Programmable Integrated Microwave Photonic Filter using a Modulation Transformer and a Double-Injection Ring Resonator

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Abstract *We experimentally demonstrate a new kind of integrated Si_3N_4 microwave photonic (MWP) signal processor that combines a programmable modulation transformer (MT) with a versatile double-injection ring resonator (DI-RR). With this circuit we show an array of MWP filtering functions unmatched by traditional MWP circuits.*

Introduction

To find applications in real radio frequency (RF) and microwave systems, integrated microwave photonic (MWP) circuits need to simultaneously exhibit advanced programmability and exceptional performance in terms of losses, noise figure, and dynamic range[1]. While routes to programmable integrated MWP circuits have extensively been explored recently, for example through mesh waveguide circuits[2],[3], few can match the performance of an application specific circuit[4].

We recently identified that a promising route to simultaneous programmability and enhanced performance is through versatile modulation transformation (MT)[5]. Modulation dictates virtually all aspects of MWP system performance. On the other hand, the type of programmable functions that can be realized in a given circuit is determined both by the type of modulation and the phase and amplitude manipulations derived from an optical filter such as a ring resonator. Combining an on-chip versatile modulation transformer (MT) with an equally versatile optical filter holds the promise to unlock programmability and high performance. Recently, an ultra-versatile optical filter based on double-injection ring resonator (DI-RR), capable of synthesizing tens of unique filtering functions, has been demonstrated[6].

Here, we experimentally demonstrate a new kind of integrated MWP combining the modulation transformer and the double-injection ring. The modulation transformer is used to synthesize a variety of RF analog modulation formats while the double-injection ring is used to create a tunable bandpass and bandstop optical filtering responses from the same port. By judicious selection of combined modulation formats and filtering responses, we show an array of filtering functions with versatility unmatched by more traditional MWP circuits. Moreover, we further improve the RF performance of the filter, achieving positive link gain at the passband and improved noise figure of 25 dB. Our results point a step forward towards the realization of practical integrated MWP circuit.

Operation principle

Figure 1(a) shows the two fundamental parts of our circuit, the MT and the DI-RR. The modulation transformer is an optical circuit consists of a spectral de-interleaver, a tuneable attenuator, a phase shifter, and a combiner[5].

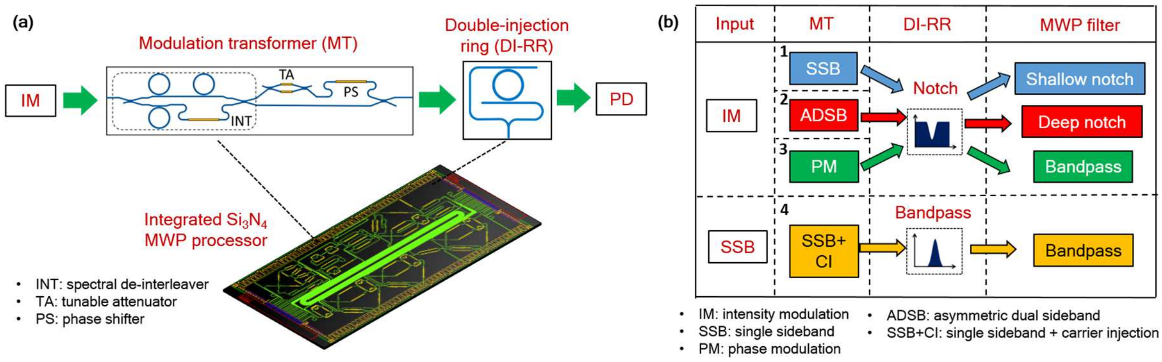

Fig. 1: (a) Schematic of two key building blocks of on-chip versatile microwave photonic spectral shaper. (b) Concept and possible scenarios applied using on-chip versatile MWP processor.

