All-Integrated Universal RF Photonic Spectral Shaper

Xin Guo[1, 2, 3], Tangman Yin[1, 3], Yang Liu[1, 3], Blair Morrison[1, 3], Chris Cantaloube[4], Wim Bogaerts[5], Benjamin J. Eggleton[1, 3], David Marpaung[2, *], and Alvaro Casas Bedoya[1, 3, **]
[1]*Institute of Photonics and Optical Science (IPOS), School of Physics, The University of Sydney, NSW 2006, Australia*
[2]*Laser Physics and Nonlinear Optics, MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands*
[3]*The University of Sydney Nano Institute (Sydney Nano), The University of Sydney, NSW 2006, Australia*
[4]*Microsoft Quantum, The University of Sydney, NSW 2006, Australia*
[5]*Ghent University - IMEC, Department of Information Technology, Photonics Research Group*
Technologiepark-Zwijnaarde 126, 9052 Gent, Belgium
* *david.marpaung@utwente.nl* ** *alvaro.casasbedoya@sydney.edu.au*

Abstract: We demonstrate a microwave photonic spectral shaper in a silicon chip enabling distinct phase and amplitude modulation transformation. We show unprecedented RF filtering through monolithic integration of the spectral shaper with tunable ring resonators. © 2019 OSA

OCIS codes: 130.0130 Integrated optics; 060.5625 Radio frequency photonics

1. Introduction

Optical modulation is arguably the most important element in microwave photonic signal processing. It entirely dictates the signal-to-noise-ratio, linearity, and losses of microwave photonic systems, and it critically impacts (or limits) how well one can map tailored optical functionalities to the radiofrequency (RF) domain [1]. Recent research have hinted that a complete control of amplitude and phase of a optical modulation spectrum can open to new RF-photonic signal processing functions, including advanced RF photonic filters with minimal loss and maximal rejection [2,3]. But such a foundational function is presently unrealizable with any type of optical modulators, which always create optical carrier and RF-sidebands with interrelated phase and amplitudes. A device that targets an entirely new level of freedom in synthesizing modulated spectrum will thus be significant to unlock unexplored optimization avenues in RF photonics.

In this work we present a device to synthesize and shape arbitrary RF photonic spectra using an all-integrated silicon photonic chip. This spectral shaper essentially acts as a universal modulation transformer that takes an input of a conventional phase or amplitude modulation and synthesize an output spectrum with components (optical carrier and RF sidebands) entirely independent in phases and amplitudes. Further, we interconnect the spectral shaper with reconfigurable ring resonator filtering elements and, for the first time, demonstrate reconfigurable notch and bandpass RF photonic filtering that would have been impossible to achieve using only a simple intensity modulator. We monolithically integrate the spectral shaper and the ring resonator filters with on-chip intensity modulator and high-speed photodetector to enable an all-integrated programmable RF photonic filter. We believe the initial results reported here will alter how microwave photonic scientists and practitioners view optical modulation and will serve as the basis of further RF photonic noise, dynamic range, and filter optimizations [4] and stabilization through modulation spectral shaping and transformation.

2. Operation principle and chip layout

We implement the spectral shaper/transformer as a dual-port spectral de-interleaver followed by an optical attenuator and a phase shifter at one of the de-interleaver outputs while the complementary output is interconnected to the ring resonator filters. The two outputs are then combined and routed to a photodetector (PD) while the entire structure's input is connected to an (off-chip or on-chip) optical modulator. The principle of operation is shown in Figure 1a. The role of the spectral de-interleaver here is to spatially separate one RF sideband from the optical carrier and the complementary sideband. The separated sideband's amplitude and phase are altered and tailored using the optical attenuator and phase shifter to synthesize a new spectrum with designer phase and amplitude relations between its spectral components. It is critical to implement this de-interleaver with maximum sharpness and rejection and a flat passband. Here we chose implement it as a Mach-Zehnder interferometer loaded with 3 ring resonators (MZI+3Ring) [5] and the attenuator as a tunable coupler.

