Advanced PIC Technologies and Recent Simulation Tools: A Survey

K.Bhuvaneshwari¹, B.Elizabeth Caroline²

¹Associate Professor, Department of Electronics and Communication Engineering, IFET College of Engineering, Villupuram.

²Professor, Department of Electronics and Communication Engineering, IFET College of Engineering, Villupuram.

*bhuvisha04@gmail.com, becaroline05@yahoo.com

Abstract. Nowadays, electronics were completely replaced by photonics as a result of substantial growth in Photonic Integrated Circuits (PICs). The expansion of photonics on various platforms such as III-V integration, silicon photonics, polymer integration and lithium Niobate techniques were reviewed and the parameters like bandwidth, data rate and bit error rate were analyzed on time and frequency domains. A study of the Photonic integration software was included such as Lumerical interconnect to interconnect PIC simulator and the co-simulation software OPTSIM tool.

Keywords. Photonic Integrated Circuits, III-V Integration, Silicon Photonics, Polymer Integration, Lithium-Niobate, Lumerical INTERCONNECT, OPTSIM

1. Introduction

Photonic Integrated Circuits (PICs) integrates multiple photonic components embedded in it. PICs are optical equivalents to electronic ICs. It involves integration of optical functions into a single chip where photons are the data carriers. PICs are implemented with few hundred ICs compared to millions of ICs used in Electronic ICs. PICs model enables simulation, validation and optimization of a full optical link. Optimisation of components are done on both transmitter and receiver portions and the response is measured using different parameters including frequency, wavelength and response.

PICs can be interfaced with electronic circuits which makes it suitable for many applications. A wide research work has been done in the field of photonics since it is highly efficient and available at lower cost. There are future scopes where electronics may be completely replaced by photonics, or combination of electronics and photonics.

Heteroepitaxy involves epitaxial growth of composite semiconductors such as Gallium Arsenide and Indium Phosphide on silicon for the manufacture of photonic devices. Many researchers integrated traditional CMOS logic with the extraordinary RF and optical properties of III-Vs [1], which is one among the leading platforms for photonic integration known as III-V Photonic Integration. The merits of the III-V Integration technology are monolithic integration of passive/active components, ultra-high speed EO characteristics and high reliability. The demerits of III-V Integration technology includes, extensive integration approach due to CMOS incompatibility, increased propagation losses (>0.5 dB/cm), limitations of mass production due to small wafers (InP), low index contrast (Δn/n).

Hybrid assembly or monolithic integration are the two basic approaches for merging electronics with photonics. In hybrid integration, photonic chips are combined with electronic chips after each of its separate fabrication [2]. Low propagation and coupling loss and other application specific improvements has led to progress of LN for photonic applications [3]–[6]. Habitually, the in-diffusion of titanium around 1000 °C has been used to form stripe waveguides (Ti:LN) in bulk LN wafers [4]–[7]. Ti:LN waveguides were widely studied and enhanced for commercial applications such as EO...
modulators. Therefore, both transverse-electric (TE) and transverse-magnetic (TM) modes are guided, depending on the nature of the Ti diffusion [8]-[9].

This manuscript is organised as follows. Section 2 depicts the overview of PIC techniques and section 3 gives a literature review of existing PIC platforms developed by various investigators. In Section 4, the simulation tools that are used for the design of PICs was explained. Section 5 concludes the paper by summarizing the PIC technologies and its applications.

2. Review of PIC Techniques

2.1 III-V Integration platform

The integrated transmitter (combining silicon modulators with hybrid III-V/Si lasers) for On-Off Keying (OOK) signal generation exhibited greater than 30 nm wavelength tunability and admirable data rate of 40 Gb/s [10] was demonstrated by De Valicourt et al. Heterogeneous integration of III-V on silicon proposed by Duan et al was evidenced to be an effective way to fabricate laser sources on silicon whose performance was outstanding that of a monolithically integrated InGaAsP laser on InP substrate [11]. The measured linewidth of the laser indicates that tunable laser design is appropriate for 100 Gb/s intelligible applications. Hybrid III-V/Si laser modulated at 10 Gb/s seems to be appropriate for access and metropolitan networks.