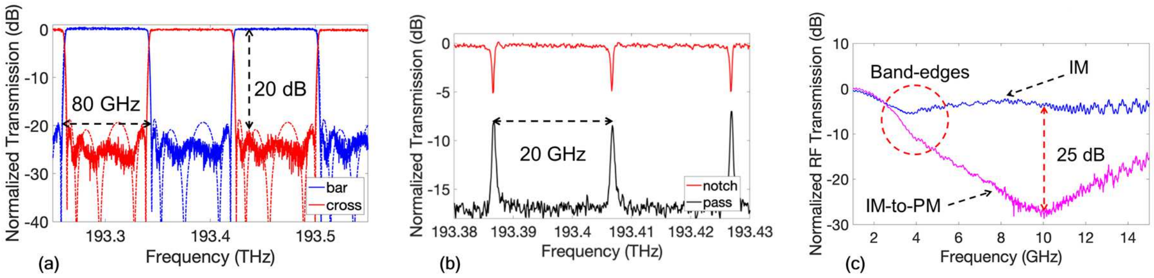

Fig. 2: (a) Modulation transformer spectral de-interleaver response (solid line: measurements, dashed line: simulations). (b) Measured notch and passband responses synthesized from double-injection ring. (c) IM-to-PM conversion measured with the modulation transformer.

This device can be used to precisely shape the phase and amplitude of any optical modulation spectrum[5],[7]. Meanwhile, a double injection ring resonator is a device containing of an add-drop ring resonator (AD-RR) that is double injected from a single input. Such a device can synthesize multiple responses from a single output, including notch and passband responses[6].

We implement the MT as two outputs spectral de-interleaver followed by a tunable attenuator and a phase shifter at one of the output while the complementary output is connected to the DI-RR. Here, the spectral de-interleaver is a “box shaped” filter with 20 dB rejection and 80 GHz of bandwidth as shown in Fig. 2(a). The narrowest transition from passband to stopband in two outputs in this device is 3.7 GHz. Concurently, the DI-RR in this device can be tuned and exhibits both notch and passband responses as shown in Fig. 2(b) that can be used for optical signal processing. To demonstrate the feasibility of the modulation transformation, we performed experiments where the intensity modulation (IM) spectrum at the input is transformed to phase modulation (PM). The result is shown in Fig. 2(c). Figure 1(b) shows the operation principle and application of four different scenarios of the proposed device. The input RF signal is upconverted to optical domain with intensity modulator generating single frequency optical carrier and two identical amplitude sidebands that are in-phase.

For the first scenario, we conducted an IM-to-single sideband (SSB) modulation convertion to create RF notch filter with low suppression. Here, an IM signal is sent to spectral de-interleaver in the MT that spatially isolated one sideband from another sideband and optical carrier. Next, the isolated sideband is fully attenuated with tunable attenuator where the other sideband and optical carrier were sent to a DI-RR which exhibited a notch response. Later, the output of DI-RR is combined with the fully attenuated sideband and synthesized an RF notch filter with low rejection.

The same notch response from DI-RR is used for the second scenario. In this case, an IM signal is sent to the MT, converted IM-to-asymmetric dual sideband (DSB) modulation, and create high rejection RF notch filter. Here, the isolated sideband is not fully attenuated as previous one, but with rather low attenuation and created amplitude difference between two sidebands. Next, the phase of the isolated sideband is changed by controlling the interconnected phase shifter from 0 to π. In parallel, the other sideband and optical carrier were processed by a notch response created by DI-RR. It is important that the rejection of notch response to be equal with the amplitude’s difference between two sidebands. The idea is to have a desctructive interference between asymmetric DSB together with notch response from DI-RR to amplify the rejectrion of synthesized RF notch filter.

In third scenario, we synthesized RF bandpass filter with phase-to-intensity modulation (PM-IM) conversion technique. For this case, we transform the modulation spectrum from intensity-to-phase modulation (IM-PM). Here, we only changed the phase of the isolated sideband by controlling the interconnected phase shifter from 0 to π. Meanwhile, the other sideband and optical carrier were processed using over-coupling (OC) notch response of DI-RR. After IM-PM conversion using MT, due to OC state in the DI-RR, a π-phase shift is introduced at the desired notch frequency, creating constructive interference for PM-IM conversion and synthesized RF bandpass filter.

