# INTEGRATED OPTICAL BEAMFORMERS

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***Abstract*—This paper discusses the challenges towards the realization of the integrated microwave photonic beamformer based on hybrid integration between InP and TriPleX $Si_3N_4/SiO_2$.**

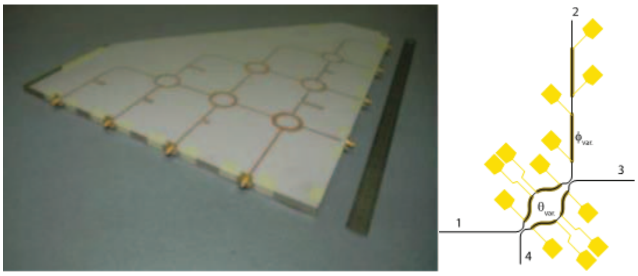
***Keywords—hybrid integration; iMWP; optical beamformer***

## I. INTRODUCTION

Microwave photonics (MWP) is an emerging field in which the radio signals are generated, distributed, processed and analysed using the strength of photonics. It is a disruptive technology which enables various functionalities which are not feasible in only the microwave or electronic domain. A particular aspect that has gained a significant interest recently is the use of photonic integrated circuit (PIC) technology in this field, i.e., integrated microwave photonics (iMWP) [1, 2, 3]. A field where iMWP can have a strong impact is the one of phased array antennas (PAA) for next generation mobile (5G) and Satcom networks. Such array antennas offer a number of attractive characteristics, including a conformal array profile, beamforming (beam shaping and beam steering), interference nulling and the capability to generate multiple antenna beams simultaneously. In many cases, however, the performance of a phased array is limited by the static characteristics of the beamforming network (BFN) used. It is generally desired to realize beamformers with broad instantaneous bandwidth, continuous amplitude and delay tunability and, at the same time, capable of feeding large arrays. This, however, is very challenging to achieve using electronics only.

## II. OPTICAL MULTIPLE-BEAMFORMING NETWORKS

The Blass/Nolen matrix is a phased array antenna feed structure which is capable to generate multiple beams. A Blass/Nolen matrix [4] is a microwave feeding network for antenna arrays consisting of a number of horizontal feed lines (rows) corresponding to the number of beams to be simultaneously generated, and a number of vertical feed lines (columns) connected to the radiating elements, as depicted in Fig. 1a. The two sets of transmission lines, usually referred to as rows and columns of the matrix, are interconnected at each crossover by a directional cross coupler. Signals applied at each input port propagates along the corresponding feed lines. At each crossover a certain (pre-designed) portion of the signal is coupled into each column, thus exciting the corresponding radiating element. The radiated beam direction is determined by the phase-differences (originating from different path lengths) between the input and the radiating element, whereas the power distribution throughout the array is controlled by the (pre-designed) coupling coefficients. The Blass/Nolen matrix is an interesting solution, whose main advantage is the capability to generate multiple beams placed in arbitrary directions, covering a wide scanning range. However, coupling coefficients and phase shifting elements (delay lines) are fixed after fabrication.



(a) (b)

Fig. 1: (a) A 4x4 RF-BFN Nolen matrix. The ruler on the right-hand side is a 50 cm ruler, the circles are 15 mm in radius and the RF connectors are about 10 cm apart from each other. This particular BFN is suitable for 3 GHz communication. This picture is copied from [5], (b) Schematic of a unit cell of the Nolen matrix consisting of a tunable 2x2 coupler and tunable phase shifter,

The optical Blass/Nolen matrix is based on a unit cell or node, as shown in Fig. 1b. Light enters the cell from the left hand side into a tunable Mach-Zehnder coupler (MZC). One of the two outputs of the MZC exits the cell on the right hand side. The other output is bent upward, passes a straight waveguide with an electrode pair, and exits the cell on the top side, to enter the adjacent cell from the bottom. A Blass/Nolen matrix can be created by cascading multiple unit cells.

For comparison, a 255 (antenna ports) x 36 (beam ports) Blass/Nolen matrix is theoretically investigated and designed. When comparing this integrated optical beam former (iOBFN) with a similar RF-BFN, the footprint of a Blass/Nolen matrix in RF is expected to be roughly 20.000 $cm^2$, while the footprint of a Blass/Nolen matrix as OBFN is expected to be around 90 $cm^2$. In footprint this is a reduction of two orders of magnitude. Simulation results are shown in Fig. 2a for a single beam and Fig. 2b for 36 beams simultaneously, tuned to a 6 x 6 grid.

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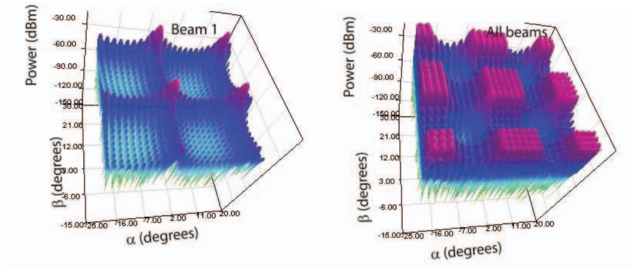

(a) (b)

Fig. 2: (a) Beam profiles for 1 beam of the 144x36 Nolen matrix, on a logarithmic scale. (b) Beam profiles for all 36 beams of the Nolen matrix, on a logarithmic scale.

