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Research progress of on-chip linearization methods for microwave photonic systems

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ABSTRACT

In this paper, we reviewed and presented our latest progress of linearization methods for microwave photonic systems based on programmable photonic circuits, including the linearization in microwave photonic transmission links and programmable functional circuits.

Keywords: Microwave photonics, photonic integrated circuit, on-chip linearization, optical spectrum shaping

1. INTRODUCTION

Communication, radar, and electronic reconnaissance systems are developing towards higher communication speed, wider detection range, and more complicated frequency agility receiving, which requires RF front-ends that can work in wide bandwidth, multi-band, and be reconfigurable[1-3]. Microwave photonic (MWP) systems upconvert the microwave signal to the optical domain via a modulator and use photonic devices to process microwave signal, which can achieve flexible processing of wideband microwave signal[4,5]. However, the nonlinear properties of the modulator and photodetector introduce nonlinear distortion to the system, which degrades the fidelity of the signal and the linearity and spurious free dynamic range (SFDR) of the system.

Plenty of studies have been carried out to improve the linearity of the MWP links and systems. Some create an auxiliary path to make the third-order intermodulation (IMD3) terms generated from two paths can cancel each other[6]. Another way to linearize MWP systems is by direct shaping modulated optical spectrum to reduce the IMD3 terms[7-11]. By processing the phase and amplitude of multi-order sidebands in the modulated optical spectrum, the IMD3 components from beating products between different frequency components in the optical spectrum can interfere destructively. However, currently, most of the works are implemented via discrete devices which are bulky and complicated, and only a few studies have implemented the linearization processing in MWP functional systems.

In this paper, we reviewed our recent research progress on on-chip linearization in MWP systems. We first present two linearized MWP transmission links using reconfigurable photonic circuits. Then we present a reconfigurable MWP filter with a high dynamic range, which achieves simultaneous programmable filtering and linearization in one photonic circuit. At last, we present a reconfigurable integrated MWP circuit with a high dynamic range that can perform both filtering and phase-shifting functionalities. The aim of our work is to unify the photonic integration, advanced functionality, reconfigurability, and high RF performance which are still fragmented.

2. LINEARIZED MWP LINKS

A linearized MWP link based on a serial spectral shaping scheme is demonstrated in Fig. 1[8]. The light wave is modulated by a two-tone RF signal via a phase modulator, generating an optical spectrum with multi-order optical sidebands. After amplification, the optical signal is sent to four cascaded ring resonators for spectral shaping. The ring resonator can impose 90 degrees phase shift at the optical carrier for PM-IM conversion so that the fundamental RF signal can be direct detected at the photodetector (PD) with IMD3 terms. To suppress the IMD3 terms, proper phase and amplitude manipulation need to be imposed on the optical carrier and the second-order optical sidebands via ring resonators. In this way, the IMD3 terms generated from the beating between different optical sidebands can be added destructively after photodetection. An

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experiment is carried out to verify the proposed method. As shown in Fig.1 (b) and (c) when the optical carrier and the second-order optical sidebands are properly tailored the fundamental to IMD3 ratio is improved from 32.6 dB to 55 dB. The decreasing of fundamental power is because of the partial PM-IM conversion as the phase shift at the optical carrier is 340.5 degrees when the linearization requirement is satisfied. This can be compensated by increasing the output power of the erbium-doped fiber amplifier (EDFA).

