2024 24th International Conference on Transparent Optical Networks (ICTON) | 979-8-3503-7732-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICTON62926.2024.10648027

Integrated microwave photonic functionalities on a hybrid integrated InP-Si_3N_4 PIC platform

Chris Roeloffzen, Paul van Dijk, Peter Maat, Ilka Visscher, Marcel Hoekman, Lennart Wevers, Edwin Klein, Roelof Bernardus Timens, Charoula Mitsolidou, Ahmad Mohammad, Robert Grootjans, Furkan Şahin, Roel Botter, Carlos Ruiz Pineda, Rick Heuvink, Ronald Dekker, Dong Liang, Sami Musa, Luis Gonzalez-Guerrero, Guillermo Carpintero
LioniX International BV, P.O. Box 456, 7500 AL, Enschede, The Netherlands
c.g.h.roeloffzen@lionix-int.com

ABSTRACT

This paper describes our hybrid integrated microwave photonic chip platform where ultra-low-loss Si_3N_4-based-TriPleX® and active InP integrated circuits are combined to enable broadband and high frequency radio signal processing in the optical domain. The platform consists of a high-power laser, high-speed modulators and detectors. Using this platform, we demonstrated reconfigurable microwave filters, multiplexers and demultiplexers, local oscillator (LO) generation, frequency converters, and repeaters.

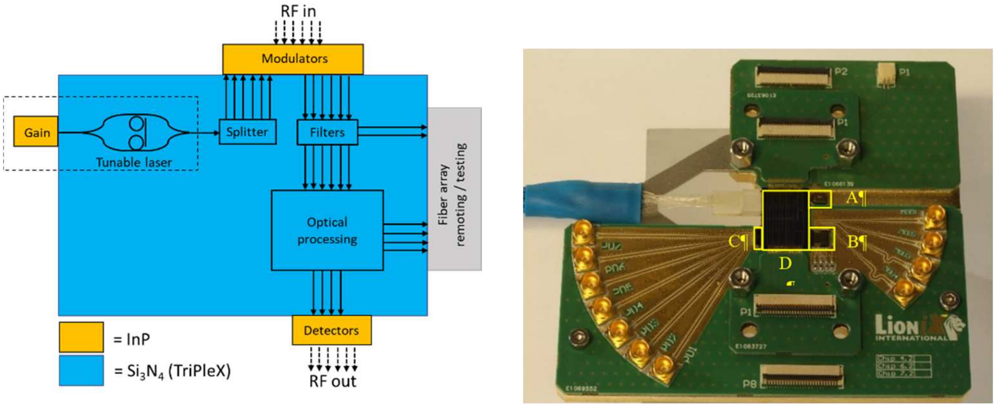
Keywords: integrated microwave photonics, hybrid integration, silicon nitride, filter, injection locking, repeater.

1. Introduction

Hybrid photonic integration offers a promising approach to overcome limitations associated with single-material platforms in photonic integrated circuits (PICs). By combining different substrate materials, such as InP and Si_3N_4, hybrid integration leverages the unique properties of each material to achieve enhanced performance and functionality in photonic devices. In the case of combining InP and Si_3N_4 PICs, as shown in Fig. 1, this hybrid approach capitalizes on the efficient optical gain, high-speed E/O and O/E conversion of InP and the ultra-low-loss and high-contrast waveguides of Si_3N_4.-based TriPleX® [1]. This synergy enables the development of compact, cost-effective, and high-volume transceivers, which are crucial for applications in telecommunications, data centers, and beyond. One notable achievement of this hybrid platform is the development of ultra-narrow linewidth lasers, which are essential for applications requiring high spectral purity and precision, such as coherent communication systems and spectroscopy [2, 3]. Additionally, microwave photonic processors based on this hybrid integration have demonstrated impressive performance, offering advantages in terms of bandwidth, power efficiency, and signal fidelity compared to conventional electronic processors. Overall, the hybrid integration of InP and Si_3N_4 holds great promise for advancing the field of photonic integrated circuits, enabling the realization of next-generation optical communication and sensing systems. The basic building blocks to realize the hybrid integrated microwave photonics platform, laser, modulator, and detector are introduced in Chapter 2 and recent developed functionalities and applications are given in Chapter 3.