The integration of hybrid III–V/Si lasers and Semiconductor Optical Amplifiers (SOA) using wafer bonding proposed by Duan et al, exhibited 28 dB internal Gain, 9 dB output saturation Power, and 10–11 dB internal Noise Factor [12]. Using a high-speed directly modulated hybrid laser with improved E/O bandwidth results in 21.4 Gb/s modulation over 12 wavelengths. Duan et al proposed a hybrid III–V/Si lasers with two integrated intra-cavity Ring Resonator (RR) that achieved an extensive thermal tuning range, with a suppression ratio > 40 dB [13]. The integrated transmitter with combined silicon modulators manifested 9 nm wavelength tunability, higher extinction ratio of 6-10 dB, and admirable data rate of 10 Gb/s.

Gallet et al demonstrated a fully integrated Chirp Modulated Laser (CML) on a III-V platform, and III-V/SOI and a RR [14]. For a 90 Km fiber, the Forward Error Correction (FEC) was done with limited penalty. A hybrid III–V/SOA proposed by Peter Kaspar et al showed an extreme gain (fiber to-fiber) of 10 dB and an internal gain of 28 ± 2 dB [15]. Transmission with a Bit Error Rate (BER) below the FEC limit was demonstrated upto ten loops using QPSK, four loops using 16QAM and six loops using 8QAM.

The electrically pumped III–V quantum well lasers proposed by Lee et al [16], facilitated the effective optical coupling with in-plane passive waveguides. The demonstrated laser device had a least threshold of 50mA, a maximum output power of 9mW, and a differential quantum efficiency of 27.6%. The integration of III-V optoelectronics with silicon circuitry was proposed by Mathine et al, provided the potential for fabricating dense parallel optical interconnects with data links capable of Terabit aggregate data rates [17]. Researchers developed a set of emitters, detectors, and electronics for the integration of high-speed EO bread board, readily compatible with CMOS circuitry provides high speed optical links.

An intense research on hybrid lasers, modulators and PDs was done by Ramirez et al to implement optical modules and photonic integrated networks resulting in improvements on packaging and thermal management of PICs [18]. The hybrid III-V integration on Si transmitters and receivers for high-speed optical communications were demonstrated. Read et al introduced the need for lasers on silicon and explained the progress of laser technology and its potential towards attaining high data rates and low energy consumption. [19].
A compact waveguide optical interconnect on a Silicon-On-Insulator (SOI) platform developed by Spuesens et al contained distinct layers for both the laser and detector, guarantees dense integration with the microdisk laser whose threshold current is 0.45 mA and a slope efficiency of 57 µW/mA [20]. Lishu Wu et al demonstrated the wafer-scale heterogeneous integration of III-V MMIC and Silicon CMOS on the same substrate based on epitaxial layer transfer technique [21]. Researchers exhibited a wide band GaAs digital controlled switch and InP HBT quantizing chip with 1:16 demultiplexer, with greater potential.

2.2 Silicon Photonics
Silicon photonics became one of the leading technologies for Photonic integration due to large-scale integration assisted by CMOS fabrication. Due to cost-efficiency and high-performance, silicon photonics are widely used in transmitters and receivers. Silicon Nitride (Si$_3$N$_4$) is a high index and a familiar substance, which offers uniformly valuable option to produce PICs. 

Wang et al demonstrated a wafer-level sorting test built for quad-channel linear driver used in 400G transceiver module [22]. The authors had analyzed wafer sorting test that covered the following: power consumption, contact test, single-ended and S-parameter test, output signal swing and total harmonic test. A monolithically integrated and frequency tunable silicon Microwave Photonic Filter (MPF) was designed by Zhang et al [23], by adjusting the wavelength of the optical carrier injected into the chip. The 3-dB bandwidth and the frequency tunable range was measured to be 2.7 GHz and 12 GHz respectively. A passive silicon photonic device designed by Cong et al converts phase input to sigmoid power output, was approved by simulation [24]. The waveguide width and the radius of ring was 430 nm and 12 µm, respectively whose Free Spectral Range (FSR) was found to be 8 nm.

Kasper Van Gasse et al developed a Si based Radio-over Fiber link PIC with directly modulated laser source. Researchers presented a link that transported data up to 16 Gbps 16-QAM on a 20 GHz carrier over 5 km of SMF [25]. Researchers demonstrated a Silicon PIC based RoF link capable of transmitting 16 Gbps of data on a 20 GHz carrier at a BER of 3x10$^{-6}$.

