Photonic time-stretched analog-to-digital converter: Fundamental concepts and practical considerations. *J. Lightw. Technol.* **2003**, *21*, 3085–3103. [CrossRef]
7. Fok, M.P.; Lee, K.L.; Shu, C. 4/spl times/2.5 GHz repetitive photonic sampler for high-speed analog-to-digital signal conversion. *IEEE Photonics Technol. Lett.* **2004**, *16*, 876–878. [CrossRef]
8. Ge, J.; Fok, M.P. Ultra High-Speed Radio Frequency Switch Based on Photonics. *Sci. Rep.* **2015**, *5*, 17263. [CrossRef] [PubMed]
9. Ge, J.; Feng, H.; Scott, G.; Fok, M.P. High-speed tunable microwave photonic notch filter based on phase modulator incorporated Lyot filter. *Opt. Lett.* **2015**, *40*, 48–51. [CrossRef] [PubMed]
10. Byrnes, A.; Pant, R.; Li, E.; Choi, D.-Y.; Poulton, C.G.; Fan, S.; Madden, S.; Barry, L.-D.; Eggleton, B.J. Photonic chip based tunable and reconfigurable narrowband microwave photonic filter using stimulated Brillouin scattering. *Opt. Exp.* **2012**, *20*, 18836–18845. [CrossRef] [PubMed]
11. Marpaung, D.; Morrison, B.; Pagani, M.; Pant, R.; Choi, D.-Y.; Barry, L.-D.; Madden, S.J.; Eggleton, B.J. Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity. *Optica* **2015**, *2*, 76–83. [CrossRef]
12. Supradeepa, V.R.; Long, C.M.; Wu, R.; Ferdous, F.; Hamidi, E.; Leaird, D.E.; Weiner, A.M. Comb-based radiofrequency photonic filters with rapid tunability and high selectivity. *Nat. Photonics* **2012**, *6*, 186–194. [CrossRef]
13. Mora, J.; Ortega, B.; Díez, A.; Cruz, J.L.; Andrés, M.V.; Capmany, J.; Pastor, D. Photonic microwave tunable single-bandpass filter based on a Mach-Zehnder interferometer. *J. Lightw. Technol.* **2006**, *24*, 2500–2509. [CrossRef]
14. Kim, H.-J.; Leaird, D.E.; Weiner, A.M. Rapidly tunable dual-comb RF photonic filter for ultrabroadband RF spread spectrum applications. *IEEE Trans. Microw. Theory Tech.* **2016**, *64*, 3351–3362. [CrossRef]
15. Zhuang, L.; Roeloffzen, C.G.H.; Hoekman, M.; Boller, K.-J.; Lowery, A.J. Programmable photonic signal processor chip for radiofrequency applications. *Optica* **2015**, *2*, 854–859. [CrossRef]
16. Capmany, J.; Gasulla, I.; Pérez, D. Microwave photonics: The programmable processor. *Nat. Photonics* **2016**, *10*, 6–8. [CrossRef]
17. Fandiño, J.S.; Muñoz, P.; Doménech, D.; Capmany, J. A monolithic integrated photonic microwave filter. *Nat. Photonics* **2017**, 124–129. [CrossRef]
18. Sancho, J.; Bourderionnet, J.; Lloret, J.; Combrié, S.; Gasulla, I.; Xavier, S.; Sales, S.; Colman, P.; Lehoucq, G.; Dolfi, D.; et al. Integrable microwave filter based on a photonic crystal delay line. *Nat. Commun.* **2012**, *3*, 1075. [CrossRef] [PubMed]
19. Capmany, J.; Ortega, B.; Pastor, D. A tutorial on microwave photonic filters. *J. Lightw. Technol.* **2006**, *24*, 201–229. [CrossRef]

20. Capmany, J.; Mora, J.; Gasulla, I.; Sancho, J.; Lloret, J.; Sales, S. Microwave photonic signal processing. *J. Lightw. Technol.* **2013**, *31*, 571–586. [CrossRef]
21. Jiang, Y.; Shum, P.P.; Zu, P.; Zhou, J.; Bai, G.; Xu, J.; Zhou, Z.; Li, H.; Wang, S. A selectable multiband bandpass microwave photonic filter. *IEEE Photonics J.* **2013**, *5*, 5500509. [CrossRef]
22. Mora, J.; Chen, L.R.; Capmany, J. Single-bandpass microwave photonic filter with tuning and reconfiguration capabilities. *J. Lightw. Technol.* **2008**, *26*, 2663–2670. [CrossRef]
23. Gao, L.; Zhang, J.; Chen, X.; Yao, J. Microwave photonic filter with two independently tunable passbands using a phase modulator and an equivalent phase-shifted fiber Bragg grating. *IEEE Trans. Microw. Theory Tech.* **2014**, *62*, 380–387. [CrossRef]
24. Lin, Y.-C.; Horng, T.-S.; Huang, H.-H. Synthesizing a multiband LTCC bandpass filter with specified transmission-and reflection-zero frequencies. *IEEE Trans. Microw. Theory Tech.* **2014**, *62*, 3351–3361. [CrossRef]