Last, the RF bandpass filter is synthesized using optical carrier insertion technique with the MT in the fourth scenario. There are two differences between this case with the previous scenarios: first, the MT already take an SSB modulation as an input spectrum and second, the filter’s rejection of spectral de-interleaver is equal. Here, a SSB modulation is sent to the spectral de-interleaver and split into two outputs containing optical carrier in one output and sideband in the other. Then, the sideband was sent to a DI-RR which tuned and synthesized a passband response. When the optical carrier is re-injected to the processed sideband, we can synthesize RF bandpass filter.

Experiments

In the experiments, an optical carrier from low relative-intensity noise (RIN) laser (Pure Photonics PPCL550) with RIN of -155 dB/Hz and wavelength set at 1550 nm is modulated using an intensity modulator (Thorlabs, LN05S-FC 40 GHz) with bias point set at quadrature ($\theta_B = \pi/2$). The intensity modulator is driven by RF signal from a vector network analyzer (VNA, Keysight P5007A). The output of the intensity modulator then sent to an erbium-doped fiber amplifier (EDFA, Amonics) before being injected into a programmable silicon nitride chip (LioniX International BV) fabricated using low-loss TriPleX (Si_3N_4/SiO_2) technology[8] with propagation loss of the optical waveguide at 0.1 dB/cm. The free spectral range (FSR) of spectral de-interleaver is 80 GHz and DI-RR is 20 GHz. The coupling coefficient and resonance frequency are tuneable through thermo-optic tuning using custom made heater controller software and the chip temperature is stabilized by a thermoelectric cooler (TEC) controller. The processed optical signal is sent to a photodetector (APIC 40 GHz) and the converted RF signal is measured with a VNA.

Figure 3(a) shows the measured RF notch filter with 5 dB rejection in the first scenario. By adjusting the phase and amplitude of isolated sideband in second scenario, the RF notch filter rejection can be amplified up to 58 dB as shown in Fig. 3(b). Here, the 3dB bandwidth of the filter is 400 MHz with the quality factor (Q-factor) of the RF notch filter at central frequency of 7 GHz was 17. The Q-factor of the RF notch filter refers to the ratio of central frequency of the RF notch filter to the filter's 3 dB bandwidth. Figure 3(c) shows the measured RF bandpass filter exhibits 10 dB rejection with PM-IM conversion technique. Last, Figure 3(d) shows the measured RF bandpass filter with 15 dB rejection in the last scenario. These four applied scenarios show the versatility of the proposed device to shape the phase and amplitude of optical modulation spectrum.

Performance metrics

We further analyze the performance of the filter in the system, including the RF link gain and the noise figure (NF). Here, the intensity modulator bias point is set to quadrature ($\theta_B = \pi/2$) to achieve maximum RF link gain. The total noise power spectral density is measured with RF spectrum analyzer (RFSA, Keysight). For the high rejection RF notch filter, the measured RF link gain is 0.7 dB, the total noise power spectral density is -148 dBm/Hz, and the NF is 25 dB.

Conclusions

We have demonstrated experimentally for the first time, to the best of our knowledge, a new kind of integrated Si_3N_4 MWP signal processor that combines a programmable MT with a versatile DI-RR. Four different scenarios were applied, creating RF notch and RF bandpass filters with only using a simple intensity modulator. However, the input spectrum is not limited to an intensity modulator, but also with any existing electro/optic (E/O) modulator, such as a phase modulator or a dual-parallel Mach Zehnder modulator (DPMZM). A high rejection RF notch filter can be synthesized, exhibits filter's suppression up to 58 dB, a 3 dB bandwidth of 400 MHz, the Q-factor of the RF notch filter at central frequency of 7 GHz of 17, the RF link gain of 0.7 dB, and the NF of 25 dB. The proposed device improved the high degree of freedom to tailor phase and amplitude of the modulation spectrum and open new paradigm of advanced functionalities unmatched with traditional MWP circuits.