Zhang et al developed an integrated MPF that consists of a high-speed Phase Modulator (PM), a thermally tunable high-Q Micro-Disk Resonator (MDR), and a high-speed PD [26]. On thermally tuning the MDR, the center frequency of the IMPF has been tuned from 7 to 25 GHz at a power consumption of 1.58 mW. The authors demonstrated the codesign and cointegration of an ultracompact silicon photonic receiver and a low-power-consumption two-channel linear transimpedance array amplifier.

Rahim et al demonstrated Planar Concave Grating (PCGs) on SOI and Silicon Nitride [27]. The SiN PCG was fabricated using 0.3 µm Low Pressure Chemical Vapour Deposition (LPCVD) SiN, whose crosstalk and insertion loss was measured to be −34 dB and 1.5 dB respectively. The researchers concluded that, the integration of high-speed modulators and detectors depends on SiN PICs. Photonic wire bonding was demonstrated by Lindenmann et al to promote efficient coupling between multicore fibers and planar silicon PICs. On coupling four-core fiber with silicon PIC, the coupling loss was 1.7 dB [28]. Zain et al fabricated a one-dimensional (1-D) photonic crystal/photonics wire (PhC/PhW) based on SOI [29]. The experimental results were enhanced to a resonance-factor from 18,700 to 24000 approximately, with normalized optical transmission of 70%.
2.3 Polymer Integration
The stress releasing property and surface tolerance of polymers make it suitable for hybrid bonding over the usage of oxides.

Takeru Amano et al fabricated a silica-based hybrid (a combination of organic and inorganic) polymer optical circuit that contained 96-channel multimode polymer optical waveguides, selectable-angle mirrors and 4 optical card edge connectors to the 96 small Multi Mode Fibers (MMF) on PCB [30]. The fabricated optical edge connector whose coupling loss was found to be 0.5 dB at 16 channels. Mangal et al explored a silicon photonic chip with polymer multimode waveguides on a package substrate using electro-optic 3D integration scheme [31] whose optical loss was measured to be 7.6 dB.

Hybrid bonding integrates vertical interconnection of various functional chips, reduces RC delay and realization of heterogeneous integration by bonding process takes place. Cheng-Hsien Lu et al tested the adhesion property of polymer by demonstrating polymer-to-polymer wafer-level bonding [32]. Hybrid photonic technology based on Polymer waveguide allowed for laser integration, wavelength splitters/combiners, receivers, and other optical functionalities. Martin Schell et al proposed PolyBoard photonic integration platform, whose experimental results showed that the single-mode optical interconnects exhibit propagation loss of 0.8 dB/cm around 1550 nm [33]. A 3-dB bandwidth of above 110 GHz was demonstrated for a waveguide of 1 mm length and the area of application of such PIC includes broad range telecom/datacom, sensing and spectroscopy.

Nano Imprint Lithography (NIL) offers high precision patterning using wafer based on roll-to-roll process. Rohit Kothari et al [34] developed a hybrid UV-NIL containing 90% nanoparticles with excellent optical transparency for generating large-area, 3D photonic crystal structures and optical gratings. Groumas et al presented a hybrid (combination of passive and electro-optic polymers) integration platform and investigated the transmission performance at 80 and 100 Gb/s. The BER was less than $10^{-10}$ at 80 Gb/s after 1625 m and $10^{-7}$ at 100 Gb/s after 1625m [35].

An ultra-fast bonding and releasing process was examined by Tsung-Yen Tsai et al towards the improvement of 3D integration [36]. The submicron release layer was a positive photoresist with the characteristic of high UV absorption while the adhesive layer provided strong mechanical strength for the wafer thinning process. Jin Tae Kim et al [37] demonstrated the replication technology for implementing the polymer Micro Opto Electromechanical System (MOEMS)-based packaging structure and concluded that replication technology plays a vital role in cost effective, high volume manufacturing of optical MOEMS systems and optical interconnection systems.
Lin Zhu et al integrated a 3-dB multimode interference coupler with a sidewall Bragg grating in planar polymer waveguide by direct electron beam writing [38] and demonstrated the fabrication of polymeric 3-dB MMI coupler, which acts as a broad-band OADM filter, at a minimal bandwidth of 2.9 nm.