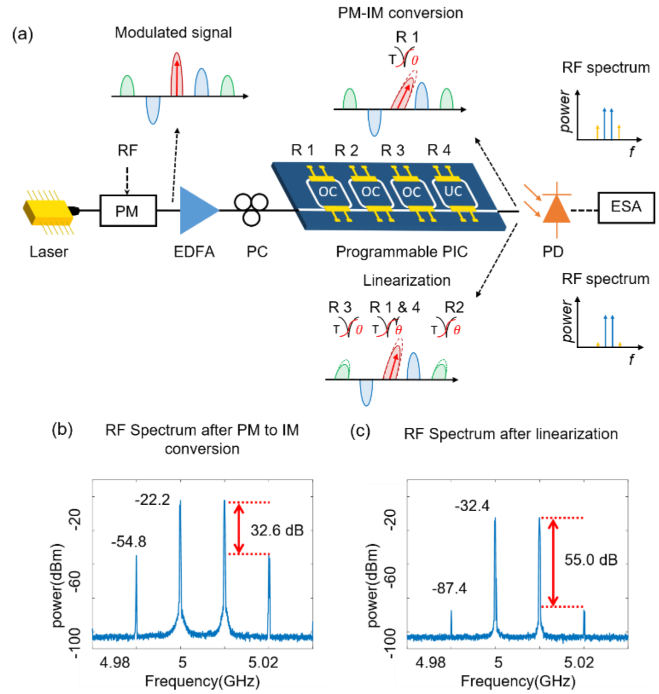

Fig.1 A linearized MWP link based on serial spectral shaping [8] (a) schematic of the proposed MWP link. (b) RF spectrum without linearization (c) RF spectrum with linearization

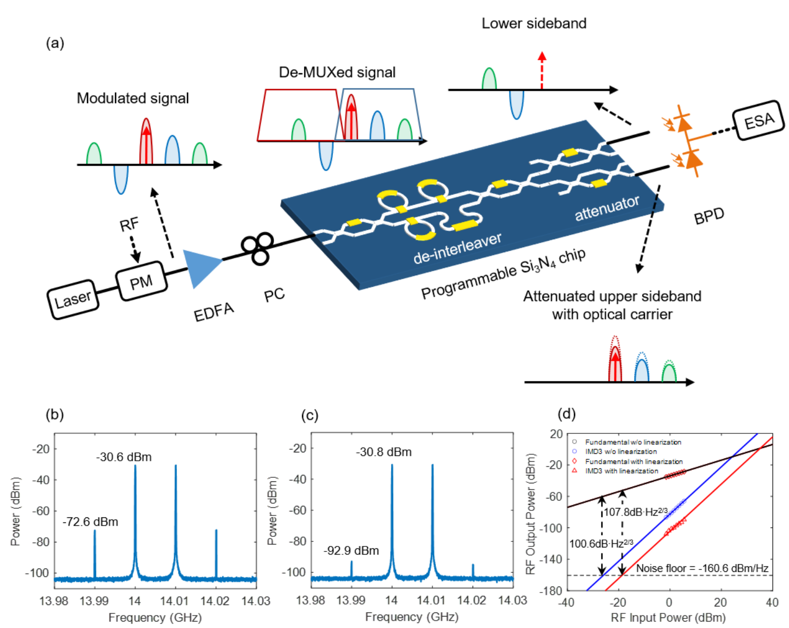

Fig.2 A linearized MWP link based on parallel spectral shaping [9] (a) schematic of the proposed MWP link. (b) RF spectrum without linearization (c) RF spectrum with linearization (d) SFDR of the proposed MWP link

The linearized MWP link depicted in Fig. 2 is based on parallel spectral shaping[9]. The phase-modulated optical signal is sent to a programmable photonic chip for processing. The photonic chip consists of a de-interleaver and two attenuators. The de-interleaver, exhibiting a complementary flat-top filter response, separates the optical signal into two paths. One consists optical carrier with upper sidebands, the other consists the lower sidebands. The attenuation imposed on these two paths is adjusted to make the IMD3 terms generated in each path have the same amplitude. In this way, the IMD3 can be canceled when the optical signal is recombined at the balanced photodetector (BPD). In the experiment, the IMD3 terms are suppressed by 20.3 dB. The SFDR of the link is improved from 100.6 dB·Hz$^{2/3}$ to 107.8 dB·Hz$^{2/3}$ with a measured noise floor of -160.6 dBm/Hz. As the optical carrier lies in the passband of the de-interleaver and is processed by an attenuator with a flat response, the intensity noise converted from the phase noise of the laser is less than the serial scheme, where the optical carrier is aligned at the slop of the amplitude response of the ring resonator. This makes the parallel spectral shaping shows a better performance in SFDR.

