Dynamic and multiband RF spectral processing

Fok, Mable, Ge, Jia, Liu, Qidi

Mable P. Fok, Jia Ge, Qidi Liu, "Dynamic and multiband RF spectral processing," Proc. SPIE 10922, Smart Photonic and Optoelectronic Integrated Circuits XXI, 109221D (4 March 2019); doi: 10.1117/12.2511176

Event: SPIE OPTO, 2019, San Francisco, California, United States

Dynamic and multiband RF spectral processing

Mable P. Fok*, Jia Ge, Qidi Liu
Lightwave and Microwave Photonics Laboratory, College of Engineering,
The University of Georgia, Athens, GA, 30602, USA

ABSTRACT

Emerging RF systems utilize multiple frequency bands to facilitate multi-function operations and to adapt to dynamic transmission conditions, making multiband RF systems an essential infrastructure for applications in the commercial, defense, and civilian federal marketplace. While multiband RF systems are the backbone for intelligence, surveillance, and reconnaissance, as well as for supporting data-intensive physical weaponry in the battlefield; Civilians also rely on multiband RF systems for all types of day-to-day applications including smart home system control, entertainment, virtual reality and augmented reality learning. With the recent development of 5G networks, the spectrum of multiband networks could spend from hundreds of MHz to tens of GHz range, which could support new applications and improve the quality of services. The benefits associated with using multiband and wideband RF technologies can only be realized if it is possible to dynamically manipulate the ultra-wide multiband spectrum to ensure high-quality transmission performance. This is challenging, however, as the bandwidth of multiband RF signal could be as wide as several GHz with a center frequency from hundreds of MHz to tens of GHz range, and neither RF electronics nor digital signal processing are capable of dynamically manipulating spectrum of GHz wide. In this paper, we will present our recent advancement on novel photonic systems for dynamically manipulating the wide RF spectrum for multiband and wideband emerging RF systems.

Keywords: Microwave Photonics, RF spectrum shaping, reconfigurable RF filtering, multiband filtering, RF signal equalization

1. INTRODUCTION

Multiband and wideband wireless systems are the backbone of emerging data-intensive applications for supporting multi-function service and to enable adaptation to dynamic transmission environment changes [1-4]. Processing wideband signals that are of hundreds of MHz to GHz wide is challenging for both RF electronics and digital signal processing, due to the intrinsic bandwidth limitation and design constrain in RF electronics, as well as the Nyquist theory that has to be met by digital signal processing. Although electronic approaches offer on-chip solutions to most signal processing tasks, it is very challenging for RF electronics based spectral processing device to tune its spectral properties because of the inherent low-tunability characteristic of RF electronics, and the challenges to satisfy the design parameters for a wide range of frequencies.

Microwave photonics have been a promising candidate to tackle challenges that RF electronics found it hard to solve. For RF spectral processing, various microwave photonic systems have been intensively studied including single passband filter, notch filter, and ultra-wideband microwave signal generation. However, most of the schemes are focused on spectrally processing a fixed single frequency band signal. For example, single passband microwave photonic filters can be implemented using chip-based stimulated Brillouin scattering [5-6], optical comb based filters [7-9], and phase-shifted fiber Bragg grating [10]. However, most single passband filter approaches cannot be translated into a spectral processor that performs dynamic, multi-point, or tunable RF spectral control [11].

Due to the heterogeneous and dynamic nature of modern RF systems, tunable and reconfigurable multiband and wideband RF spectral control are critical for supporting flexible and dynamic multiband RF communications. In this paper, we will discuss our recent research progress on dynamic and multiband RF spectral processor including: (i) High passband count reconfigurable multiband RF filter (ii) Multiband RF filter with high-speed switchable passband (iii) Multiband RF filter with heterogeneous and independently tunable spectral properties, and (iv) Wideband RF spectral shaper with tunable and reconfigurable spectral functions. The demonstrated microwave photonic schemes can potentially benefit a variety of fields including emerging communication systems, wideband radar, and multiband satellite systems [12-13], where the capability to precisely and flexibly process a wide range of frequency components is highly desired.

Smart Photonic and Optoelectronic Integrated Circuits XXI, edited by Sailing He,
El-Hang Lee, Proc. of SPIE Vol. 10922, 109221D · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2511176

2. HIGH PASSBAND COUNT TUNABLE MULTIBAND RF FILTER

In multiband RF system where multiple frequency bands are used simultaneously for various applications, a multiband RF filter is essential to pre-select the desired band, and prevent interference in multiband communications. Unfortunately, RF electronics is not good at achieving multiple passband because it is difficult to simultaneously satisfy all the design parameters for all passbands [14-19]. To date, a six passband RF filter is demonstrated based on the use of several cascaded resonators, however, the resultant passband profiles are not consistent and are not of high spectral quality. Although the designs of microwave photonic bandpass filter have been studied intensively, most existing approaches are either unable to scale up to support multiband operation, or only periodic passbands are resulted that limit its ability to isolate unwanted frequencies at designated frequency range.

