# Photonic Integrated Circuits for Space Communications

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**Abstract:** We present a hybrid integrated microwave photonic (iMWP) chip platform where $Si_3N_4$-based-TriPleX and InP optical waveguides are combined to enable broadband and high frequency radio signal processing. An iMWP beamformer for phased array antenna systems will be presented.

## 1. Introduction

The TriPleX® $Si_3N_4/SiO_2$ optical waveguide technology is the enabling technology for high performance integrated microwave photonic systems such as a beamforming network for phased array antennas [1]. The key enabler for this system is an ultra-low loss (< 0.08 dB/cm) integrated optical waveguide with a minimum bending radius of 85 µm [2]. Photonic chip integration is essential to meet the reliability requirements and future cost levels for consumer applications. This will enable industrial-volume deployment of the antenna systems in the future. However, to realize microwave photonic functionalities with sufficient performance, efficient conversion from RF to optical signals and back is required. The active InP platform enables the use of high-speed modulators and detectors (up to 40 GHz) as well as optical gain sections required for high power lasers (more than 100 mW), however InP suffers from high intrinsic propagation losses making signal processing on InP unfeasible instead the processing is performed on the low loss TriPleX® chip, including spot size converters for very low coupling losses to the InP chips (<1 dB/facet). These properties are mandatory for the processing of the microwave and mmWave signals as shown in Fig. 3a. In our approach, we hybridly combine the two chip technologies featuring RF interfacing and the advantages of MWP processing. In our MWP platform we generate [3] and modulate (RF-to-optical) the light with InP, filter and process the signals in TriPleX® , and, finally, detect the signals (optical-to-RF) using InP.

## 2. Link analysis

Optical Beamforming Networks (OBFNs) can be implemented with different types of Analog Photonic links (APLs). In this paper, the focus is on a Phase Modulator (PM) with single-sideband full carrier (SSBFC) link. The theory of the PM-SSBFC link, as shown in Fig. 1, is presented here.

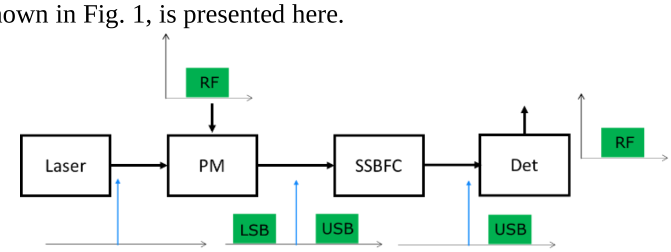



Figure 1: Analog optical link consisting of laser carrier, phase modulator, sideband suppression filters and photodetector.

For the PM link the DC photocurrent at the output of the detector is defined by Eq. 1.

$$I_{pd_{DC,q}} = R_{pd}\frac{P_0}{L} \tag{1}$$

Where $P_0$ is the optical laser power, $R_{pd}$ is the photodiode responsivity in A/W, and $L$ is the total optical loss. The RF output power of the fundamental tone is given by Eq. 2 assuming a 50 Ohm matched load system.

$$P_{ml\_RF} = \frac{I^2_{pd_{DC,q}}\,\varphi^2_{RF} R_L |H|^2}{2} \tag{2}$$

where $R_L$ is the load resistance, $|H|$ is response of the photodetector and the circuit between the photodiode and the load, and $\varphi^2_{RF} = 2\pi^2 P_{in} R_{in}/V_\pi^2$, where $\varphi$ is the phase deviation of the PM, which depends on the average RF input power, $P_{in}$, the input resistance $R_{in}$, and the frequency-dependent voltage to achieve a π phase shift in the modulator $V_\pi$. The most applicable definition of link gain for an APL is the so-called RF gain, which is defined as the ratio of the power delivered to the load $P_{ml\_RF}$, to the power available from the source, $P_{in}$. The RF link gain for a PM with single sideband full carrier (PM-SSBFC) is given by Eq. 3.

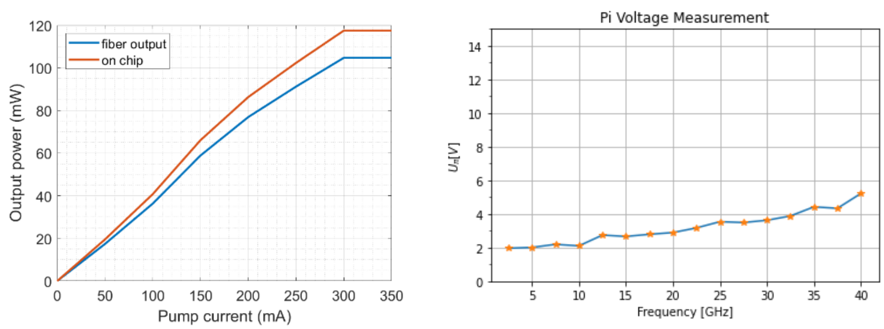
$$G_{PM-SSBFC} = \frac{P_{ml\_RF}}{P_{in}} = \frac{I_{pd_{DC,q}}^2}{V_\pi^2}\pi^2 R_L^2 |H|^2 = \left(\frac{R_{pd} P_0 R \pi |H|}{L V_\pi}\right)^2 \quad (3)$$

## 3. Integrated optical components and performance results

In this section the individual components from Fig. 1 and their impact on the link performance will be discussed.