3. HIGH DYNAMIC RANGE MWP FILTER

In the previous work, linearization is implemented in the MWP transmission link, however, the combination of integration, functionality, and linearization is still elusive. We further studied the linearization method in a programmable MWP circuit to achieve simultaneous programmable functions and linearization in the same photonic chip[10]. The photonic chip in our scheme has a unique combination of a modulation transformation (MT) device[12] and a double-injected ring resonator (DI-RR)[13], as shown in Fig, 3 (a). The MT consists of a de-interleaver, attenuator, and phase shifter, which can generate arbitrary relative phase and amplitude relations between two optical sidebands. The DI-RR is a programmable ring resonator that can generate plenty of filtering responses with different shapes. With the combination of MT and DI-RR, we achieve an MWP filter that can be switched between bandpass response and notch response with record-low NF by implementing low biasing in an intensity modulation link. And we achieved a notch filter with ultra-high SFDR in a phase modulation link.

To implement linearization in the MWP notch filter, the MT generates asymmetric double sidebands optical spectrum with anti-phase relation. The amplitude and phase of the optical carrier and multi-order sidebands are properly manipulated to meet the linearization condition so that the IMD3 can be suppressed after photodetection. The DI-RR is used to filter the first-order optical sideband to create a notch filter based on phase cancellation[14]. In this way, the MWP notch filter and linearization are achieved simultaneously. The experimental setup is illustrated in Fig.3 (a). The proposed notch filter shows a deep rejection of over 55 dB as shown in Fig.3 (b). After linearization the IMD3 is reduced by 29 dB, leading to an enhanced SFDR of 123 dB·Hz$^{4/5}$. This is a record-high SFDR in a programmable functional circuit.

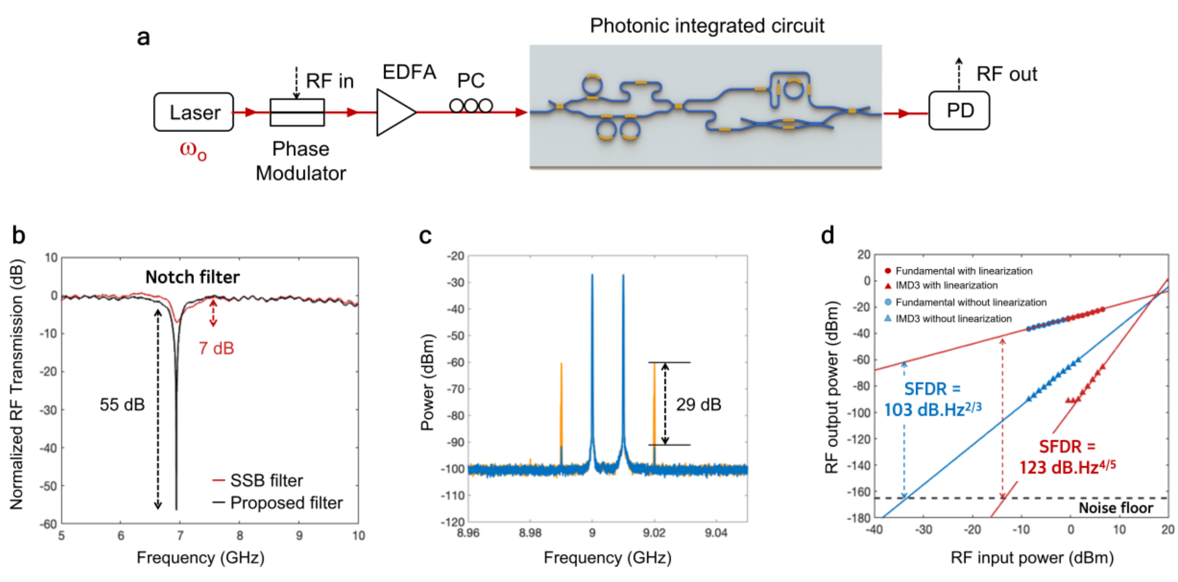

Fig.3 High dynamic range MWP filter [10] (a) schematic of the proposed MWP filter (b) amplitude response of the notch filter (c) comparison of RF spectrum with and without linearization (d) SFDR of the proposed MWP filter