We then used a pair of an all-pass and an add-drop ring resonator to precisely impress a complex optical response to the sideband and the optical carrier at the MZI+3Ring complementary output. The combined spectrum sent to the PD can be precisely tailored to exhibit phase modulation (PM), intensity modulation (IM), single sideband modulation (SSB) or anything in between these spectra, where the sidebands strengths are unequal and their phase differences are not simply 0 or π. As a result, various filtering functions including conventional SSB bandpass and bandstop filters as well as the high-extinction RF-interference notch filter can be implemented in a single device, using a simple intensity or a phase modulator, which prior to this work would have been impossible.

The schematic and photograph of our photonic spectral shaper are shown in Figures 1b and 1c, respectively. The silicon chip was designed with the IPKISS parametric design framework by and fabricated in IMEC's iSiPP50G process through the Europractice multi-project wafer service. The key building blocks are implemented as SOI nanowires with 220 nm × 450 nm dimension. The optical waveguide loss is 1.2 dB/cm. The MZI+3Rings was designed to have a passband width of 30 GHz and peak rejection of > 20 dB (Figure 1d). The FSR, maximum Q factor of the all-pass and add-drop rings are 50GHz, 149,000 and 80,000 respectively (Figure 1e). All components are tunable using thermo-optic tuning. The modulator is a 1.5mm long Mach-Zehnder modulator with depletion-type phase shifters with 11 GHz RF bandwidth and the photodetector is a 40 GHz Ge-PD with responsivity of 0.8 A/W, both from the provided iSiPP50G design kit. The silicon chip was wire bonded locally into a bespoke PCB for ease of experiments. The optical signal is coupled in and out of the chip using grating couplers with 6 dB loss.

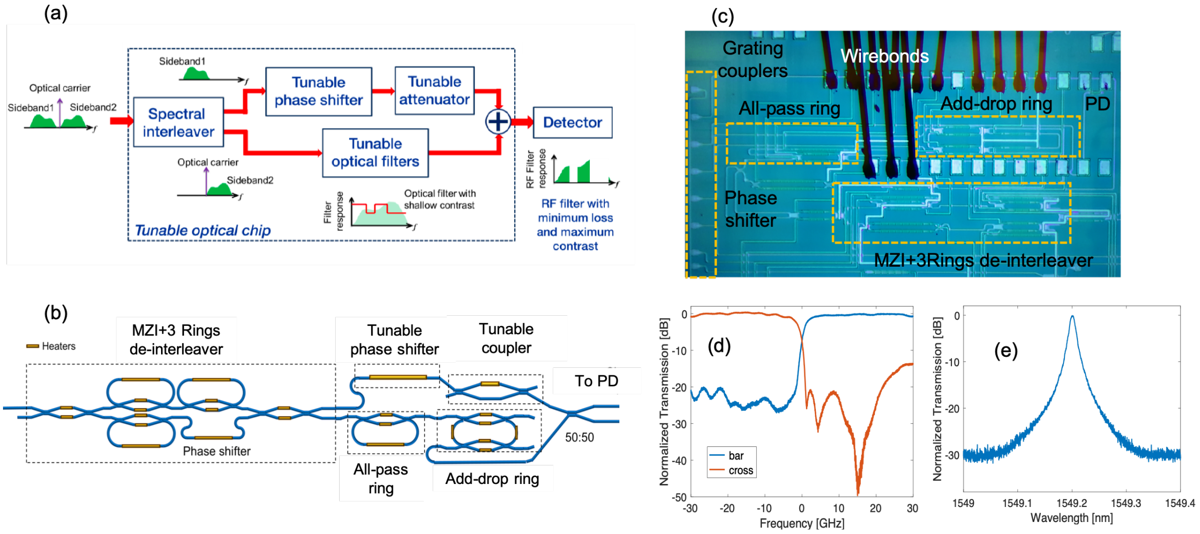

Figure 1: (a) Principle of operation of the spectral shaper and the filter. (b) Schematic of the spectral shaper and tunable filter. (c) Microscope image of the all-integrated spectral shaper in a silicon chip. (d) Spectral response of the MZI+3Ring de-interleaver. (e) Spectral response of the add-drop ring resonator.