2. Integrated microwave photonic processor and building blocks

The schematic overview (a) and photo (b) of the state-of-the-art integrated microwave photonic processor is shown in Fig. 1 where light from an integrated laser (A) is split in the TriPleX® PIC (D) and modulated by incoming RF signals in the InP PIC with array of 40 GHz modulators (B). The modulated signals are then processed in the TriPleX® PIC (D) after processing the signal is converted back to RF by the InP PIC with array of 40 GHz detectors (C). An additional fiber array is connected to the TriPleX® chip for the purpose of testing and calibration, or remoting of the signal.



(a) (b)

Fig 1: a) Schematic overview of a microwave photonic processor. b) Photo of a recent microwave photonic processor: (A) is the gain section, (B) the modulators, (C) the detectors, and (D) the optical processing chip.

979-8-3503-7732-3/24/$31.00 ©2024 IEEE

In an analog photonic link (APL) [2] the laser serves as the single-tone carrier, where its output power and intensity and frequency noise are critical parameters. Improvements in either of these parameters directly enhance APL performance. The optical laser power is particularly crucial because link gain increases quadratically with optical power. Our hybrid integrated lasers used in APLs typically have powers of around 100 mW or higher at optical wavelengths of 1530-1560 nm. The relative intensity noise (RIN) is well below -165 dBc/Hz and low compared to the RIN of a DFB laser with typical RIN of –150 dBc/Hz. With this low intensity noise, the dominating noise will become the fundamental shot noise of the system. While the linewidth (or frequency noise) of typical DFB (Distributed Feedback) lasers is approximately 1 MHz, high-performance hybrid external cavity lasers (ECL), as described in reference [3], can achieve linewidths of 300 Hz or less. This is in particularly important for dual laser heterodyning functionalities. The gain of an APL also depends on the sensitivity, insertion loss, and bandwidth of the modulator. The sensitivity of the modulator is given by its half-wave voltage V_π. The measured V_π as a function of modulation frequency for the used phase modulator (PM), which is ~2 V at DC, and increases to 3.8 V at a frequency of 30 GHz. Typical achieved TriPleX® to InP modulator coupling losses are < 1 dB. The RF photodiodes, have three important properties which have direct impact on the link gain: responsivity, diode bias, and detection bandwidth. The responsivity, R_{pd}, of the detector is a measure for the efficiency in the conversion of the optical power into an electrical current. The responsivity of the detectors used are around 0.8 A/W for optical wavelengths between 1530-1570 nm. The bandwidth of modern highspeed photodetectors is > 40 GHz at a reverse bias of 2 V with a frequency slope of 0.1 dB/GHz. Typical TriPleX® to InP detector coupling losses are also < 1 dB.

3. Applications

This chapter will highlight three recent realized integrated microwave photonic applications using our hybrid integrated platform. The first is a higher order filter used in dense WDM communication networks. The second example is a high frequency ultra stable microwave tone generator and the third application is a fully integrated repeater module in future high throughput satellites.

3.1 Microwave filters

One notable function enabled by TriPleX® circuits is Nyquist-filtering (de)interleaving, realized through a ring resonator-assisted Mach-Zehnder interferometer (RAMZI) circuit [4]. This RAMZI circuit consists of an asymmetric Mach-Zehnder interferometer with each arm coupled to a ring resonator. Experimental demonstration of this concept involves a RAMZI with an interleave period (Free Spectral Range, FSR) of 25 GHz and a 3 dB passband bandwidth of 12.5 GHz. The RAMZI serves as a pre-deinterleaving stage in conjunction with a commercial wavelength selective switch (WSS), enabling the implementation of a resolution enhanced WSS. This combination facilitates the realization of a Wavelength Division Multiplexing (WDM) super channel Reconfigurable Optical Add-Drop Multiplexer (ROADM), supporting a sub-channel spacing of 12.5 GHz, which is four times smaller than the current 50 GHz Dense Wavelength Division Multiplexing (DWDM) grid. Overall, TriPleX® circuits offer a versatile platform for implementing advanced functionalities in optical communication networks, facilitating higher spectral efficiency, finer granularity, and improved resolution in wavelength management.