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References

[1] D. Marpaung, J. Yao, and J. Capmany, “Integrated

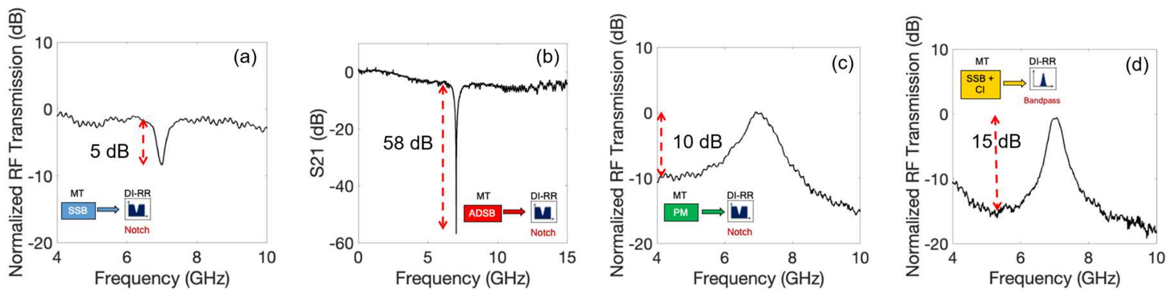

Fig. 3: Measured of four applied scenarios using on-chip versatile microwave photonic spectral shaper. (a) RF notch filter with SSB modulation. (b) High rejection RF notch filter with asymmetric DSB modulation. (c) RF bandpass filter with PM-IM conversion. (d) RF bandpass filter with SSB modulation and optical carrier injection

microwave photonics”, *Nat. Photon.*, vol. 13, pp. 80-90, Feb. 2019.
[2] L. Zhuang, C. Roeloffzen, M. Hoekman, K. Boller, and A. Lowery, "Programmable photonic signal processor chip for radiofrequency applications", *Optica*, vol. 2, no. 10, pp. 854-859, Sept. 2015
[3] D. Pèrez, I. Gasulla, L. Crudgington, D. J. Thomson, A. Z. Khokhar, K. Li, W. Cao, G. Z. Mashanovich, and J. Capmany, "Multipurpose silicon photonics signal processor core", *Nature Commun*., vol. 8, pp. 1-9, Sept. 2017
[4] Y. Liu, J. Hotten, A. Choudhary, B. J. Eggleton, and D. Marpaung, ”All optimized integrated RF photonic notch filter”, *Opt. Lett.*, vol. 42, no. 22, pp. 4631-4634, Nov. 2017
[5] X. Guo, Y. Liu, T. Yin, B. Morrison, M. Pagani, O. Daulay, W. Bogaerts, B.J. Eggleton, and A. Casas-Bedoya, “Versatile silicon microwave photonic spectral shaper”, *APL Photon.,* vol. 6, Mar. 2021
[6] R. A. Cohen, O. Amrani, and S. Rushcin, “Response shaping with a silicon ring resonator via double injection”, *Nat. Photon.*, vol. 12, pp. 706–712, Nov. 2018.
[7] O. Daulay, G. Liu, X. Guo, M. Eijkel, and D. Marpaung, “A tutorial on integrated microwave photonic spectral shaping”, *J. Lightwave Technol.*, vol. 39, no. 3, pp. 700-711, Feb. 2021
[8] C. G. H. Roeloffzen, M. Hoekman, E. J. Klein, L. S. Wevers, R. B. Timens, D. Marchenko, D. Geskus, R. Dekker, A. Alippi, R. Grootjans, A. van Rees, R. M. Oldenbeuving, J. P. Epping, R. G. Heideman, K. Worhoff, A. Leinse, D. Geuzebroek, E. Schreider, P. W. L. van Dijk, I. Visscher, C. Taddei, Y. Fan, C. Taballione, Y. Liu, D. Marpaung, L. Zhuang, M. Benelajla and K. J. Boller, “Low-loss Si3N4 TriPleX optical waveguides: Technology and applications overview”, *IEEE J. Sel. Top. Quantum Elect.,* vol. 24, no.4, pp. 1-21, July-Aug. 2018.