3. Experiments and results

First we verify the operation of the spectral shaper to synthesize various RF modulation schemes from a conventional phase or intensity modulation input. An off-chip intensity modulator is applied to get larger RF bandwidth. The principle of modulation transformation is shown in Figure 1a. We use the optical phase shifter to modify the phase of the separated sideband. When both sidebands are in phase, intensity modulation in is achieved, and the measured RF transmission is highest. The opposite happens when the sidebands are out of phase, indicating phase modulation, and minimized RF transmission. Figure 2a shows the modulation transformation when an input intensity modulation is used. Extinction up to 15 dB can be achieved solely by tuning the phase shifter. This extinction is impacted by a variety of aspects including the dispersion of the MZI+3Rings de-interleaver. We are currently performing theoretical investigations on the optimized complex response of the de-interleaver to achieve maximum extinction. The frequency range of operation is currently limited from 15-25 GHz due to the roll-off of the de-interleaver, and could be enlarged by using lower loss waveguides. Similar results can be achieved if phase modulator is used in the input instead of an intensity modulator and we achieved extinction as high as 20 dB (Figure 2b). We verified that the extinction is purely coming from phase effects by inspecting the optical spectra of each trace, where all of them are nearly identical (Figure 2c). These results confirm the universality of our spectral shaper.

We demonstrate three distinct RF photonic filtering topologies to verify the universality of the spectral shaper. First configure the spectral shaper to synthesize single sideband (SSB) modulation by activating the tunable attenuator/coupler to completely block the separated sideband. We sent the remaining carrier and sideband to an all-pass ring resonator (AP-RR) to form an SSB RF photonic notch filter. The result is shown in Figure 2d, dashed trace. We deliberately tuned the AP-RR to a shallow (~ 7 dB rejection) under-coupling state. Next, we reconfigure the spectral shaper to synthesize an unbalanced amplitude, phase modulation spectrum [6]. Here the separated sideband is attenuated by 7 dB and rotated in phase to exhibit pi phase shift with respect to the other sideband. We then sent this spectrum to the AP-RR. For a particular frequency, the amplitude of the two sidebands are equal (attenuated by 7 dB) but they are opposite in phase. Upon photodetection this frequency will form an ultra-high rejection notch filter through phase cancellation (solid line of Figure 2d). With this pair of experiments we demonstrate the flexibility of the spectral shaper to synthesize two distinct spectrum and hence distinct RF photonic filters.

Further, demonstrate bandpass filtering using an add-drop ring resonator (AD-RR). The challenge in this filtering is that the passband of the ring is too narrow to pass both the optical carrier and a tunable-frequency sideband, so forming a tunable RF photonic bandpass filter without precise carrier re-insertion is, in fact, impossible. We mitigate this limitation using our spectral shaper. First we synthesize an SSB with carrier spectrum at the input. We used the spectral shaper to separate the carrier and the sideband, where the latter is being passed to the AD-RR to be filtered. The 3-dB coupler re-combined the carrier and the processed sideband to form a true SSB RF photonic bandpass filter (Figure 2e). This shows the universality of the spectral shaper to for spectral syntheses and optical carrier processing. Finally, the central frequency of both bandpass and notch filters can be tuned simply by thermo-optically tuning the center frequencies of the rings, as shown in Figure 2e and 2f, respectively.