One promising scheme for designing microwave photonic filter is using optical frequency comb [7-9]. In order to achieve multiple passbands in optical comb based microwave photonic filter, the corresponding optical frequency comb either has to consist of multiple combs with different comb spacing simultaneously [20] or the optical comb has to be sampled spectrally [21]. Examples of photonic based scheme include a loop mirror filter based multiband RF filter with three passbands, and a multiple passband filter with sidelobe suppression of 10 dB using wavelength sampling technique [21]. However, it is very challenging to increase the number of passbands as well as to improve the uniformity and tunability of the multiband RF filter due to the lack of flexibility and scalability of the demonstrated schemes. In this section, we will discuss photonic approaches that can achieve multiband RF filter with up to 12 switchable and tunable passbands.

2.1 Principle and Experimental Setup

The demonstrated high-passband count multiband RF filter approach is based on conventional finite impulse response filter principle with an optical frequency comb based architecture. The generation of optical taps is achieved using a unique dual-pass Lyot loop filter [22-24] where light propagates bidirectionaly in the filter. Figure 1(a) illustrates the experimental setup of the scheme: a Lyot loop filter is used to spectrally slice a broadband light source for generating the taps, a Gaussian filter is for weighting and shaping the taps, an electro-optic phase modulator is for modulating the input RF signal onto the optical taps, and the dispersive element is for providing delay to each optical tap. Based on the finite impulse response filter principle, the resultant passband frequency is governed by:

$$\Omega_0 = \frac{2\pi}{\beta_2 L_D \Delta\omega} = \frac{BL_e}{\beta_2 L_D C}$$

where B and L_e are the birefringence and effective length of the polarization maintaining fiber, β_2 and L_D are the dispersion coefficient and length of the dispersion element, $\Delta\omega$, is the optical comb spacing (free spectral range), and C is the speed of light. With one polarization maintaining fiber of length L1 in the Lyot loop filter, four spectral states – all block, single passband at two different frequencies (L_D = L1 and 2L1, respectively), and two simultaneous passbands can be achieved through the control of polarization rotation inside the Lyot loop filter [22-24].

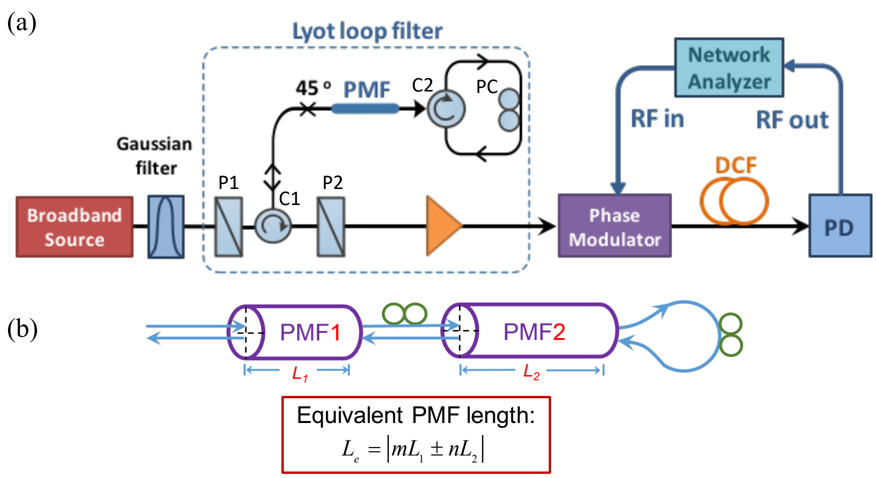

Figure 1: Experimental setup of the passband switchable microwave photonic multiband filter. BBS: broadband source; P1-P2: polarizers; C1-C2: circulators; PC: polarization controller; PMF1-PMF2: polarization maintaining fibers; DCF: dispersion compensating fiber; PD: photo-detector.

Due to the unique dual pass structure of the Lyot loop filter, a large number of effective PMF length is resulted, which turns into a large number of possible passbands. 12 different passbands can be achieved by using two pieces of polarization maintaining fiber in the Lyot loop filter, as illustrate in Figure 1(b). With two pieces of polarization maintaining fibers, 12 different equivalent lengths ($L_e = |mL_1 \pm nL_2|$, with m, n = 0, 1, or 2) are obtained, with L_1 and L_2 being the physical lengths of PMF1 and PMF2, respectively. As a result, multiband RF filter with three operating states, i.e. single-band state at one of the 12 frequency, multiband state with passband number between 2 to 12, and all-block state (no passband) is achieved. To tune the number of passband in the multiband RF filter, polarization rotation angles between the two polarization maintaining fibers and that of the feedback path can be set to between 0° and 90°, such that different effective fiber length and different number of interleaving optical combs are resulted. Figure 2 is several sample spectral response of the multiband RF filter achieved through polarization tuning [22-24].