2.4 Lithium Niobate Photonic Integration
Lithium Niobate (LN) has incredible flexibility as a substrate for integrated optics. In many applications, the fiber to chip losses were greater than 10 dB in LN PIC. Lingyan et al [39] experimentally demonstrated a low-loss converter for coupling a standard lensed fiber and sub-micrometer LN waveguide. The coupling loss was found to be less than 1.7 dB/facet with high fabrication tolerance and repeatability.

Integration of telecom quantum dots [40] with LN photonics was implemented by Aghaeimeibodi et al using photon correlation measurement. The performance of on-chip beam splitter confirmed the nature of single-photon emission. Sohler et al [41] designed the first RR fabricated LN with a diameter of 60 mm for rotation rate sensing and a programmable wavelength filter was designed with 85 mm length and 65 converter sections that produced a group delay of 22 ps.

Shengqian Gao et al implemented a high-speed optical switch LN integration platform [42] in which the fabricated device exhibited drive voltage < 10 V, and low power dissipation due to electrostatic operation. The proven optical switch provided a polarization dependence loss of 0.8 dB. The integration of optical waveguides with LN waveguides was demonstrated by Honardoost et al. Thin-film LN and chalcogenide (ChG) glass waveguides were combined and an optical mode transition was achieved, with a measured loss of ∼1.5 dB and ∼1.75 dB for TE and TM input polarizations respectively [43].

Loridat et al proposed a method to overcome the sub-sampling limitations by using an electro-optic crystal which showed improvement in the sampling ratio, and an enhancement factor of 46 was obtained in the electrooptic device. Mahmoud et al demonstrated an Electro-Optic Modulator (EOM) based on racetrack resonator whose quality factor was $1.3 \times 10^5$ and a propagation loss of 2.3 dB/cm [45] and the performance parameters are tabulated in Table 1.

Ashutosh Rao et al observed that Ion-sliced thin-film LN compact waveguide technology offered magnitude improvement in optical confinement and bending radius compared to conventional LN waveguides. Yong-Ha Song et al presented MEMS filters based on shear horizontal (SH0) mode Lithium Niobate (LiNbO3) Laterally Vibrating Resonators (LVRs). The measured performance exhibited in-band ripple-free response, excellent piezoelectric coupling and low acoustic loss in LiNbO3, ensured the low IL of 1.7 dB and large FBW of 9.6%. The filters had a device footprint less than 360 x 350 μm², making it suitable for wireless handheld devices.

Compact LN polarization-independent EOM using integration of polarization splitters and mode converters were presented by Chia-Wei Hsu et al [48]. Experimental results showed the polarization dependent loss was 0.04 dB at 26 Volts. The external-modulator technology of lithium-niobate was reviewed by Wooten et al showed the performance and reliability requirements of current 2.5-, 10-, and 40-Gb/s digital communication systems.

Table 1 Comparison of Different PIC Techniques
3. Simulation Tools of PICs

Modelling of optical circuit includes, building circuit models using programming languages such as MATLAB, implementing the optical models in an EDA environment (Luxtera) using Verilog and a commercial tool, Advanced Simulator for Photonic Integrated Circuits (ASPIC) for simulating the

| Sl no. | PIC Techniques                                                                 | Comparison of Performance measures                                                                 |
|--------|--------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|
| 1      | Integration of hybrid III–V/Si lasers and Semiconductor Optical Amplifiers      | Internal gain- 28 dB                                                                                  |
|        |                                                                                  | Saturation power- 9 dB                                                                                |
|        |                                                                                  | Internal noise factor- 10.11 dB                                                                       |
|        |                                                                                  | Transmission over 60 km Single Mode Fiber (SMF) at 10 Gb/s                                           |
|        |                                                                                  | 21.4 Gb/s modulation over 12 wavelengths                                                               |
| 2      | Compact optical interconnect on a SOI platform                                   | Microdisk Threshold current- 0.45 mA                                                                 |
|        |                                                                                  | Slope efficiency- 57 µW/mA                                                                            |
|        |                                                                                  | Responsivity of detector- 0.69 A/W                                                                     |
|        |                                                                                  | Full optical link static efficiency-3%                                                                |
|        |                                                                                  | Bandwidth- 7.6 GHz.                                                                                   |
| 3      | Si based Radio-over Fiber (RoF) link PIC with a directly modulated laser        | Transport data up to 16 Gbps 16-QAM on 20 GHz carrier over 5 km of SMF                                  |
|        |                                                                                  | RoF link transmit 16 Gbps of data                                                                     |
|        |                                                                                  | BER- 3x10^-6                                                                                          |
| 4      | Combination of passive and electro-optic polymers                               | BER- 10^-10 at 80 Gb/s after 1625 m                                                                  |
|        |                                                                                  | <10^-10 at 100 Gb/s after 500 m                                                                       |
|        |                                                                                  | <10^-9 at 100 Gb/s after 1000m                                                                        |
|        |                                                                                  | 10^-7 at 100 Gb/s after 1625m                                                                        |
| 5      | Electro-Optic Modulator (EOM) based on racetrack resonator                      | Quality factor- 1.3 x 10^5                                                                             |
|        |                                                                                  | Propagation loss- 2.3 dB/cm.                                                                           |
|        |                                                                                  | Modulation bandwidth- 4 GHz                                                                           |
|        |                                                                                  | Wavelength tuning rate- 0.32 pm/V                                                                      |
|        |                                                                                  | ER < 10 dB                                                                                            |
| 6      | MEMS filters based on shear horizontal mode Lithium Niobate                     | Center frequency- 400 and 750 MHz                                                                     |
|        |                                                                                  | Exhibited in-band ripple-free response                                                                |
|        |                                                                                  | Low insertion loss- 1.7 dB                                                                            |

