‘Beyond Moore's Law’ Photonic Integrated Circuits for RF Photonics and Sensing Systems

Paul A. Morton
Morton Photonics Inc.
West Friendship, MD 21794
pmorton@mortonphotonics.com

John E. Bowers
University of California at Santa Barbara
Santa Barbara, CA 93106
bowers@ece.ucsb.edu

Jacob B. Khurgin
Johns Hopkins University
Baltimore, MD 21218
jakek@jhu.edu

Abstract— **We describe silicon photonic PICs that are needed for RF photonics and sensing systems and are enabled by heterogeneous integration. This ‘beyond Moore's law’ technology includes III-V semiconductors for high-performance lasers, modulators, photodetectors; silicon nitride for filters, time-delay; Ce:YIG for isolators; PZT for ultra-low power tuning. These advanced PICs enable high SFDR analog links, simultaneous RF beamforming, plus sensing and timing applications.**

Keywords - Beyond Moore’s law; silicon photonics; heterogeneous integration; RF photonics; photonic integrated circuit; RF photonic link; simultaneous RF beamforming

I. Introduction

The first generation of silicon photonics products, photonic integrated circuits (PICs) based on CMOS foundry fabricated all-silicon devices have been out for almost a decade, led by devices from Luxtera. These led to active optical cables and an entrance into the interconnect business - a major step forward for silicon photonics. These devices, however, rely on separate laser chips to power the CMOS fabricated optical circuits.

The second generation of silicon photonics products utilize heterogeneous integration of III-V materials onto the silicon waveguides, through wafer bonding, to allow these PICs to efficiently generate and modulate light within the chip, e.g. [1]. Products being released by Intel and others address the burgeoning data-center interconnect market, e.g. [2, 3] enabling continued growth in mega-data-center capabilities. These heterogeneously integrated PICs have achieved the reliability and yield required for commercial applications, albeit for shorter distance, digital communication systems.

The next generation of silicon photonics based PICs is required to meet the far higher performance requirements of DoD applications, in particular for high dynamic range analog microwave and millimeter wave systems. These ‘beyond Moore’s law’ PICs will utilize the lithography and process control of an advanced CMOS foundry, with the inclusion of multiple other material systems required for the highest performing devices and systems. These include high-performance III-V multiple quantum well (MQW) and quantum dot (QD) materials for efficient light generation, modulation and detection - as already included in the second generation of silicon photonics products, but also additional materials such as silicon nitride for ultralow loss waveguides and devices, magneto optic (MO) materials such as Ce:YIG for use in high performance optical isolators and circulators, piezoelectric materials such as PZT for ultralow power actuators in tunable devices and to enable large scale integration (LSI)-PIC devices, plus other material systems.

This paper addresses the advanced integrated components being developed in these beyond Moore’s law silicon photonics devices, through the partnership of the silicon photonics research group at the University of California at Santa Barbara (UCSB), and novel device and system designs from Morton Photonics Inc. (MP). World leading component technologies have been developed througth the heterogeneous integration of these different materials on the basic silicon photonics platform, and novel system designs providing improved or unique performance capabilities compared to all-electronic approaches have been demonstrated or validated through detailed system simulations. This new generation of beyond Moore’s law silicon photonics devices will provide unique capabilities for DoD systems based on novel, flexible photonic architectures and ultra-wideband devices and systems, to keep the U.S. well ahead of its adversaries - however, investment in these device and integration technologies, and a US based foundry (potentially AIM Photonics) and its associated infrastructure is crucial to its success.