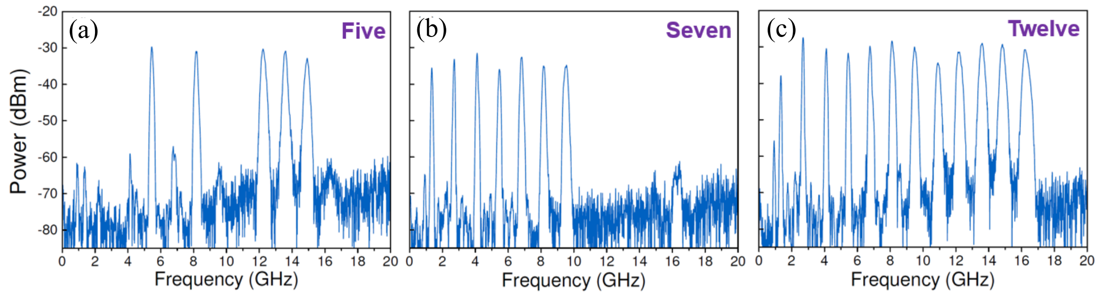

Figure 2: Experimentally measured RF spectral response of the proposed passband switchable multiband RF filter. (a) with 5 passbands; (b) with 7 passbands; (c) with 12 passbands [22-24].

2.2 High-Speed Switching and Tuning of Passbands

In order to adapt to fast changes in dynamic RF systems, passband selection through manually tuning of polarization is too slow to satisfy the needs. We have demonstrated a fast passband switching technique based on nonlinear polarization rotation effect in a semiconductor optical amplifier. The polarization controller in the feedback loop of the Lyot loop filter is replaced by a semiconductor optical amplifier, enabling optical-control of light polarization [25-26]. Nonlinear polarization rotation is an ultrafast optical effect at GHz speed that occurs when a strong optical pump light is launched into a semiconductor optical amplifier [27-28]. To investigate the switching ability of the optical-control polarization tuning, Lyot loop filter with just one polarization maintaining fiber is used in the RF filter. When the optical pump is turned off, the RF filter is at its all-block state (Figure 3(a)), when the pump is set to 4.9 dBm, the RF filter is at single passband state. Therefore, by controlling the optical pimp power, it is possible to switch the multiband RF filter passband at high speed. Figure 2(c) shows the switching speed measurement by switching on and off an RF signal at the passband, a 200 ps switching time is observed.

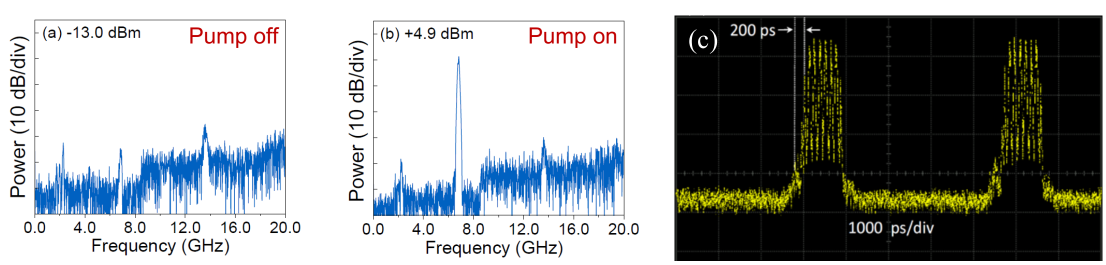

Figure 3: Experimentally measured optical switching response of the RF filter. (a) RF filter is at all-block state when the optical pump is turned off; (b) RF filter is at single passband state when the optical pump is set to 4.9 dBm; (c) Passband switching speed measurement [25-26].

With the use of Lyot loop filter, the passbands can be switched on and off at a designated frequency determined by the effective length of the polarization maintaining fiber in the Lyot loop filter. However, since the only way to change the effective fiber length is by adding or subtracting the birefringence in the polarization maintaining fiber, it is not possible to tune the passband frequency using a Lyot loop filter. In order to achieve continuous passband tuning, Lyot loop filter can be replaced by a tunable Mach-Zehnder interferometer [29]. A tunable Mach-Zehnder interferometer has a tunable optical delay line and variable optical couplers, such that both passband frequency and passband amplitude can be continuously tuned. With three cascaded tunable Mach-Zehnder interferometers, a maximum of 13 passbands can be achieved, as shown in Figure 4(a). All the passband has a sidelobe suppression ratio of over 35 dB and a 3-dB bandwidth of 100 MHz. Through the control of coupling ratio of the tunable couplers, some of the passband can be switched off, as shown in Figure 4(b)and (c). Furthermore, passbands can be tuned over a 20 GHz range using the tunable delay line, as shown in Figure 4(d).

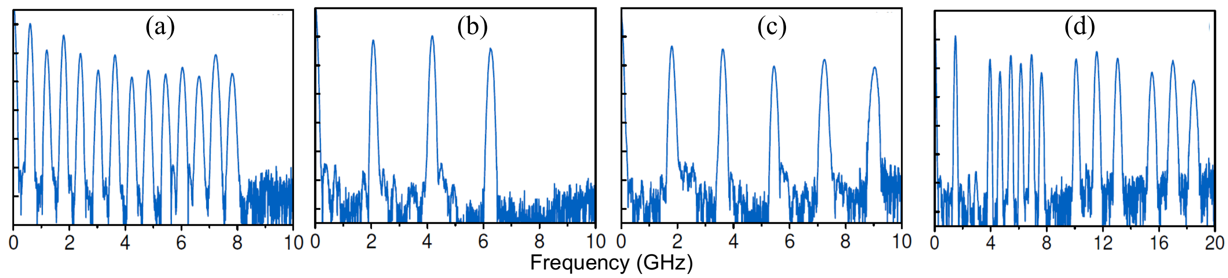

Figure 4: Experimentally measured passband frequency tuning in the RF filter. (a) 13 passbands that are evenly distributed; (b) Some passbands are switched off, resulting in 3 passbands; (c) 5 passbands; (d) some of the passbands are tuned to a different frequency range [29].