3. Simulation Tools of PICs

Modelling of optical circuit includes, building circuit models using programming languages such as MATLAB, implementing the optical models in an EDA environment (Luxtera) using Verilog and a commercial tool, Advanced Simulator for Photonic Integrated Circuits (ASPIC) for simulating the
steady-state response for time-domain modelling, such as Photon Design PIC Wave and Optiwave OptiSystem, and using tools that simulate both the time-domain and frequency-domain circuit response, including Synopsys RSoft OptiSim and ModeSYS. Numerical INTERCONNECT is one of the optical circuit modelling tools that allows for the design, simulation and analysis of integrated circuits. INTERCONNECT includes both time and frequency domain simulators. Very close coupling between components can be done for the analysis of optical resonators. Frequency domain simulations are performed to calculate the overall circuit response, by solving a sparse matrix that represents the circuit as connected scattering matrices. The individual elements can be built using experimental data, analytic models, or numerical models.

OPTSIM is a simulation program developed by Synopsys that offers many opportunities in optical network design. The application supports simulation of various WDM techniques such as Coarse and Dense Wavelength Division Multiplexing, OTDM (Optical Time Domain Multiplexing) networks, FTTC (Fiber To The Curb) method of terminating optical fiber, Amplitude modulation techniques and so on. The main advantage is its cooperation with external applications such as MATLAB and SPICE, and lot of examples with final solutions that are provided by Synopsys.

The performance parameters of each technique can be analyzed in terms of BER, eye diagram, jitter and Q factor.

4. Conclusion
An extensive survey has been done on various platforms of PICs in this paper. Several methods have been analyzed for design and evaluation of PICs such as III-V Integration, Silicon photonics, Polymer integration and Lithium Niobate technologies and their advantages and disadvantages were discussed. Several techniques on PICs were narrated in various sections and reviewed elaborately. PICs are widely used because of its small size, high data rates and low power consumption. Finally, a comprehensive study has been done on diverse key elements like the type of laser waveguides, photodetector, modulator being used. There are future scopes where electronics may be completely replaced by photonics, or integration of photonics and electronics. PIC finds its application in various fields such as Fibre-optics, Bio-photonics, Photonic Computing, Nano Photonics and Sensors.