II. ‘Beyond Moore's Law’ Photonic Integrated Circuits

The key integrated photonic devices required for systems as simple as an RF photonic link, or as complex as the Multiple Channel Simultaneous RF Beamforming (MCSB)-PIC for a Receive Phased Array Sensor (Rx-PAS) [4, 5], are being developed by the MP/UCSB team. These include high-performance integrated lasers, with high-power and ultra low noise; as required for RF links and RF mixing (up-conversion and down-conversion) links; integrated isolators to protect the lasers from the effects of optical reflections; highly linear, highly efficient integrated modulators - used in the same RF systems together with high-power, highly linear photodetectors and photodetector arrays. Additional key components for the more complex systems include tunable optical filters providing narrow and flat RF passbands (both flat amplitude and group delay) together with high suppression outside of the passband, and widely tunable true time delay (TTD) devices - also with flat amplitude and group delay responses.

Now that the first generation of these high-performance beyond Moore’s law integrated devices have been demonstrated, the focus is switching to integration technologies (transitions between devices), and the foundry, PDK,

DISTRIBUTION STATEMENT A. Approved for public release: distribution is unlimited.

simulations [6] and processes, required to manufacture these PICs and transition them to DoD systems / applications.

An RF photonic or sensing PIC requires the combination of multiple high-performing components. Standard wire or ridge silicon waveguides, or much lower loss silicon nitride waveguides, provide for routing, multiplexing, demultiplexing, filtering, splitting and combining within a PIC, with low loss/reflection transitions between different waveguide designs and materials being key. The ability to bond different III-V, MO or other epitaxially grown films onto a single die allows for optimization of individual device performance; a high performance PIC will utilize optimized III-V materials each for the laser gain section, phase modulator sections, and photodetectors, all on the same SOI die, as shown in Figure 1. Simultaneous processing of all the bonded III-V layers is possible - reducing the number of processing steps, directly reducing cost and improving yield.

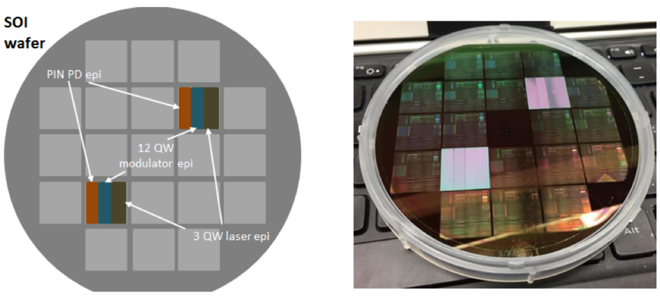

Fig. 1. (left) A schematic of a 4-inch SOI wafer with three III-V epitaxial layers bonded on each die, (right) Photograph of the 4-inch SOI wafer processed and bonded with III-V in the UCSB cleanroom.

III. 'BEYOND MOORE'S LAW' INTEGRATED DEVICES

Some examples of integrated photonic devices required for complex RF photonic PICs and DoD applications are briefly described in the following sections.

A. *Tunable Lasers*

The UCSB team is well known for developing the first electrically pumped silicon photonics lasers [7], and for continuing development of a variety of single wavelength and wideband tunable integrated lasers. An example of such a tunable laser is shown in Figure 2 [8, 9]. This device is an integrated laser with ~4 cm extended cavity, made possible by a low-loss silicon waveguide. Tuning in excess of 54 nm in the O-band with linewidth below 100 kHz is achieved. Research at UCSB also includes the direct epitaxial growth on silicon of QD semiconductor gain material for lasers [10].

MP is known for its development and commercialization of ultra-low noise (ULN) hybrid lasers, utilizing a high performance semiconductor gain chip in a custom fiber Bragg grating (FBG) reflector/external cavity [11], providing excellent performance for RF photonic links and mixing applications [12], including >100mW ouput power, with RIN < -165 dB/Hz, and Lorentzian linewidth as low at 15 Hz. The MP/UCSB team is now developing integrated versions of these ULN lasers, both single wavelength versions based on waveguide gratings similar to MPs FBG based devices [13], plus novel multiple ultra-low loss (ULL) microresonator based tunable lasers [14], with high power and similar ULN performance expected.

