Reconfigurable microwave photonic spectral shaper

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Abstract: *A reconfigurable RF spectral shaper for dynamic wideband frequency component manipulation is experimentally demonstrated. Spectral functions including positive and negative slopes, low-pass, parabolic, inverted-parabolic functions, as well as triangular and saw-tooth functions have been achieved.*

OCIS codes: (060.5625) Radio frequency photonics; (350.4010) Microwaves; (070.2615) Frequency filtering.

1. Introduction

Modern RF system is the backbone of data intensive applications like 5G networks, data-driven physical weaponry, and multi-function RF systems, which occupy a wide bandwidth in the RF spectrum and have dynamic operation condition, making it challenging to transmit and process the information using electronics. Therefore, novel system that has the capability to dynamically manipulate a wide spectral bandwidth is essential. As the operation bandwidth increases, frequency response of the RF channel and the associated RF components are non-uniform, therefore, it is important to dynamically equalize and balance the non-uniform frequency response of wideband RF components and transmission medium to guarantee consistence and reliable performance [1]. Although the capability to flexibly manipulate a wide range of RF spectral components is extremely desired, spectral shaping using RF electronics is impossible due to its tight design criteria to satisfy a wide range of frequency range as well as its limited tuning and reconfiguring abilities. Therefore, RF electronics can only provide very limited shaping functions and can hardly be tuned, such as limited gain slope control, bandpass filtering, and pulse superimposing [2]. In recent years, microwave photonic (MWP) signal processing has brought significant improvements and breakthroughs in a wide range of RF signal processing, due to its unique properties including ultra-wide bandwidth operation, high tunability, and fast switching capability. Although microwave photonic filters have been studied intensively over the last decade, all the approaches are focusing on filtering of individual channel using fixed profile [3-6]. There is no research on the dynamic manipulation of the RF spectrum over a wide bandwidth of several of GHz to tens of GHz due to the lack of tunability and reconfigurability in the MWP filter design.

In this paper, for the first time, a reconfigurable RF spectral shaper based on MWP technique is proposed and demonstrated. Various spectral functions including positive and negative slopes, parabolic and inverted-parabolic functions, low-pass response, as well as triangular and saw-tooth functions have been achieved. Besides performing different spectral functions, the RF spectral shaper can be used for RF pulse shaping through direct manipulation of the pulse's RF spectrum. The proposed RF spectral shaper is based on an alternated architecture of a passband switchable MWP multiband filter that we previously demonstrated [7,8]. Since RF spectral shaping requires multiple spectral control points to achieve the desired spectral shape, conventional tunable MWP single-bandpass filter approaches which limited to basic filtering functions will not serve the purpose. A reconfigurable RF spectral shaper must cover a wide frequency range, have multiple spectral control points, and able to flexible tuned to achieve reconfigurable spectral shaping. The demonstrated reconfigurable RF spectral shaper has 4 independent spectral control points, 40 dB dynamic amplitude control, and customizable frequency control across a 10 GHz bandwidth, for achieving various wideband and flexible spectral shaping curves. The RF spectral shaper has been used for dynamically shaping of RF pulse through the manipulation of the RF spectrum of the pulse.

2. Principle and Experimental Setup

Figure 1 shows the experimental setup of the proposed reconfigurable RF spectral shaper, which is based on a finite impulse response (FIR) design with multiple tunable spectral control points. A superluminescent diode is used as the broadband light source which is shaped by an optical waveshaper for adjusting the overall profile of the optical

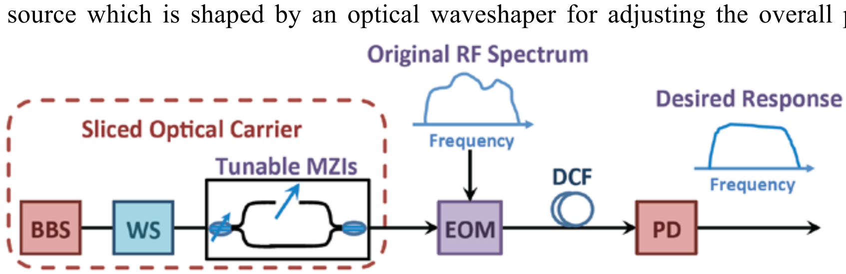

Fig. 1. Experimental setup of reconfigurable MWP spectral shaper. BBS: broadband source; WS: waveshaper; MZI: Mach-Zehnder interferometer; EOM: electro-optic intensity modulator; DCF: dispersion compensating fiber; PD: photo-detector.