25. Hsu, K.-W.; Lin, J.-H.; Tu, W.-H. Compact sext-band bandpass filter with sharp rejection response. *IEEE Microw. Compon. Lett.* **2014**, *24*, 593–595. [CrossRef]
26. Roberto, G.-G.; Guyette, A.C. Reconfigurable multi-band microwave filters. *IEEE Trans. Microw. Theory Tech.* **2015**, *63*, 1294–1307. [CrossRef]
27. Yang, T.; Rebeiz, G.M. Three-pole 1.3–2.4-GHz diplexer and 1.1–2.45-GHz dual-band filter with common resonator topology and flexible tuning capabilities. *IEEE Trans. Microw. Theory Tech.* **2013**, *61*, 3613–3624. [CrossRef]
28. Jia, T.; Ye, J.; Liu, Z. A RF-MEMS based dual-band tunable filter with independently controllable passbands. In Proceedings of the 2014 12th IEEE International Conference on Solid-State and Integrated Circuit Technology (ICSICT), Guilin, China, 28–31 October 2014; pp. 1–3. [CrossRef]
29. Chio, C.-K.; Ting, S.-W.; Tam, K.-W. Novel reconfigurable multipleband quasi-elliptic bandpass filter using defected ground structure. In Proceedings of the 2013 IEEE MTT-S International Microwave Symposium Digest (IMS), Seattle, WA, USA, 2–7 June 2013; pp. 1–4. [CrossRef]
30. Long, H.; Chen, D.; Zhang, F.; Xiang, P.; Zhang, T.; Wang, P.; Lu, L.; Pu, T.; Chen, X. Microwave photonic filter with multiple independently tunable passbands based on a broadband optical source. *Opt. Express* **2015**, *23*, 25539–25552. [CrossRef]
31. Hao, C.; Xu, Z.; Fu, H.; Zhang, S.; Wu, C.; Wu, H.; Xu, H.; Cai, Z. Switchable and tunable microwave frequency multiplication based on a dual-passband microwave photonic filter. *Opt. Express* **2015**, *23*, 9835–9843. [CrossRef]
32. Choudhary, A.; Aryanfar, I.; Shahnia, S.; Morrison, B.; Vu, K.; Madden, S.; Barry, L.-D.; Marpaung, D.; Eggleton, B.J. Tailoring of the Brillouin gain for on-chip widely tunable and reconfigurable broadband microwave photonic filters. *Opt. Lett.* **2016**, *41*, 436–439. [CrossRef] [PubMed]
33. Ge, J.; James, A.E.; Mathews, A.K.; Fok, M.P. Simultaneous 12-passband microwave photonic multiband filter with reconfigurable passband frequency. In Proceedings of the Optical Fiber Communication Conference, Anaheim, CA, USA, 22–24 March 2016. [CrossRef]
34. Ge, J.; Fok, M.P. Passband switchable microwave photonic multiband filter. *Sci. Rep.* **2015**, *5*, 15882. [CrossRef] [PubMed]
35. Ge, J.; Fok, M.P. Optically Controlled Fast Reconfigurable Microwave Photonic Dual-Band Filter Based on Nonlinear Polarization Rotation. *IEEE Trans. Microw. Theory Tech.* **2017**, *65*, 253–259. [CrossRef]
36. Ge, J.; Fok, M.P. Continuously tunable and reconfigurable microwave photonic multiband filter based on cascaded MZIs. In Proceedings of the 2017 IEEE Photonics Conference, Lake Buena Vista, FL, USA, 1–5 October 2017.
37. Fok, M.P.; Shu, C.; Tang, W.-W. A cascadable approach to produce widely selectable spectral spacing in birefringent comb filters. *IEEE Photonics Technol. Lett.* **2006**, *18*, 1937–1939. [CrossRef]
38. Fu, S.; Wang, M.; Zhong, W.D.; Shum, P.; Wen, Y.J.; Wu, J.; Lin, J. SOA nonlinear polarization rotation with linear polarization maintenance: Characterization and applications. *IEEE J. Sel. Top. Quantum Electron.* **2008**, *14*, 816–825. [CrossRef]
39. Lee, K.L.; Fok, M.P.; Wan, S.M.; Shu, C. Optically controlled Sagnac loop comb filter. *Opt. Exp.* **2004**, *12*, 6335–6340. [CrossRef]

40. Fok, M.P.; Lee, K.L.; Shu, C. Waveband-switchable SOA ring laser constructed with a phase modulator loop mirror filter. *IEEE Photonics Technol. Lett.* **2005**, *17*, 1393–1395. [CrossRef]
41. Jaehoon, J.; Lee, Y.W. Continuously wavelength-tunable passband-flattened fiber comb filter based on polarization-diversified loop structure. *Sci. Rep.* **2017**, 7. [CrossRef]
42. Wang, J.; Zheng, K.; Peng, J.; Liu, L.; Li, J.; Jian, S. Theory and experiment of a fiber loop mirror filter of two-stage polarization-maintaining fibers and polarization controllers for multiwavelength fiber ring laser. *Opt. Exp.* **2009**, *17*, 10573–10583. [CrossRef]