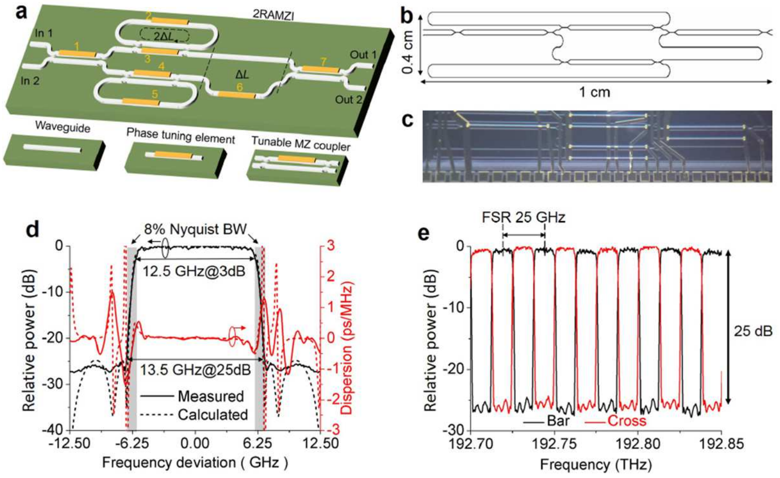


Fig. 2. (a) A schematic of the circuit, comprising a RAMZI. (b) Mask layout of a proof-of-concept chip using Si_3N_4 waveguide. (c) A photograph of a fabricated PIC, showing the waveguide circuit. (d) Measured passband power response and dispersion. (e) Measured bar- and cross-port responses. [4]

3.2 Stable LO generation

A microwave photonics application that has been recently explored in our hybrid PIC platform is mm-wave heterodyne tone generation [5] by beating two frequency stabilized lasers on one hybrid integrated PIC. Recent works integrating two InP-Si_3N_4 lasers on the same chip have shown that, while the two lasers can have very low intrinsic linewidth, the RF beat note still exhibits a long-term drift due to thermal instabilities. This drift, however, can be eliminated by optical injection locking (OIL) of the two lasers to an optical frequency comb. OIL is a process in which a “secondary” laser is synchronized to a “primary” laser by injecting light of the latter into the former. Ultra-stable mm-wave generation at 93 GHz is demonstrated by locking the dual-laser PIC to an external modulator-based comb generator.

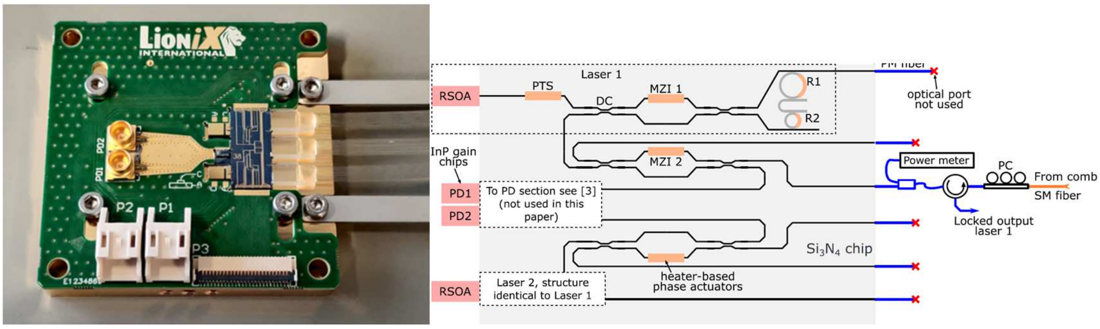


Fig. 3. Image of the hybrid module and schematic representation of it together with the experimental setup used to couple the light in and out of the photonic circuit. [5]