### 3.1 Laser, Modulator & Photodetector

The laser acts as the single tone carrier in the system. The most important parameters of a laser in an APL is its output power and intensity noise. Improving any of these two laser parameters will improve the APL performance directly, as can be derived from Eq. 1 to 3. The noise analysis is not included in this paper. Of the two parameters, the optical laser power, $P_0$, is most crucial as the link gain increases quadratically with an increase in optical power. Hybrid integrated lasers as used in our APLs have powers of ~100 mW or higher at optical wavelengths of 1530-1560 nm. While the linewidth (or frequency noise) of typical DFB lasers is around 1 MHz, our high-performance hybrid external cavity lasers, such as described in [4], can exhibit linewidths of 300 Hz and less. Furthermore, the relative intensity noise (RIN) for hybrid integrated lasers is well below -165 dBc/Hz, making the system shot noise limited, while the RIN of DFB lasers is typically around – 150 dBc/Hz. The optical power of the InP-TriPleX based laser in shown in Fig 2a.




(a) (b)

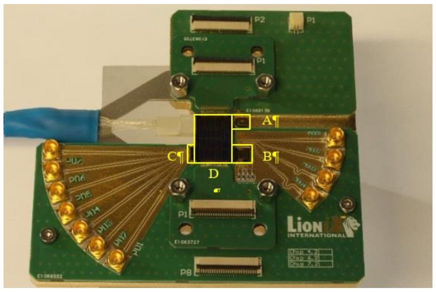
Figure 2: (a) Optical power vs injected current in the gain section measurement results hybrid integrated laser, (b) Measured sensitivity of the used phase modulator as function of RF frequency

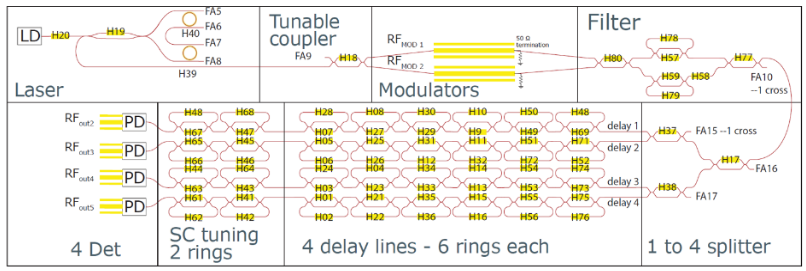
The gain of an analog photonic link also depends on the sensitivity, insertion loss, and bandwidth of the modulator. The sensitivity of the modulator is given by its half-wave voltage $V_\pi$. The measured $V_\pi$ as a function of modulation frequency for the used PM is shown in Fig. 2b, which is ~2 V at DC, and increases to 3.8 V at a frequency of 30 GHz.

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.

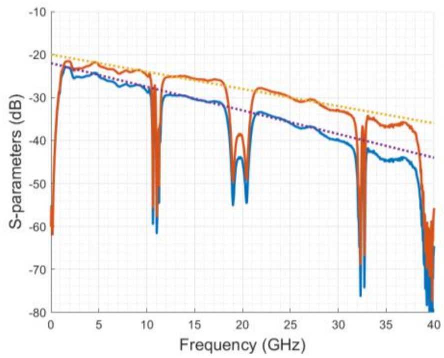
### 3.2 Optical beamfoming network

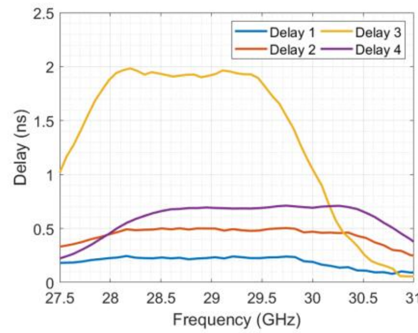
Link gain measurement from 10 MHz to 40 GHz of the analog photonic link is shown in Fig. 3c, blue with and red without the RF PCB. The link gain is -20 dB at DC with a slope of 0.4 dB/GHz. The transitions from USB to LSB or vice-versa due to the SSB filter are around 0 GHz, 20 GHz and 40 GHz. After characterization of the analog photonic link the delay responses of a cascade of 6 ring resonators in an optical beamforming network as shown in Fig. 3b were measured for varying delay settings from relative values of 0 to 0.8 ns, with a delay ripple smaller than 10 ps over the frequency range of 28.5 to 30.5 GHz as depicted in Fig. 3d. The delay (light blue curve) has also been increased to a delay value of 1.8 ns, with a ripple of 20 ps at the cost of a reduced bandwidth of 0.8 GHz.






(a) (b)




(c) (d)

Figure 3: (a) Photo of a recent microwave photonic beamformer for satellite communication, (b) schematic of a 1x4 Optical beamforming network, (c) measured RF optical link gain performance as function of the RF frequency. The red curve is from modulator input to detector output. The blue curve also includes the RF PCB losses and group delay measurement of a cascade of 6 ring resonators, (d) delay variation from 0 ns delay to 1.8 ns by tuning of the ring resonators.

## 4. Conclusion

In this paper we presented an integrated microwave photonics platform realized by hybrid integration of active and passive photonic integrated chip technology. The platform was used to realize an optical beamfoming network used Ka-band satellite communications. The individual building blocks and the link performance have been analyzed and measured. And the delay performance of the beamformer has been analyzed. This performance already shows the possibilities of using microwave photonic processing to facilitate wideband applications in the RF domain, such as phased array antenna systems.

## ACKNOWLEDGEMENTS

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