2.3 Discussion

Optical frequency comb based RF filter schemes are a promising way to achieve high-passband count RF filtering, which require the use of an optical spectral slicer to generate a number of interleaving optical combs with different free spectral range – the taps. The choice of optical spectral slicer is important because it governs the tunability and reconfigurability of the multiband RF filter. Lyot loop filter provides a large combination of passband choice due to the dual-pass design; however, the frequency of each passband is pre-defined by the lengths of the polarization maintaining fibers used in the Lyot loop filter and can only be switched on and off through polarization control. Fast switching of the passband at GHz speed can be achieved using nonlinear polarization rotation in semiconductor optical amplifier. To increase the tunability of the multiband RF filter, Mach-Zehnder interferometer can be used in place of a Lyot loop filter. Since the free spectral range of the resultant optical comb is governed by the path length difference in the Mach-Zehnder interferometer, a variable optical delay line can be used to tune the optical comb which in turn tunes the frequency of the passband continuously. While the Mach-Zehnder interferometer provides good tunability, the number of passband resulted is less (i.e. more Mach-Zehnder interferometer is needed to be cascaded to achieve the same amount of passband in the Lyot loop filter approach). By combining both Mach-Zehnder interferometer and Lyot loop filter in the design, a high-passband count RF filter with continuous tuning capability can be achieved [30].

3. MULTIBAND RF FILTER WITH HETEROGENEOUS PASSBAND PROPERTIES

In the above demonstrations, high-passband count multiband RF filter has been successfully achieved with good tunability and reconfigurability. However, all the passbands are having the same spectral profile, i.e. Gaussian, which is determined by the Gaussian optical filter for weighting all the optical comb. This conventional RF filter design process propose a major limitation to the resultant RF filter, that all the passband properties (i.e. shape, bandwidth, group delay) will always be the same among the same RF filter because the optical combs that governs the RF passband properties are shaped by the same shaping filter. This limitation is highly undesired in emerging multiband RF system because modern RF systems carry heterogeneous traffic that have different spectral properties. Therefore, a new design algorithm that enable independent control of passband properties is essential to support dynamic and heterogeneous multiband RF systems.

Recently, a programmable microwave photonic multiband filter with full control of amplitude, frequency, bandwidth, group delay slope, and spectral shape of each passband has been proposed and experimentally demonstrated [31]. The filter is based on a new design algorithm that consider each RF passband as an individual, such that the optical comb parameters of each passband are designed independently using inverse Fourier transform approach and filter design rules. Cosine functions of the optical combs for spectral slicing the broadband light source are first mathematically superimposed (i.e. interleaving) such that a final slicing function is achieved. Through the control of each cosine function based on the RF filter requirement, passband properties including frequency, amplitude, bandwidth, spectral shape, and group delay slope can be individually controlled amount each passband. The principle and results of this heterogeneous multiband RF filter will be discussed in the following sections.

3.1 Principle and Experimental Setup

To achieve independent control of passband properties, the same multiband RF filter architecture as shown in Figure 1(a) is used [31]. However, the Gaussian filter and the optical comb filter is replaced by a programmable optical spectral slicer that is controlled by the design algorithm that we developed, as illustrated in Figure 5.

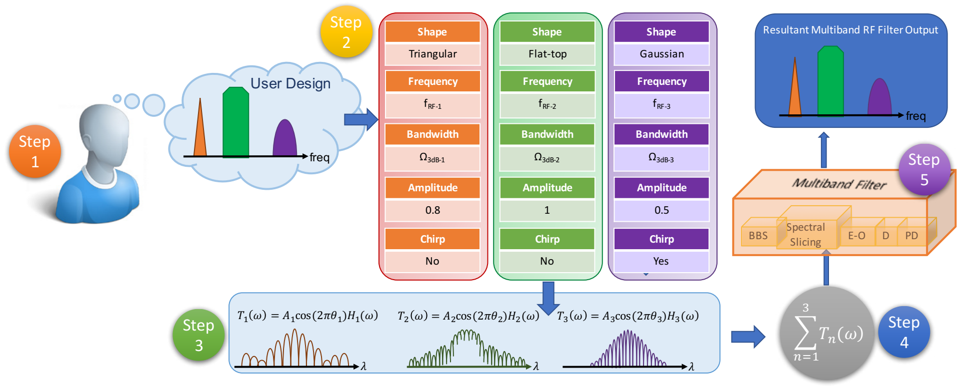

Figure 5: Illustration of the proposed multiband filter design algorithm. BBS: broadband source; E-O: electro-optical modulator; D: dispersive medium; PD: photodetector.

The design algorithm has five steps: Step 1: Determine the desired frequency response of the multiband filter by user. Step 2: Design the parameters of each passband individually including frequency, amplitude, bandwidth, shape, and group delay slope. Step 3: Generate the corresponding shaped cosine function for each passband based on inverse Fourier transform and microwave photonic filter design rules. Step 4: Combine all the shaped cosine function into one single final shaping function. Step 5: Control the programmable spectral slicing device in the multiband filter using the final shaping function. Since the parameter of the passbands are designed and generated individually, it is possible to tailor the desired parameters for each passband.