4. HIGH DYNAMIC RANGE MULTI-FUNCTIONAL MWP CIRCUIT

Another linearized integrated MWP circuit that can achieve both tunable notch filter function and phase shifting function is illustrated in Fig.4[11]. The chip consists an MT, four cascaded ring resonators, and a de-interleaver. The MT can manipulate the phase and amplitude of modulated optical spectrum in large bandwidth. The ring resonators can precisely tailor the optical spectrum locally. The de-interleaver can act as a combiner or further process the optical signal.

The signal flow of the proposed notch filter is shown in Fig. 4 (e). Similar to the linearized MWP filter in section III, the MT tailors the phase and amplitude of multi-order sidebands to make the IMD3 terms from the beating between different optical sidebands can add destructively at PD and create asymmetric first-order sidebands with a π-phase difference. Then an all-pass ring resonator is used to process the first-order sideband to create a notch filter based on phase cancellation. Fig. 4 (f) demonstrates the signal flow of the linearized phase shifter. First, the lower sideband of the phase-modulated optical spectrum is filtered out by an external filter. The optical carrier is also pre-attenuated by the external filter. The processed single sideband (SSB) optical spectrum is then sent to the programmable photonic chip for spectral shaping. The MT separates the optical carrier and the first-order sideband from the second-order sideband and manipulates the relative phase of the second-order sideband. The optical carrier is processed by two over-coupled ring resonators to introduce phase shift from 0 to 2π. This optical phase shift can be converted to an RF phase shift after photodetection. When the optical carrier is properly attenuated by the external filter and the relative phase of the second-order sideband is properly tuned by the MT the linearization condition can be satisfied while the MWP phase shifter tuning in the 2π range.

The experimental results of the proposed filter are shown in Fig 5(a-d). The proposed notch filter exhibits a deep rejection of over 50 dB while tuning from 6 ~16 GHz. The IMD3 terms are suppressed by 28.7 dB after linearization, leading to an improvement of SFDR from 103.8 dB·Hz$^{2/3}$ to 123.6 dB·Hz$^{4/5}$. This high SFDR can be maintained while tuning the working frequency of the filter. The proposed MWP phase shifter exhibits a tuning range of 2π, and a relatively flat phase response during the tuning as shown in Fig.5 (e). After linearization, an IMD3 suppression of 20dB is observed. And the SFDR is improved to 121.2 dB·Hz$^{4/5}$.