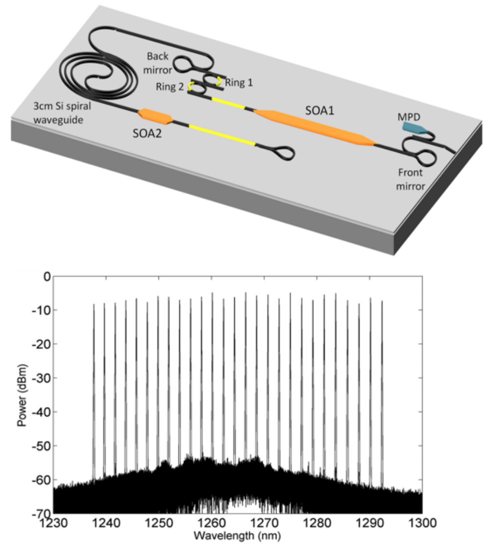

Fig. 2. (top) Schematic of silicon microresonator based tunable laser and (bottom) measured spectra demonstrating tuning over 1240nm to 1290nm [8].

B. *Integrated Isolators*

The UCSB/MP team have developed integrated isolators and circulators based on microresonator and MZI structures [15, 16], using non-reciprocal phase shift (NRPS) from a wafer bonded MO material (Ce:YIG) to create the required isolation. These devices also utilize a novel metal strip based tunable magnet to control and switch the isolator/circulator, i.e. they do not require a permanent magnet. The microresonator based devices demonstrated high isolation of 32 dB, with low loss of 2.3 dB (with potential for sub-dB operation), however, they only provide narrowband (GHz) isolation. Alternatively, the MZI based devices demonstrated 20 dB of isolation over 18 nm bandwidth, tunable over 100 nm, however, the loss these devices is much higher, at 9 dB. Research is ongoing to develop practical implementations of these devices, and transition them to a commercial foundry.

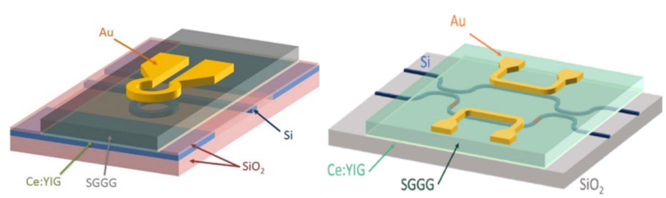

Fig. 3. (left) Schematic of (narrowband) microresonator based integrated isolator and (right) schematic of (broadband) MZI based integrated isolator.

C. *Linear Modulators*

Linear Mach Zehnder interferometer (MZI) modulators, and linearized Ring-Assisted (RA)MZI modulators were developed by the MP/UCSB team, using heterogeneously integrated III-V on silicon sections in MZI structures in order to provide linear or controllable linearity phase modulation. The MZI based modulators, shown in Figure 4 (left), achieved record spurious free dynamic range (SFDR) of 112 dB.Hz$^{2/3}$ while operating at 10 GHz [17], similar to commercially available Lithium Niobate modulators. The novel RAMZI modulators utilized ring phase modulation structures, see Figure 4 (right), to counteract the sinusoidal transfer characteristic of an MZI modulator and increase the achievable SFDR up to 117 dB.Hz$^{2/3}$ [18]. R&D continues [19] to increase power handling and modulation bandwidth of these devices.

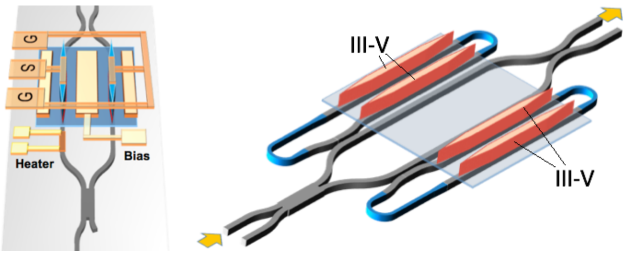

Fig. 4. (left) Schematic of heterogeneously integrated MZI modulator and (right) schematic of heterogeneously integrated RAMZI modulator.