3.2 Heterogeneous and Independently Controllable Passband Properties

To achieve independent control of passband properties, it is important to understand the relationship between the desired RF spectral parameters and the corresponding optical comb parameters. To decrease the passband bandwidth, the corresponding optical comb envelope bandwidth should be increased. Figure 6(a) shows a four-passband RF filter with individually tunable passband bandwidth. To change the spectral shape of the passband, we will need to take the inverse Fourier transform of the desired RF spectral shape and use it to shape the optical comb. Figure 6(b) shows a three-passband RF filter with mixed passband shape of Gaussian, triangular, and flat-top. To introduce non-zero group delay slope to each of the passband, a chirped optical comb is needed instead of the one with fixed free spectral range. A chirping coefficient is incorporated into the cosine shaping function, such that optical comb with gradually changing comb spacing can be achieved, as shown in Figure 6(c). Group delay slope can be applied to passband of the same bandwidth as well as passband of different bandwidth, as shown in Figure 6(d).

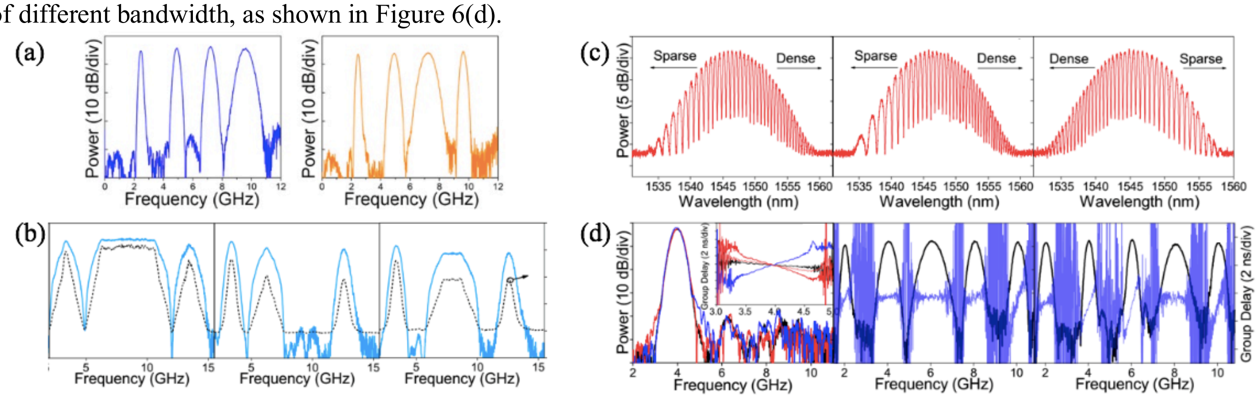

Figure 6: Multiband RF filter with independent control and heterogeneous spectral properties. (a) Tunable bandwidth; (b) Mixed spectral shape; (c) Chirped optical comb; (d) Independent control of group delay slope among different passbands [31].

The above multiband filter design algorithm facilitates fully and individually tuning capability in a multiband RF filter. Spectral shape for each passband can be independently reconfigured, passband bandwidth can be tuned by 278%, and both the amplitude and frequency of each passband can also be tuned independently by 40 dB over a 10 GHz frequency band. In addition, the group delay slope of each passband can be tuned individually over a range of ±4.5 ns/GHz [31].

3.3 Discussion

Although optical frequency comb based RF filter schemes has a number of inherent advantages including continuous frequency tuning, high speed switching, high-passband count, for achieving RF filter, the use of an interferometric comb filter for slicing the optical taps proposed a major limitation to multiband RF filter design – the inability to achieve individual spectral properties control for each passband. While we have to sacrifice the continuously tuning capability due to the programmable nature of the optical spectral slicer, the introduction of new design algorithm and a programmable optical spectral slicer provide one significant advantage - all the parameters in each of the passband can be individually controlled and tuned, including passband shape, bandwidth, frequency, amplitude, and group delay slope. This is a major breakthrough to support multiband RF system where dynamic multi-function applications with different quality of service can be supported.

4. TUNABLE AND RECONFIGURABLE WIDEBAND RF SHAPING

Looking beyond channel-by-channel RF filtering, another type of RF spectral processing device that is essential to wideband RF systems is a RF equalizer or RF shaper. Operation bandwidth of modern microwave system is getting wider due to the data intensive applications that wireless systems are supporting. Unfortunately, the wide operation bandwidth also leads to degradation in frequency response uniformity of both RF components and transmission medium, which in turn severely deteriorate the transmission performance. The situation becomes more problematic when the transmission channel is dynamic, where the frequency response uniformity changes over time. Therefore, it is essential to have a tunable and reconfigurable RF shaper to dynamically manipulate the whole RF spectrum for compensating the undesired channel characteristic and to tailor the transmission channels for optimizing system performance.