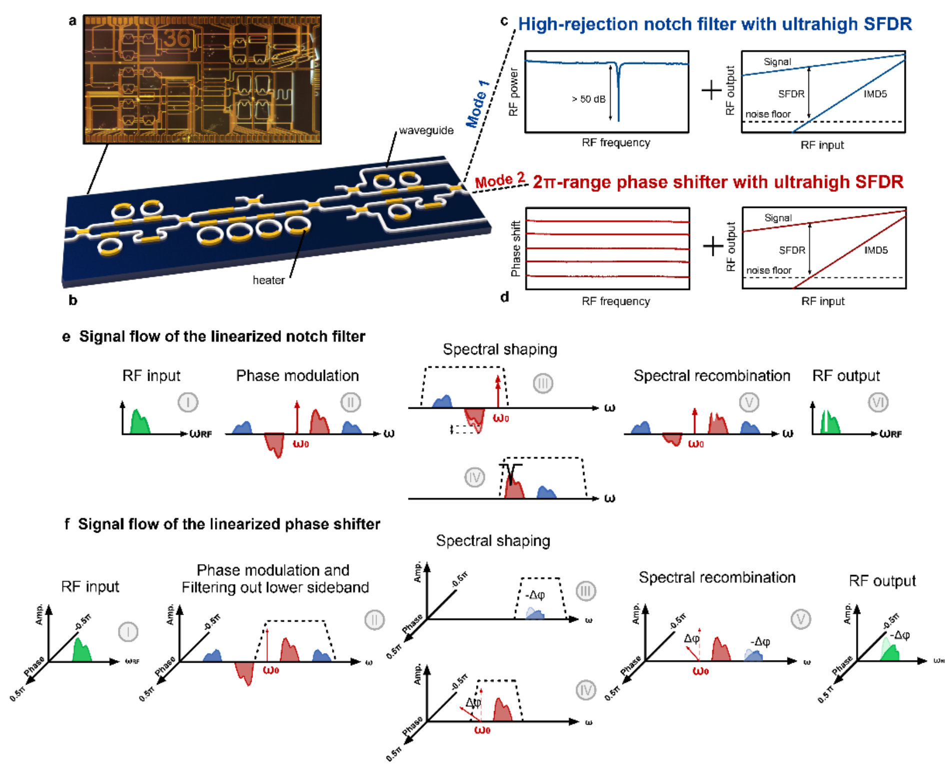

Fig.4 High dynamic range multi-functional MWP circuit [11] (a) The photo of the photonic chip. (b) Schematic of the proposed integrated MWP circuit. (c, d) The illustration of the two functions (e) signal flow of the proposed notch filter (f) signal flow of the proposed phase shifter.

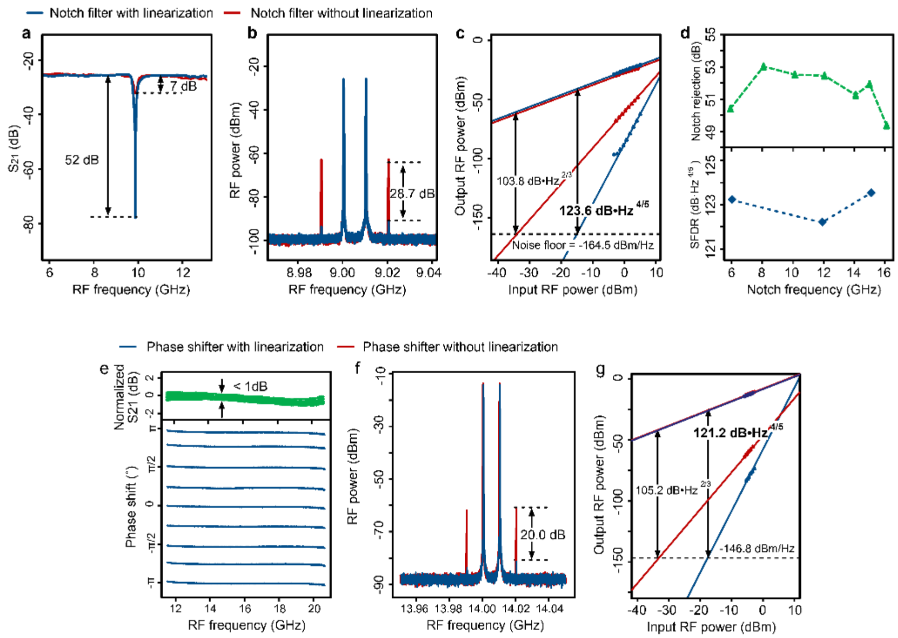

Fig.5 Experimental results of the proposed MWP filtering function (a-d) and phase shifting function(e-g)[11].

5. CONCLUSION

In summary, we reviewed our research progress of linearizing the MWP system using programmable photonic circuits. We start from the linearized MWP transmission link without any signal processing function and then implement the linearization in the programmable functional circuits. Our ambition is to combine high integration density, versatile programmability, and high RF performance. Our studies pave the way for high-performance integrated MWP subsystems with multiple RF functions.

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