D. True Time Delay (TTD) Devices

MP has been developing silicon photonics based TTD devices since 2009, based on novel device and system designs - including 4 issued patents. Initial devices were developed using silicon wire waveguides, demonstrating key concepts [20-23], however, silicon nitride waveguide devices providing significantly lower loss were used to demonstrate practical devices, including hermetically packaged 40 microresonator devices, shown in Figure 5. Demonstrated results include record low loss for high bandwidth, high tunable delay [24], as well as a demonstration of the 'Super-Ring' concept enabling simpler TTD control and larger delay.bandwidth capabilities, plus operation with high SFDR [25]. Recent results for devices with 8 ULL microresonators [26], shown schematically in Figure 5, demonstrated delays for the multi-GHz bandwidth signals of an optical down-conversion system with a record delay.loss of only 0.89 dB per ns of delay.

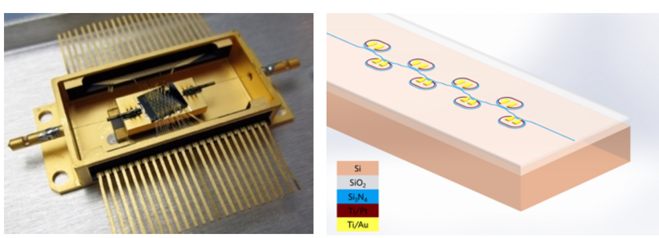

Fig. 5 (left) Hermetically packaged TTD device incorporating 40 thermally tunable microresonators, and (right) schematic of an 8 ring TTD device.

E. Ultra-Low Power PZT Actuators

While the use of silicon nitride ULL waveguides provides for very low loss TTD devices, and also low-loss high-performance tunable filters, the tunable microresonators that make up these devices are typically thermally tuned - which requires significant power dissipation, e.g. 100's mW per microresonator. In a complex PIC that may require hundreds, or thousands of tunable microresonators, inefficient thermal tuning is not an option. The MP/UCSB team has developed novel PZT actuator devices for tuning the optical resonances of silicon nitride microresonators [27], using geometric deformation of the microresonator waveguide rather than the stress / index or thermal index tuning used by others. A key advantage of this new approach is that it can provide the required full free spectral range (FSR) of resonance tuning - required to tune an optical resonance to any wavelength (e.g. across C-band), as demonstrated in Figure 6, and also that the tuning range (in FSRs) increases as the microresonator diameter reduces (contrary to other approaches), supporting smaller device sizes. This again supports LSI PICs that include large numbers of tunable microresonators - as in MPs MCSB-PIC devices for Rx-PAS systems. Figure 6 includes schematics of the PZT actuator on the left; a microresonator (cut in half) coupled to a bus waveguide plus a cross-section through the key area, and on the right; a simulation showing how the device deforms under PZT actuation, plus measurements demonstrating resonance tuning of over one FSR for < 20V tuning voltage.

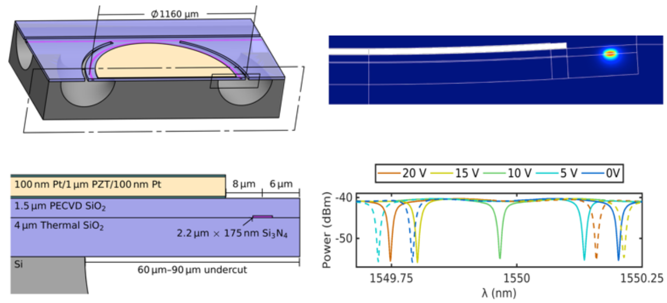

Fig. 6 (left) Schematic of PZT actuator in 3D and side view, and (right) simulated deformation utilizing PZT, and measurements demonstrating resonance tuning of over one FSR (measured spectra vs. applied voltage) [27].