RF electronic based RF equalizer is based on a combination of bandpass filter, notch filters, tunable attenuators, and RF switches, which is only capable of achieving basic shaping functions including linear compensation slopes and parabolic functions. Furthermore, most of the resultant spectral shaping functions are either fixed or with limited amplitude and compensating slope tunability over a narrow bandwidth through the adjustment of attenuation coefficient. The inaccurate spectral compensation and lack of tunability in RF electronic based schemes limit it efficiency to dynamically manipulate and compensate undesired RF spectral response over a wide spectral bandwidth. Using photonic approaches, parabolic function can easily be achieved using a single passband filter. However, most photonic based RF filter does not have the ability to tune its spectral parameter freely, not to mention to dynamically manipulate the RF spectrum over a wide bandwidth of several of GHz to tens of GHz range.

4.1 Photonic based Reconfigurable and Tunable RF Shaper

Recently, we have demonstrated a reconfigurable RF spectral shaper [32] using photonics that is capable of achieving a large variety of tunable spectral functions including positive and negative slopes, parabolic and inverted-parabolic functions, low-pass and notch responses, linear attenuation and tunable floor, as well as triangular and saw-tooth functions. The uniqueness of the demonstrated RF spectral shaper is its multi-spectral point control, reconfigurability between various spectral functions, and its high-precision tunability.

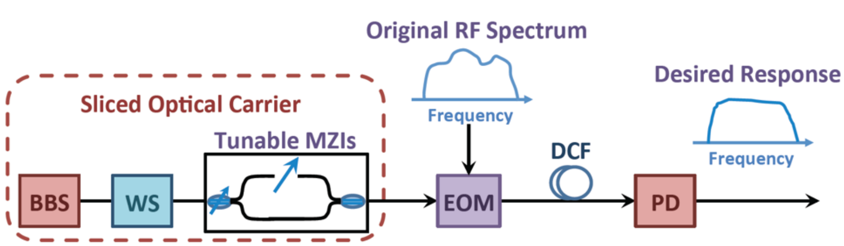

Figure 7: Experimental setup of the reconfigurable RF spectral shaper. BBS: broadband light source; WS: optical spectral slicer; MZI: Mach-Zehnder interferometer; EOM: electro-optics modulator; DCF: dispersive element; PD: photodetector or balanced photodetector.

Figure 7 illustrates the architecture of the RF spectral shaper [32], which has a similar architecture as the multiband RF filter in section 2.1. In the RF spectral shaper, cascaded tunable Mach-Zehnder interferometers are used as the spectral slicer and an optical spectral shaper is used for weighting the envelope of the optical comb. Therefore, the number and frequency of spectral control points are controlled by the tunable Mach-Zehnder interferometers, the spectral profile of each spectral control point is governed by the optical spectral slicer. Figure 8(a) shows an overview of most spectral functions the proposed RF spectral shaper can achieve [32], including positive and negative slopes, parabolic and inverted-parabolic functions, low-pass responses, and triangular function. By setting the number of spectral control points to four, a saw-tooth shaping function can be achieved as shown in Figure 8(b). Four spectral control points is generated using four interleaving optical combs with different comb spacing that are corresponding to the spectral point frequency. The optical comb is weighted by a Sinc-square function to achieve the resultant saw-tooth function in the RF domain. To increase the comprehensiveness of the spectral functions supported by the RF spectral shaper, an all-pass branch is added in parallel with the bandpass branch before photodetection such that addition or subtraction between the bandpass branch and all-pass branch can be performed to achieve notching function and tunable floor function. Figure 8(c) shows the all-pass response (black solid curve), and the resultant spectral response when it is added (color solid curve) or subtracted (pink dashed curve) from the bandpass branch. It is worth to notice that all the spectral shaping curves are tunable in terms of slope, frequency, and bandwidth. Figure 8(d) shows an example of low pass response with tunable bandwidth.