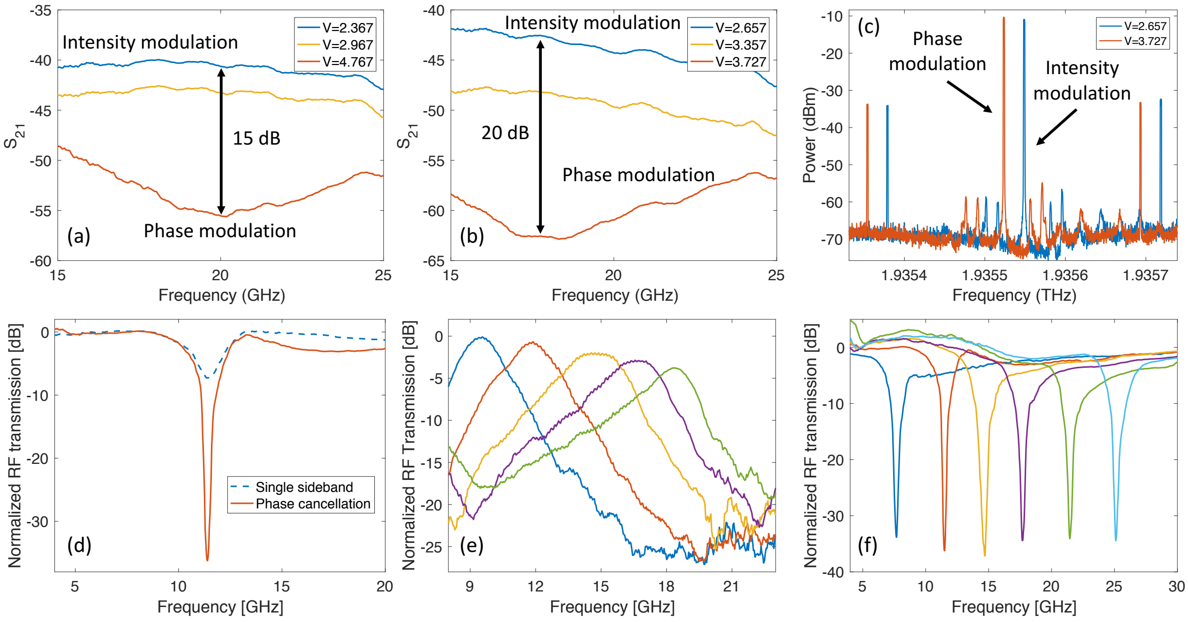

Figure 2: (a) Intensity-to-phase modulation (IM-PM) conversion ("V" is the applied voltage to the phase shifter). (b) Phase to intensity modulation (PM-IM) conversion. (c) Synthesized IM and PM optical spectra. (d) Comparison of single sideband and phase cancellation notch filter. (e) True tunable bandpass RF photonic filter enabled by carrier reinsertion. (f) Frequency tuning of the notch filter.

4. Conclusion

We demonstrated the first universal RF photonic spectral shaper with both passive and active components on a monolithic silicon photonic chip. The spectral shaper allows independent tailoring of phase and amplitude of the optical carrier and RF sidebands leading to the first universal RF photonic modulation transformer. With this entirely novel concept, we demonstrated three distinct kinds of RF photonics filter using a simple intensity modulator. This work will serve as the basis of further RF photonic noise, dynamic range, and filter optimizations and stabilization through modulation spectral shaping and transformation.

5. References

[1] D. Marpaung, J. Yao, and J. Capmany, "Integrated microwave photonics," Nat. Photonics, vol. 13, no. 2, pp. 80–90, 2019.

[2] D. Marpaung et al. "Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity," Optica, vol. 2, no. 2, pp. 76-83, 2015.

[3] L. Zhuang et al. "Integrated microwave photonic splitter with reconfigurable amplitude, phase, and delay offsets," Opt. Lett., vol. 40, no. 23, pp. 5618-5621, 2015.

[4] Y. Liu et al. "All-optimized integrated RF photonic notch filter," Opt. Lett., vol. 42, no. 22, pp. 4631-4634, 2017.

[5] L. Luo et al. "High bandwidth on-chip silicon photonic interleaver," Opt. Express, vol. 18, no. 22, pp. 23079-23087, 2010.

[6] D. Marpaung et al. "Si_3N_4 ring resonator-based microwave photonic notch filter with an ultrahigh peak rejection," Opt. Express, vol. 21, no.20, pp. 23286-23294, 2013.