IV. Heterogeneously Integrated PIC Device Examples

Some examples of more complex PIC devices previously fabricated by the UCSB team are briefly described in this section. These devices demonstrate some of the capabilities and level of complexity already available in heterogeneously integrated devices fabricated within a university clean room.

A simple way to generate a microwave or mm-wave signal in the optical domain is based on optical heterodyning, in which two optical waves of different wavelengths are beaten on a photodetector. A chip-scale device providing that functionality is shown in Figure 7 [28].

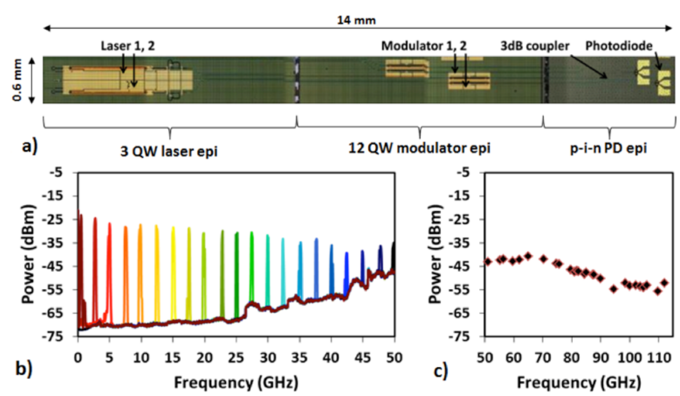

Fig. 7. (a) Microscope image of fully integrated photonic microwave generator chip and measured microwave signals (b) from 1 to 50 GHz on an ESA, and (c) from 50 to 112 GHz using an E-band power meter [27].

The fully integrated photonic microwave generator includes lasers that tune over 42 nm with 150 kHz linewidth, combined with waveguide photodiodes with a 3 dB bandwidth of 65 GHz and 0.4 A/W responsivity. This PIC provides microwave signal generation from 1 to 112 GHz.

Free-space optical beam-steering is important for light detection and ranging (LIDAR), with autonomous cars driving a need for low cost, lightweight LIDARs. Photonic integration allows for integration of a phased array beam steering system on a chip [29], as shown in Figure 8. This heterogeneous PIC consists of 164 optical components including lasers, amplifiers, photodiodes, phase tuners, grating couplers, splitters, and a photonic crystal lens. The scanner beam steers over 23° x 3.6° with beam widths of 1° x 0.6° giving a total of 138 resolvable spots in the far field with 5.5 dB background suppression.

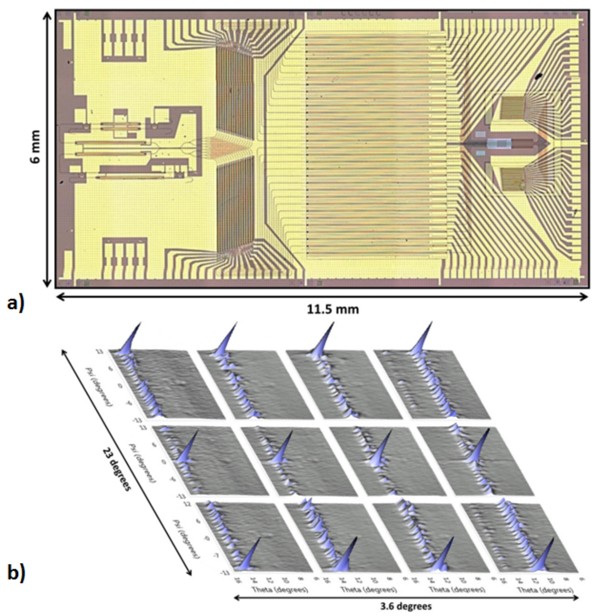

Fig. 8. (a) Microscope image of fully integrated beam-steering PIC. The chip is 11.5 mm x 6 mm (b) Two-dimensional beam-steering plots spanning 23° in ψ and 3.6° in θ planes [29].