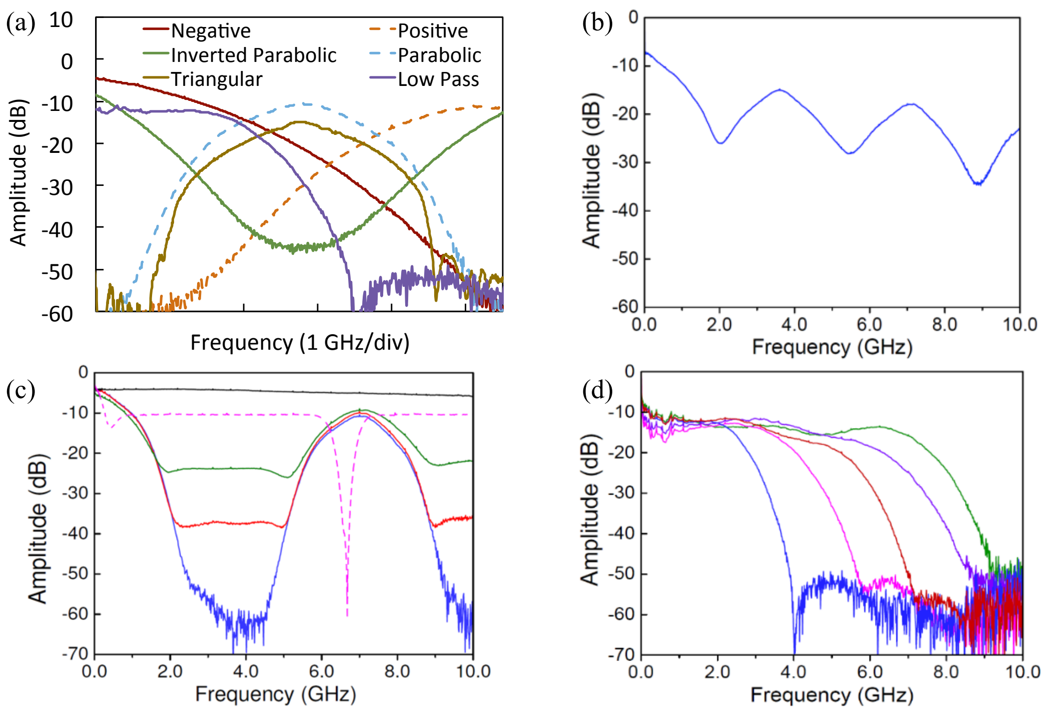

Figure 8: Measured frequency response of the RF spectral shaper. (a) Examples of achievable spectral functions; (b) Saw-tooth function (four spectral control points); (c) With the addition of an all-pass branch, notch function and tunable floor functions can be achieved; (d) Low-pass response with tunable bandwidth.

4.2 Discussion

The demonstrated RF spectral shaper provides a reconfigurable, high-precision, and multi-point spectral shaping solution to tailor and manipulate the RF spectrum. Unlike RF electronics, photonics provides high flexibility to reconfigure the desired spectral shaping function without the need to switch hardware. The large variety of reconfigurable and tunable shaping functions demonstrated above are essential to support dynamic and adaptive RF systems. Furthermore, shaping the RF spectrum in the RF spectral domain using photonic approach results in a higher resolution than shaping the RF spectrum in the optical spectral domain – which is limited by the optical spectral resolution. The cascaded tunable Mach-Zehnder interferometer provides multi-point spectral control for precise RF spectral tailoring – a maximum of 13 spectral control points can be achieved with three cascaded Mach-Zehnder interferometers.

SUMMARY AND DISCUSSION

This paper reviewed our recent development of reconfigurable wideband and multiband RF spectral processing devices, including (i) High passband count multiband RF filter with reconfigurable passbands (ii) Multiband RF filter with high speed switchable passband (iii) Multiband RF filter with heterogeneous spectral properties, and (iv) Wideband RF spectral shaper with tunable and reconfigurable spectral functions. Dynamic spectral processing devices are essential to support data intensive applications like 5G networks, data-driven physical weaponry, and multi-function RF systems. As the capacity of RF channel has been exponentially increased over the last decade, bandwidth of emerging RF signal could span over hundreds of MHz to GHz, proposing a major challenging in processing and optimizing such a wideband signal. Turning to photonics for a solution – high-passband count multiband RF filter enable RF system to support multi-function applications and the high-speed reconfigurability allow fast adaptation to a dynamic transmission environment. While heterogeneous and individually customizable spectral properties allow heterogeneous quality of service being supported by the RF system. Furthermore, wideband RF spectral tailoring and manipulation can effectively compensate the uneven frequency response of wideband RF transmission medium and to guarantee consistence and reliable performance. Although moving spectral processing from the wireless to the photonics domain does not relieve some of the shaping and filtering requirements (specifically, spectral resolution, amplitude tuning, and frequency tunability) and may have to sacrifice RF power and linearity during electrical--to--optical conversion, photonics is still a more promising solution because it supports other desirable filtering and shaping properties, such as complex shaping functions, tunability, and shaping function reconfigurability.

REFERENCE

[1] Hueber, G. and Staszewski, R. B., [Multi-mode/Multi-band RF transceivers for wireless communications: Advanced techniques, Architectures, and Trends], John Wiley & Sons (2011).

[2] Mitola, J., "Cognitive radio for flexible mobile multimedia communications. Mobile Multimedia Communications," IEEE International Workshop, 3-10 (1999).

[3] Molisch, A. F., [Wireless communications], John Wiley & Sons (2007).

[4] Cavalier, M. D. and Shea, D., "Antenna system for multi-band satellite communications. MILCOM 97 Proceedings," 276-280 (1997).

[5] Byrnes, A., Pant, R., Li, E., Choi, D.-Y., Poulton, C.G., Fan, S., Madden, S., Barry, L.-D., and Eggleton, B.J. "Photonic chip based tunable and reconfigurable narrowband microwave photonic filter using stimulated Brillouin scattering," Opt. Exp. 20(17), 18836-18845 (2012).

[6] Marpaung, D., Morrison, B., Pagani, M., Pant, R., Choi, D.-Y., Barry, L.-D., Madden, S.J., and Eggleton, B.J., "Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity," Optica 2(2), 76-83 (2015).

[7] Supradeepa, V.R., Long, C.M., Wu, R., Ferdous, F., Hamidi, E., Leaird, D.E., and Weiner, A.M., "Comb-based radiofrequency photonic filters with rapid tunability and high selectivity," Nat. Photonics 6, 186-194, (2012).

[8] Mora, J., Ortega, B., Diez, A., Cruz, J.L., Andres, M.V., Capmany, J., and Pastor, D., "Photonic microwave tunable single-bandpass filter based on a Mach-Zehnder interferometer," J. Lightwave Technol. 24(7), 2500-2509, (2006).