The comb line spacing of an externally generated comb was set to 15.5 GHz, with the two hybrid lasers locking to the + and −3rd-order sidebands, giving a heterodyne frequency of 93.16 GHz. The spectrum of the injected comb, and that of the locked output are shown in Fig. 4a. Fig. 4b shows the obtained max-hold spectrum for the free-running and OIL heterodyne signals after a period of five minutes. Using a resolution bandwidth of 10 kHz in the ESA, no drift was observed from the locked signal over this period. On the other hand, the max.-hold spectrum from the free-running source stretched over more than 16 MHz. The phase noise of the generated 93-GHz locked signal was measured with the Electrical Spectrum Analyzer (ESA) to confirm the quality of the locking. Fig. 4c shows the phase noise of the 93-GHz signal and that from the 15.5-GHz synthesizer signal used to drive the Optical Frequency Comp Generator (OFCG). As the multiplication factor was 6 (i.e., 15.5 × 6 = 93), the theoretically expected difference between the two curves is 20 log10(6) = 15.6 dB, which is approximately the difference observed in Fig. 4c.

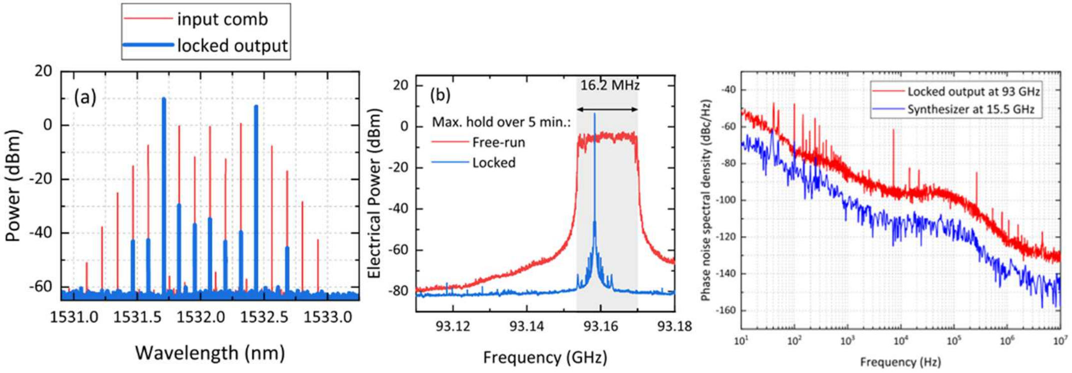
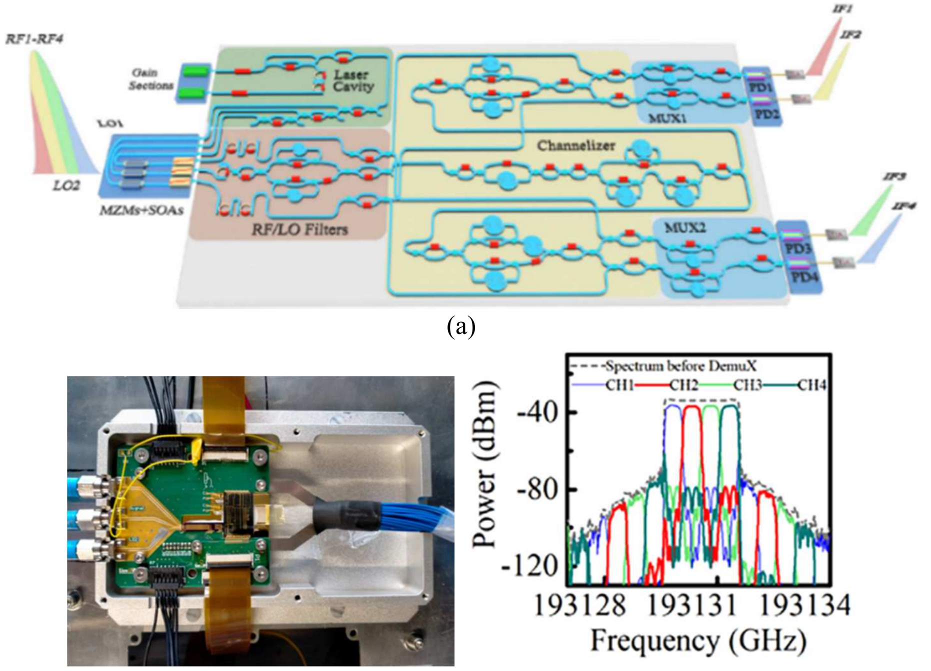