ACKNOWLEDGMENT

Morton Photonics and UCSB acknowledge funding from DARPA, the Air Force, and Army contracts, including W31P4Q-09-C-0298, W91CRB-10-C-0099, W911NF-16-C-0072, FA8650-16-C-1758 and FA8650-15-C-1863.

REFERENCES

[1] Tin Komljenovic, Duanni Huang, Paolo Pintus, Minh A. Tran, Michael L. Davenport, and John E. Bowers, ‘Heterogeneous III-V Silicon Photonic Integrated Circuits’, IEEE Proceedings (2018).

[2] C. Zhang and J. Bowers, ‘Silicon Photonic Terabit/s Network-on-chip for datacenter interconnection’, Invited Paper, Optical Fiber Technology, Dec. (2017).

[3] D. Liang, G. Kurczveil, X. Huang, C. Zhang, S. Srinivasan, Z. Huang, A. Seyedi, K. Norris, M. Fiorentino, J. Bowers, R. Beausoleil ‘Heterogeneous silicon light sources for datacom applications.’ Invited, Special Issue, Fiber Optics for Data Center Comms, Opt Fiber Tech., (2017).

[4] Air Force SBIR ‘Simultaneous RF Beamforming Phased Array Sensors through Wafer Scale Photonic Integration’, # FA8650-15-C-1863.

[5] P. A. Morton, ‘Photonic Integration for Phased Array Systems’, Invited paper, IEEE Photonics Conference (IPC), TuF3.4, (2015).

[6] Z. Zhang, R. Wu, Y. Wang, C. Zhang, E. J. Stanton, C. Schow, T. Cheng, and John Bowers, ‘Compact Modeling for Silicon Photonic Heterogeneously Integrated Circuits’, JLT, (35)14, 2973-2980, (2017).

[7] A.W. Fang, et al., ‘A Continuous Wave Hybrid AlGaInAs-Silicon Evanescent Laser’, IEEE PTL, 18 (10), 1143-1145, (2006).

[8] T. Komljenovic, S. Srinivasan, E. Norberg, M. Davenport, G. Fish, J. E. Bowers, ‘Widely tunable narrow linewidth monolithically integrated external cavity semiconductor lasers’, IEEE JSTQE, 21, 6, (2015).

[9] T. Komljenovic, S. Liu, E. Norberg, G. A. Fish and J. E. Bowers, “Control of Widely-Tunable Lasers with High-Q Resonator as an Integral Part of the Cavity”, JLT, (35)18, 3934-3939, (2017).

[10] D. Jung, J. Norman, MJ Kennedy, C. Shang, B. Shin, Y. Wan, A. C. Gossard, and J. E. Bowers. ‘High efficiency low threshold current 1.3 µm InAs quantum dot lasers on on-axis (001) GaP/Si’, Applied Physics Letters, (111)12, 122107, (2017).

[11] P. A. Morton, Z. Mizrahi, ‘Low-Cost, Low-Noise Hybrid Lasers for High SFDR RF Photonic Links’, IEEE AVFOP, WD2, Sept. (2012).

[12] Paul A. Morton*, Michael J. Morton, Steven J. Morton, ‘Ultra Low Phase Noise, High Power, Hybrid Lasers for RF Mixing and Optical Sensing Applications’, Invited talk, AVFOP, TuB.1, (2017).

[13] D. T. Spencer, M. Davenport, S. Srinivasan, J. B. Khurgin, P. A. Morton, and J. E. Bowers, ‘Low kappa, narrow bandwidth Si_3N_4 Bragg gratings’, Optics Express, 23, 23, 30329 (2015).

[14] DARPA STTR # W911NF-16-C-0072. US Patents 9,559,484 9,748,726

[15] P. Pintus, D. Huang, C. Zhang, Y. Shoji, T. Mizumoto, and J. E. Bowers, “Microring-based Optical Isolator and Circulator with Integrated Electromagnet for Silicon Photonics”, Invited Paper, Journal of Lightwave Technology, (35)8, 1429-1437, April 15, (2017).