[9] Kim, H.-J., Leaird, D.E., and Weiner, A.M., "Rapidly tunable dual-comb RF photonic filter for ultrabroadband RF spread spectrum applications," IEEE Trans. Microw. Theory Tech. 64(10), 3351-3362, (2016).

[10] Gao, L., Zhang, J., Chen, X., and 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. 62(2), 380-387, (2014).

[11] Fok, M.P. and Ge, J., "multiband microwave photonics filters," MDPI Photonics: Special Issue – Microwave Photonics 4, (2017).

[12] Yao, J. P., "Microwave photonics," J. Lightwave Technol. 27(3), 314-335 (2009).

[13] Capmany, J., Mora, J., Gasulla, I., Sancho, J., Lloret, J., and Sales, S., "Microwave photonic signal processing," J. Lightwave Technol. 31(4), 571-586 (2013).

[14] Lin, Y. S., Liu, C. C., Li, K. M., and Chen, C. H., "Design of an LTCC tri-band transceiver module for GPRS mobile applications," IEEE Trans. Microw. Theory Techn. 52(12), 2718-2724 (2004).

[15] Liou, C. Y., and Mao, S. G., "Triple-band marchand balun filter using coupled-line admmittance inverter technique," IEEE Trans. Microw. Theory Techn. 61(11), 3846-3852 (2013).

[16] Lin, S. C., "Microstrip dual/quad-band filters with coupled lines and quasi-lumped impedance inverters based on parallel-path transmission," IEEE Trans. Microw. Theory Techn. 59(8), 1937-1946 (2011).

[17] Chen, C. F., Huang, T. Y., and Wu, R. B., "Design of dual-and triple-passband filters using alternately cascaded multiband resonators," IEEE Trans. Microw. Theory Techn. 54(9), 3550-3558 (2006).

[18] Lin, Y. C., Horng, T. S., and Huang, H. H., "Synthesizing a multiband LTCC bandpass filter with specified transmission-and reflection-zero frequencies," IEEE Trans. Microw. Theory Techn. 62(12), 3351-3361 (2014).

[19] Luo, S., Zhu, L., and Sun, S., "Compact dual-mode triple-band bandpass filters using three pairs of degenerate modes in a ring resonator," IEEE Trans. Microw. Theory Techn. 59(5), 1222-1229 (2011).

[20] Jiang, Y., Shum, P.P., Zu, P., Zhou, J., Bai, G., Xu, J., Zhou, Z., Li, H., and Wang, S., "A selectable multiband bandpass microwave photonic filter," IEEE Photonics J. 5(3), 5500509, (2013).

[21] Mora, J., Chen, L.R., and Capmany, J., "Single-bandpass microwave photonic filter with tuning and reconfiguration capabilities," J. Lightwave Technol. 26(15), 2663–2670, (2008).

[22] Ge, J. and Fok, M. P., "passband switchable microwave photonic multiband filter," Sci. Rep 5, 15882, (2015).

[23] Ge, J., James, A., and Fok, M. P., "Simultaneous 12-passband microwave photonic multiband filter with reconfigurable passband frequency," Optical Fiber Communication Conference and Exposition, W1G.2 (2016).

[24] Ge, J. and Fok, M. P., "Frequency band selectable microwave photonic multiband bandpass filter based on Lyot filter," OSA Conference on Lasers and Electro-Optics, STh3F.2 (2015).

[25] Ge, J. and Fok, M. P., "Optically controlled fast reconfigurable microwave photonic dual band filter based on nonlinear polarization rotation", IEEE Trans. Microw. Theory Tech. 65(1), pp. 253 – 259, (2017).

[26] Ge, J., Mathews, A., James, A., and Fok, M. P., "Optically controlled microwave photonic dual-band filter with ultrafast reconfigurable capability," OSA Conference on Lasers and Electro-Optics, STh1F.6 (2016).

[27] Fu, S., Wang, M., Zhong, W.D., Shum, P., Wen, Y.J., Wu, J., and Lin, J., "SOA nonlinear polarization rotation with linear polarization maintenance: Characterization and applications," IEEE J. Sel. Top. Quantum Electron. 14(3), 816–825 (2008).

[28] Lee, K.L., Fok, M.P., Wan, S.M., and Shu, C, "Optically controlled Sagnac loop comb filter," Opt. Exp. 12(25), 6335–6340 (2004).

[29] Ge, J. and Fok, M. P., "Continuously tunable and reconfigurable microwave photonic multiband filter based on cascaded MZIs," IEEE Photonics Conference, WA.1. (2017).

[30] Ge, J. and Fok, M. P., "Reconfigurable RF multiband filter with widely tunable passbands based on cascaded optical interferometric filters," J. Light. Technol. 36(14), 2933 – 2940 (2018).

[31] Liu, Q., Ge, J., and Fok, M. P., "Microwave photonic multiband filter with independently tunable passband spectral properties," Opt. Lett., 43(22), 5685-5688 (2018).

[32] Ge, J., Garon, D., Liu, Q., and Fok, M. P., "Reconfigurable microwave photonic spectral shaper," Optical Fiber Communication Conference and Exposition, W2A.36, (2019).