References
[1] Liu, A. Y., & Bowers, J. (2018). Photonic Integration with Epitaxial III–V on Silicon. IEEE Journal of Selected Topics in Quantum Electronics, 24(6), 1–12.
[2] Dagli, N. (n.d.). Hybrid integration of polymers and semiconductors for photonic integrated circuits. Technical Digest. CLEO/Pacific Rim ‘99. Pacific Rim Conference on Lasers and Electro-Optics (Cat.No.99TH8464). doi:10.1109/cleopr.1999.811402
[3] Rao, A., & Fathpour, S. (2018). Heterogeneous Thin-Film Lithium Niobate Integrated Photonics for Electro-optics and Nonlinear Optics. IEEE Journal of Selected Topics in Quantum Electronics, 24(6), 1–12.
[4] Rao, A., & Fathpour, S. All integrated Lithium Niobate Standing Wave Fourier Transform Electro-optic Spectrometer. (2018). Journal of Lightwave Technology, 1–1.
[5] Hsu, C.-W., Huang, C.-F., Tsai, W.-S., & Wang, W.-S. (2017). Lithium Niobate Polarization-Independent Modulator Using Integrated Polarization Splitters and Mode Converters. Journal of Lightwave Technology, 35(9), 1663–1669.
[6] Gao, S., Xu, M., He, M., Chen, B., Zhang, X., Li, Z., Cai, X. (2019). Fast Polarization-Insensitive Optical Switch Based on Hybrid Silicon and Lithium Niobate Platform. IEEE Photonics Technology Letters, 1–1.
[7] Mahmoud, M., Cai, L., Bottenfield, C., & Piazza, G. (2018). Lithium Niobate Electro-Optic Racetrack Modulator Etched in Y-Cut LNOI Platform. *IEEE Photonics Journal*, 10(1), 1–10.

[8] Honardoost, A, Gonzalez, G. F. C., Khan, S., Malinowski, M., Rao, A., Tremblay, J.-E,Fathpour, S. (2018). Cascaded Integration of Optical Waveguides with Third-Order Nonlinearity with Lithium Niobate Waveguides on Silicon Substrates. *IEEE Photonics Journal*, 10(3), 1–9.

[9] De Valicourt, G., Chang, C.-M., Eggleston, M. S., Melikyan, A., Zhu, C., Lee, J. Chen, Y. K. (2018). Photonic Integrated Circuit Based on Hybrid III–V/Silicon Integration. *Journal of Lightwave Technology*, 36(2), 265–273.

[10] Duan, G.-H., Olivier, S., Malhouitre, S., Accard, A., Kaspar, P., de Valicourt, G., Gentner, J.-L. (2015). New Advances on Heterogeneous Integration of III–V on Silicon. *Journal of Lightwave Technology*, 33(5), 975–983.

[11] Duan, G.-H., Accard, A., Kaspar, P., Jany, C., Le Liepvre, A., Make, D., Menezo, S. New advances on heterogeneous integration of III-V on silicon. 2014 The European Conference on Optical Communication (ECOC).

[12] Guang-Hua Duan, Jany, C., Le Liepvre, A., Accard, A., Lamponi, M., Make, D., Reed, G. T.(2014). Hybrid III–V on Silicon Lasers for Photonic Integrated Circuits on Silicon. *IEEE Journal of Selected Topics in Quantum Electronics*, 20(4), 158–170.

[13] Gallet, A., Shen, A., Levaufre, G., Make, D., Provost, J.-G., Brenot, R., Duan, G.-H. (2017). Integrated Hybrid III-V/SOI Directly Modulated DFB Laser and Ring Resonator at 10 Gbit/s. *IEEE Photonics Technology Letters*, 29(17), 1424–1426.

[14] Kaspar, P., de Valicourt, G., Brenot, R., Mestre, M. A., Jenneve, P., Accard, A., Menezo, S. (2015). Hybrid III-V/Silicon SOA in Optical Network Based on Advanced Modulation Formats. *IEEE Photonics Technology Letters*, 27(22), 2383–2386.

[15] Lee, C.-W., Ng, D. K.-T., Ren, M., Fu, Y.-H., Kay, A. Y. S., Krishnamurthy, V., Wang, Q. (2016). Generic Heterogeneously Integrated III–V Lasers-on-Chip with Metal-Coated Etched-Mirror. *IEEE Journal of Selected Topics in Quantum Electronics*, 22(6), 7–15.

[16] Mathine, D. L. (1997). The integration of III-V optoelectronics with silicon circuitry. *IEEE Journal of Selected Topics in Quantum Electronics*, 3(3), 952–959.

[17] Ramirez, J. M., Elfaiki, H., Verolet, T., Besancon, C., Gallet, A., Neel, D., Achouche, M. III-V-on-Silicon Integration: From Hybrid Devices to Heterogeneous Photonic Integrated Circuits. *IEEE Journal of Selected Topics in Quantum Electronics*, 1–1.

[18] Read, G. W., Marko, I. P., Hosain, N., & Sweeney, S. J. (2015). Physical Properties and Characteristics of III-V Lasers on Silicon. *IEEE Journal of Selected Topics in Quantum Electronics*, 21(6), 377–384.