[16] D. Huang, P. Pintus, Y. Shoji, P. Morton, T. Mizumoto and J. E. Bowers, “Integrated broadband optical isolators for silicon photonics with over 100nm tuning range”, Optics Letters, (42) 23, (2017).

[17] C. Zhang, P. A. Morton, J. B. Khurgin, J. Peters, and J. E. Bowers, ‘Highly linear heterogeneous-integrated Mach- Zehnder interferometer modulators on Si’, Optics Express, 24, 17, p19040 (2016).

[18] C. Zhang, P. A. Morton, J. B. Khurgin, J. Peters, and J. E. Bowers, ‘Ultralinear heterogeneously integrated ring-assisted Mach–Zehnder interferometer modulator on silicon’, Optica, 3, 12, p1483 Dec (2016).

[19] Air Force SBIR ‘Integrable High Performance Analog Optical Modulators’, # FA8650-17-P-1114.

[20] J. B. Khurgin, P. A. Morton, ‘Tunable wideband optical delay line based on balanced coupled resonator structures,’ Opt. Lett. 34 (17), (2009).

[21] P. A. Morton and J. B. Khurgin, ‘Microwave Photonic Delay Line With Separate Tuning of the Optical Carrier’, IEEE PTL, 21, p1686 (2009).

[22] J. Cardenas, M. Foster, N. Sherwood-Droz, C. B. Poitras, H. L. R. Lira, B. Zhang, A. L. Gaeta, J. B. Khurgin, P. A. Morton, M. Lipson, ‘Wide-bandwidth continuously tunable optical delay using silicon microring resonators’, Optics Express, 18, p26525-26534 (2010).

[23] P. A. Morton, J. Cardenas, J. B. Khurgin, M. Lipson, ‘Fast Thermal Switching Of Wideband Optical Delay Line With No Long Term Transient’ IEEE Phot. Tech. Lett., 24, p512 (2012).

[24] Paul A. Morton, Jacob B Khurgin, Zemer Mizrahi, Steven J. Morton, ‘Commercially Packaged Optical True-Time-Delay Devices With Record Delays of Wide Bandwidth Signals’, CLEO, AW3P.6, (2014).

[25] Paul A. Morton, Jacob B Khurgin, Zemer Mizrahi, Steven J. Morton, ‘High SFDR ‘Super-Ring’ Microresonator Based True-Time-Delay (TTD)’, 2014 IEEE AVFOP Conference, TuD2, (2014).

[26] C. Xiang, M. L. Davenport, J. B. Khurgin, P. A. Morton, and J. E. Bowers ‘Low Loss Continuously Tunable Optical True Time Delay Based on Si_3N_4 Ring Resonators’ IEEE JSTQE, 99, Dec. (2017).

[27] W. Jin, E. J. Stanton, N. Volet, R. G. Polcawich, D. Baney, P. A. Morton and J. E. Bowers ‘Piezoelectric tuning of a suspended silicon nitride ring resonator’ IEEE Photonics Conference (IPC), MD3.2, (2017).

[28] J. Hulme, MJ Kennedy, R-L Chao, L. Liang, T. Komljenovic, J-W Shi, B. Szafraniec, D. Baney, and J. E. Bowers, ‘Fully integrated microwave frequency synthesizer on heterogeneous silicon-III/V’, Opt. Express, vol. 25, no. 3, pp. 2422-2431, (2017).

[29] J. C. Hulme, J. K. Doylend, M. J. R. Heck, J. D. Peters, M. L. Davenport, J. T. Bovington, L. A. Coldren, and J. E. Bowers, "Fully integrated hybrid silicon two dimensional beam scanner," *Opt. Express*, vol. 23, no. 5, pp. 5861-5874, (2015).