Fig. 4: (a) Input comb and locked output spectra, and (b) max.-hold power spectrum over 5 minutes of the free-running and locked signals (c). Phase noise spectral density of the 93-GHz locked signal and that from the 15.5-synthesizer signal used to drive the OFCG. [5]

3.3 Repeater

A photonic repeater configuration enables an HTS (High Throughput Satellite) communication payload to receive N broadband signals from gateways and transmit N×M narrowband signals to a set of user beams, where the repeater converts four 500 MHz broad signals in a 2 GHz from the 27 – 31 GHz Ka band into four 500 GHz channels in the lower Ka band 18 – 21 GHz [6]. A schematic and photo of the photonic repeater PIC is shown in Fig. 5a and 5b respectively. On the platform are the laser for the optical carrier, three modulators, where one modulator is used for RF to optical conversion and the additional modulators to create to additional optical LOs for the frequency down conversion. A 1x4 demux network splits the 2 GHz band into four separated 500 MHz channels (Fig. 5b). The frequency shifted LOs are added to the individual bands before the O/E conversion in the photodetectors. The photonic integrated payloads solution proposed in the paper offers significant advancements over traditional HTS payloads architectures based on microwave technology and photonic HTS payloads architectures relying on discrete optical modules. By leveraging chips fabricated from InP and Si_3N_4 materials, this solution achieves higher levels of integration in RF front-end processing. With an instantaneous processing bandwidth exceeding 2 GHz in the Ka-band and a channelization granularity of less than 500 MHz, it enables precise extraction of specific RF signal segments from continuous spectra.



(a)

(b)

(c)

Fig, 5: (a) The 3D drawing of the proposed chip, including different functional parts. These parts belong to different sub-chips, wherein the gain sections are on sub-chip; MZMs and SOAs are on the sub-chip; laser cavity, RF/LO filters, channelizer, MUX1, and MUX 2 are on the sub-chip; the four PDs and their corresponding TIAs (trans-impedance amplifiers) are on the sub-chip, (b) Photo of the photonic repeater chip, (c) Graph of the 4 channel demux with 500 MHz channel spacing. [6]

4. CONCLUSIONS

In this paper we presented an integrated microwave photonics link realized by hybrid integration of active and passive PIC technology. The individual building blocks and the link performance have been presented. And three applications have been highlighted. This proves the possibility of using integrated microwave photonic processing to facilitate wideband applications in the RF domain.

ACKNOWLEDGEMENTS

This work has been supported by the European Space Agency (ESA) within the TRP program “Tuneable Photonic RF Demultiplexer for Broadband Satellites - THORMUX” and by H2020 within the program “BlueSpace”, Contract no. 762055.

REFERENCES

[1] C. G. H. Roeloffzen et al., "Low-Loss Si_3N_4 TriPleX Optical Waveguides: Technology and Applications Overview," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 24, no. 4, pp. 1-21, July-Aug. 2018.

[2] C. Roeloffzen et al., "Integrated Microwave Photonics: A Chip Platform by Hybrid Integration of InP and SiN TriPleX," 2023 23rd International Conference on Transparent Optical Networks (ICTON), Bucharest, Romania, 2023, pp. 1-4, doi: 10.1109/ICTON59386.2023.10207429.

[3] Boller et al., “Hybrid Integrated Semiconductor Lasers with Silicon Nitride Feedback Circuits. Photonics” 2020, 7, 4. https://doi.org/10.3390/photonics7010004.

[4] Leimeng Zhuang et al., "Sub-GHz-resolution C-band Nyquist-filtering interleaver on a high-index-contrast photonic integrated circuit," Opt. Express 24, 5715-5727, 2016.

[5] Luis Gonzalez-Guerrero et al., "Injection Locking Properties of an Dual Laser Source for mm-Wave Communications," in Journal of Lightwave Technology, vol. 40, no. 20, pp. 6685-6692, 15 Oct.15, 2022.

[6] Dong Liang, et al., “Chip-Based Microwave Photonic Payload Repeater for High Throughput Satellites,” Laser & Photonics Reviews, vol. 18, no. 2, Feb 2024.