[19] Spuesens, T., Bauwelinck, J., Regreny, P., & Van Thourhout, D. (2013). Realization of a Compact Optical Interconnect on Silicon by Heterogeneous Integration of III–V. *IEEE Photonics Technology Letters*, 25(14), 1332–1335.

[20] Wu, L., Kong, Y., Cheng, W., Zhang, Y., & Chen, T. (2017). Heterogenous integration of III-V MMIC and Si CMOS. 2017 IEEE Electrical Design of Advanced Packaging and Systems Symposium (EDAPS). doi:10.1109/edaps.2017.8276907.

[21] Wang, Y., Ding, H., Blakely, B., & Yan, A. Wafer-Level Test Solution Development for a Quad-Channel Linear Driver Die in a 400G Silicon Photonics Transceiver Module. 2019 IEEE 32nd International Conference on Microelectronic Test Structures (ICMTS). doi:10.1109/icmts.2019.8730947

[22] Zhang, J., Zhang, W., & Yao, J. (2019). A Monolithically Integrated and Widely Tunable Silicon Photonic Microwave Photonic Filter. 2019 International Topical Meeting on Microwave Photonics (MWP). doi:10.1109/mwp.2019.8892200
[23] Cong, G., Okano, M., Maegami, Y., Ohno, M., Yamamoto, N., & Yamada, K. Method to Generate Sigmoid-like Function in Silicon Photonic Devices Towards Applications in Photonic Neutral Network. 2018 IEEE 15th International Conference on Group IV Photonics (GFP). doi:10.1109/group4.2018.8478746

[24] Van Gasse,K., van Kerrebrouck,J., Abbasi,A., Torfs,G., Bauwelinck,J., & Roelkens.G. 16 Gbps RoF link at 20 ghz carrier frequency using a silicon photonics transmitter and receiver. International Topical Meeting on Microwave Photonics.

[25] Zhang, W., & Yao, J. A silicon photonc integrated frequency-tunable microwave photonic bandpass filter. 2017 International Topical Meeting on Microwave Photonics (MWP). doi:10.1109/mwp.2017.8168635

[26] Rahim, A., Ryckebroel, E., Subramanian, A. Z., Clemmen, S., Kuyken, B., Dhakal, A., Baets, R. (2017). Expanding the Silicon Photonics Portfolio with Silicon Nitride Photonic Integrated Circuits. Journal of Lightwave Technology, 35(4), 639–649.

[27] Lindemann, N., Dottermusch, S., Goedcke, M. L., Hoose, T., Billah, M. R., Onanuga, T. P., Koos, C. (2015). Connecting Silicon Photonic Circuits to Multicore Fibers by Photonic Wire Bonding. Journal of Lightwave Technology, 33(4), 755–760.

[28] Md Zain, A. R., Johnson, N. P., Sorel, M., & De La Rue, R. M. (2009). High Quality-Factor 1-D-Suspended Photonic Crystal/Photonic Wire Silicon Waveguide

[29] Amano, T., Noriki, A., & Mori, M. (2018). High density optical card edge connector for polymer optical waveguide on printed circuit board. 2018 IEEE CPMT Symposium Japan (ICSJ). doi:10.1109/icsj.2018.8602602

[30] Mangal,N., Missinne,J., Van Steenberge,G., Van Campenhout,J., & Snyder,B. Packaging silicon photonics with polymer waveguides for 3D electro-optical integration. 2017 IEEE Photonics Conference (IPC). doi:10.1109/ipcon.2017.8116289

[31] Lu.C.H, Kho.Y.T, Cheng.C.A, Huang.Y.J, & Chen.K.N. Polymer for wafer-level hybrid bonding and its adhesion to passivation layer in 3D integration. 2017 International Conference on Electronics Packaging (ICEP). doi:10.23919/icep.2017.7939437

[32] Schell,M., & de Felipe.D. Polymer based photonic integration for sensors, communication, and active optical PCB. 2017 IEEE CPMT Symposium Japan (ICSJ).

[33] Kothari, R., Howell, I., Zhou, Y., Hendricks, N. R., Beaulieu, M. R., & Watkins J, “Direct imprint patterning of 2-D and 3-D nanoparticle/polymer hybrid and crystalline metal oxide structures for printed optical, electronic, and energy devices”. 2016 6th Electronic System-Integration Technology Conference.