carriers. The waveshaper has a spectral resolution of 10 GHz, which is good enough to shape the overall profile of the optical carriers, however, it is not fine enough for generating the optical carriers needed for the desired FIR. Therefore, the shaped broadband light source is spectrally sliced by a cascaded Mach-Zehnder interferometer (MZI) such that a multi-wavelength optical carrier is generated. Each MZI consists of a tunable delay line and a tunable coupler, such that both the comb spacing and the extinction ratio of the MZI can be adjusted. As a result, the cascaded MZI can generate optical comb with multiple interleaving comb spacing. Then, the input RF signal is modulated onto this optical carrier through an electro-optic intensity modulator. A piece of dispersion compensating fiber (DCF) is used to provide a constant time delay between each optical carrier wavelength, i.e. taps. In other words, the weight of each FIR taps is governed by the waveshaper, while the delay is governed by the dispersion of the DCF. The optical signal is then converted back to an RF signal using a photodetector. The FIR parameters of the system are designed such that a desired RF spectral shape can be resulted for shaping the RF channel or an RF signal. Since the spectral shaper is highly reconfigurable, arbitrary shaping of the input RF pulses can be achieved.

Arbitrary spectral shaping in RF domain requires the capability of manipulating the RF frequency components over a wide frequency range, therefore, multiple spectral control points are needed in the spectral shaper. The multiple spectral control points in the spectral shaper are achieved by generating high-order optical frequency comb with multiple simultaneous comb spacings in the cascaded MZIs. The center frequency of each spectral control point (Ω_0) is determined by the comb spacing ($\Delta\omega$) of the optical frequency comb, as

$$\Omega_0 = \frac{2\pi}{\beta_2 L_D \Delta\omega} \tag{1}$$

where β_2 and L_D are the group velocity dispersion and length of the DCF. 3-dB bandwidth of the generated spectral point is determined by equation (2), which can be controlled by the total bandwidth of the optical carrier ($\delta\omega$).

$$\delta\Omega_{3dB} = \frac{\sqrt{8ln2}}{\beta_2 L_D \delta\omega} \tag{2}$$

When a high-order optical frequency comb with various comb spacings is used as the optical carrier, multiple RF transmission peaks are generated at the same time [7,8]. In the proposed setup, two cascaded MZIs are used such that four different RF transmission peaks are generated. The comb spacing ($\Delta\omega$) of the MZI is determined by the path difference ($\Delta\tau$) in the MZI, while the extinction ratio of the comb is determined by the coupling ratio (α) between the two branches. Here, transmission function of each tunable MZI is expressed as T_i,

$$T_i(\omega) = (1-\alpha_i)^2 + \alpha_i{}^2 - 2\alpha_i(1-\alpha_i)\cos(\omega\Delta\tau_i) \tag{3}$$

Since the time delays in the MZIs are tunable, center frequencies of all the spectral control points can be tuned. Furthermore, by controlling the coupling ratio of the tunable coupler in each MZI, amplitudes of each of the spectral control points are also adjustable. Inverse Fourier transform is performed to precisely tailor and modify the overall amplitude and phase of the optical carrier for the generation of the desired reconfigurable wideband RF profiles.

3. Results and Discussion

Relationship between the optical carrier and the resultant RF spectral profile can be demonstrated by configuring the optical carrier to have a Sinc-square profile (shaped by the waveshaper) and optical comb spacing of 0.2 nm (spectrally sliced by the cascaded MZI). Figure 2(a) shows a Sinc-square shaped optical spectrum will result in a triangular RF profile in linear scale (Fig. 2(a) inset). When four interleaved optical combs with different comb spacing are generated from the cascaded MZI and a Sinc-square profile is used, a saw-tooth-like frequency response is generated (Fig. 2(b)), which is a composition of four triangular profiles. Instead of shaping the RF spectrum in optical domain, which is limited by the resolution of the waveshaper (~10 GHz), high spectral resolution shaping function is realized by the highly reconfigurable RF frequency response of the proposed RF spectral shaper. Figure

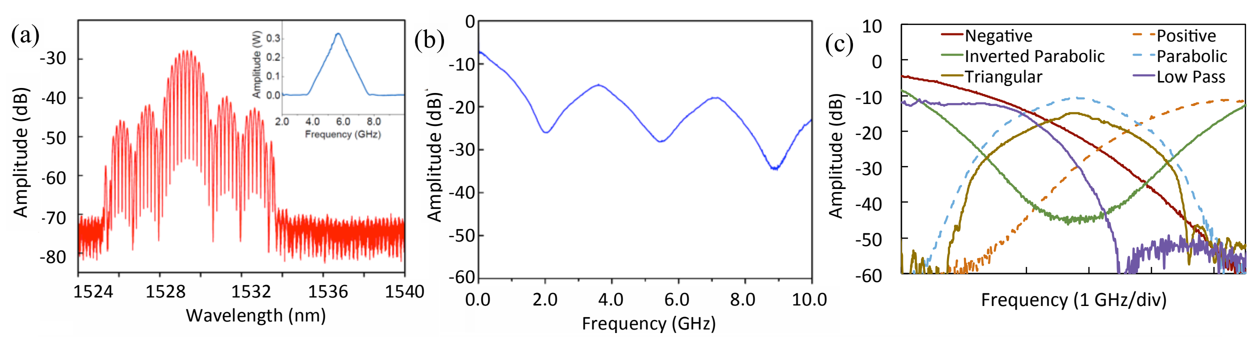

Fig. 2. (a) Optical frequency comb with Sinc-square profile. Inset: corresponding triangular frequency response. (b) The system is reconfigured into a saw-tooth-like frequency response. (c) Various spectral functions achieved by the RF spectral shaper.