[34] Groumas. P, Zhang. Z, Katopodis. V, Konczy kowska. A, Dupuy. J.Y, Beretta. A, Kouloumentas. C,“ Tunable 100 GbAud Transmitter Based on Hybrid Polymer-to-Polymer Integration for Flexible Optical Interconnects”, Journal of Lightwave Technology, 34(2), 407–418.

[35] Tsung-Yen Tsai, Chien-Hung Lin, Chia-Lin Lee, Shan-Chun Yang, & Kuan- Neng chen “An ultra-fast temporary bonding and release process based on thin photolysis polymer in 3D integration”, 2015 International 3D Systems Integration Conference.

[36] Kim, J. T., Ju, J. J., Park, S., & Lee, M.-H. (2007). O/E Integration of Polymer Waveguide Devices by Using Replication Technology. IEEE Journal of Selected Topics in Quantum Electronics, 13(2), 177–184.

[37] Lin Zhu, Yanyi Huang, & Yariv, A. Integration of a multimode interference coupler with a corrugated sidewall Bragg grating in planar polymer waveguides. IEEE Photonics Technology Letters, 18(6), 740–742.

[38] Lingyan He, Mian Zhang, Amirhassan Shams-Ansari, Rongrong Zhu, Cheng Wang, and Lončar Marko, "Low-loss fiber-to-chip interface for lithium niobate photonic integrated circuits," Opt. Lett. 44, 2314-2317 (2019)
[39] S.Aghaeimeibodi, B.Desiatov, J.Kim, C.Lee, M.Buyukkaya, A.Karasahin, C.Richardson, R.Leavitt, M.Lončar, and E.Waks, "Integration of Quantum Emitters with Lithium Niobate Photonics," in Conference on Lasers and Electro-Optics, OSA Technical Digest (Optical Society of America, 2019), paper FM1M.3.

[40] W. Sohler, H. Hu, R. Ricken, V. Quiring, C. Vannahme, H. Herrmann, D. Büchter, S. Reza, W. Grundkötter, S. Orlov, H. Suche, R. Nouroozi, and Y. Min, "Integrated Optical Devices in Lithium Niobate," Opt. Photon. News 19(1), 24-31 (2008).

[41] Gao, S., Xu, M., He, M., Chen, B., Zhang, X., Li, Z., … Cai, X. (2019). Fast Polarization-Insensitive Optical Switch Based on Hybrid Silicon and Lithium Niobate Platform. IEEE Photonics Technology Letters, 1–1.

[42] Honardoost, A, Gonzalez. G. F, Khan, S, Malinowski M, Rao, A, Tremblay. J. E, Fathpour, Cascaded Integration of Optical Waveguides with Third-Order Nonlinearity with Lithium Niobate Waveguides on Silicon Substrates. IEEE Photonics Journal, 10(3), 1–9.

[43] Loridat et al, All integrated Lithium Niobate Standing Wave Fourier Transform Electro-optic Spectrometer. (2018). Journal of Lightwave Technology, 1–1.

[44] Mahmoud, M., Cai, L., Bottenfield, C., & Piazza, G. (2018). Lithium Niobate Electro-Optic Racetrack Modulator Etched in Y-Cut LNOI Platform. IEEE Photonics Journal, 10(1), 1–10.

[45] Rao, A., & Fathpour, S. (2018). Heterogeneous Thin-Film Lithium Niobate Integrated Photonics for Electrooptics and Nonlinear Optics. IEEE Journal of Selected Topics in Quantum Electronics, 24(6), 1–12.

[46] Song, Y.-H., & Gong, S. (2017). Wideband RF Filters Using Medium-Scale Integration of Lithium Niobate Laterally Vibrating Resonators. IEEE Electron Device Letters, 38(3), 387–390.

[47] Hsu.C.W, Huang.C.F, Tsai.W.S, & Wang.W.S. Lithium Niobate Polarization Independent Modulator Using Integrated Polarization Splitters and Mode Converters, Journal of Lightwave Technology, vol.35, no.9, pp.1663–1669.

[48] Wooten.E.L, Kissa.K.M, Yi-Yan.A, Murphy.E.J, Lafaw.D.A, Hallemeyer.P.F, Bossi.D.E. A review of lithium niobate modulators for fiber-optic communication systems. IEEE Journal of Selected Topics in Quantum Electronics, 6(1), 69–82.