2(c) shows the spectral functions that the RF spectral shaper can achieved, which include positive and negative slopes, parabolic and inverted-parabolic functions, low-pass function, as well as triangular and saw-tooth functions.

To generate a negative slope equalization curve, spectral control point with a Gaussian or triangular profile is generated such that the right portion of the profile is served as the negative equalization curve. A triangular profile is used to generate a positive slope equalization curve, center frequency of the triangular profile is set to the highest frequency of the frequency range of interest, such that the left portion of the profile serves as the positive equalization curve. Parabolic shaped compensation curves can be generated by the design of a Gaussian profile at the spectral shaper. inverted-half-sine parabolic can be achieved through the combination of two Gaussian profiles at two spectral control points. While low-pass response with tunable bandwidth is implemented by two spectral control points and both with Gaussian profile, i.e. one centered at 0 GHz and one centered at a higher frequency.

Besides shaping the frequency response of an RF system or RF channel, the proposed RF spectral shaper is capable of RF pulse shaping. To demonstrate RF pulse shaping capability of the proposed RF spectral shaper, a 125 Mbit/s square-like pulse train is used as the input RF signal and is launched into the RF spectral shaper for reshaping. The original waveform and RF spectrum are shown in Fig. 3(a). To shape the square-like pulse into a Gaussian pulse, the RF spectral shaper is configured into a low-pass response with a Gaussian profile and cut off frequency at 1 GHz, as shown in Figure 3(b). The resultant RF pulse is now reshaped into a Gaussian pulse, as shown in Fig. 3(b) inset. Next, we reconfigured the RF spectral shaper to reshape the square-like pulse into a triangular pulse, by setting the RF spectral profile into a saw-tooth-like function. The waveshaper is then set to have a Sinc-square profile while the cascaded MZI is set to have 4 interleaving comb spacings. Figure 3(c) inset shows the resultant shaped triangular pulse, while the corresponding RF spectrum is shown in Fig. 3(c). Four spectral control points are used at the same time to shape the RF spectrum into a Sinc-square profile. Insertion loss of the RF spectral shaper is about 4 to 10 dB depending on the frequency, which can be compensated through optical amplification. As a result, the noise floor of the reshaped waveforms is 5 dB higher than the original RF input.

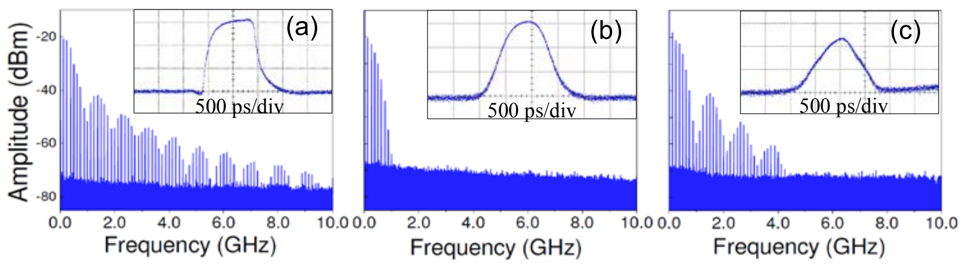

Fig. 3. Demonstration of arbitrary pulse shaping using the proposed RF spectral shaper. (a) RF spectrum of the original square-like pulse (b) Reshaped to a Gaussian pulse. (c) Reshaped to a triangular pulse. Insets: Time domain pulse profiles.

4. Conclusion

A highly reconfigurable RF spectral shaper with multiple spectral control points is experimentally demonstrated based on cascaded tunable MZI architecture. The spectral control points are reconfigurable in terms of frequency, amplitude, and spectral profile, such that various spectral functions including positive and negative slopes, parabolic and inverted-parabolic functions, low-pass function, as well as triangular and saw-tooth functions can be achieved. The proposed spectral shaper can be used for tailoring the frequency response of RF systems and RF channels, as well as manipulating spectrum of RF signals. The demonstrated capability of the RF spectral shaper to manipulate a wide range of RF spectrum making it a powerful tool for emerging dynamic microwave and wireless systems.

Acknowledgment

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