## III. INTEGRATION

The TriPleX™ $Si_3N_4/SiO_2$ optical waveguide technology is the enabling technology for high performance integrated microwave photonic systems for phased array antennas [2]. The key elements of this technology are extremely low-loss (< 0.1 dB/cm) integrated optical waveguides with a minimum bending radius of 60 µm [6]. Photonic integration of the beam forming functionalities, is essential to meet the reliability requirements and future cost levels for consumer applications. This will enable industrial-volume deployment of the antenna system in the future.

However, to realize microwave photonic functionalities with sufficient performance, efficient conversion from RF to optical signals and back is required. The gain of this conversion is given by the following equation.

$$G_{MZM} = \left(\frac{\pi R_L r_{PD} P_i}{4 L_m V_\pi}\right)^2$$

where $R_L$ is the load resistance at the output of the photodiode (usually 50 Ω), $r_{PD}$ is the responsivity of the photodiode (0.8 A/W), $P_i$ is the optical output power of the laser (10 – 400 mW), $L_m$ is the optical link loss, and $V_\pi$ is the voltage sensitivity of the external Mach-Zehnder modulator (< 4 V). The higher the gain the better the performance of the link. Typical values are between -20 and 0 dB.

Hybrid integration between InP and TriPleX™ waveguides allow functionalities using the best of both worlds: active components on InP and passive components with low optical propagation loss on $Si_3N_4/SiO_2$.

## IV. DESIGN AND FABRICATION

Both, InP and TriPleX, chips will be realized as part of the ACTPHAST program and the mask layouts of the iOBFN are shown in Fig. 3. where an InP chip (left) is directly end-face coupled to TriPleX chip (right). The active InP chip consists of a gain section, 8 modulators and 16 detectors. The TriPleX chip consists of an 8x8 Blass matrix BFN, additional filter structures and ring resonator mirrors.

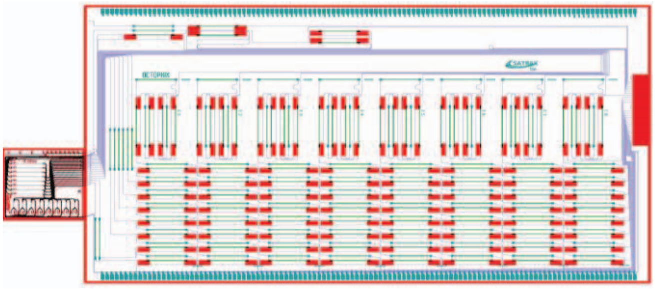

Fig. 3: Example of an integrated optical beamformer mask design. Left: InP design with gain (SOA), modulators and detectors, size 4 mm x 4.6 mm. Right: TriPleX design with Blass-matrix, filters and tunable laser cavity mirror, size 32 mm x 16 mm.

The InP design has been fabricated at SMART Photonics (see Fig. 4) and the characterization of the building blocks has been started. The TriPleX chip is in fabrication at LioniX.

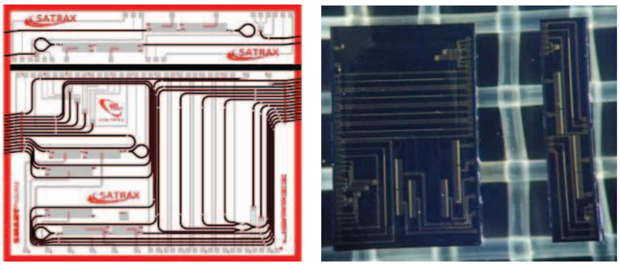

Fig. 4: Mask design and photograph of the InP chip showing gain section (SOA), 4 modulators and 4 detectors, size 3 mm x 4,6 mm (SMART Photonics). These basic components are also placed separately on the chip.

## V. PRELIMINARY RESULTS

The gain, modulators and detectors will be characterized separately using the test chip as shown in Fig. 5. The chip is placed on a temperature controlled chuck and stabilized at a temperature of 20°C. The light can be coupled in or out via a (lensed) fiber.

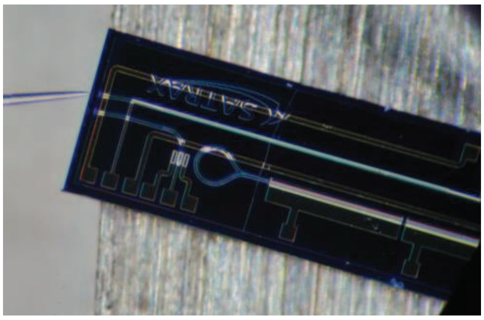

Fig. 5: Photograph of the fabricated InP test chip. The lensed fiber to couple light in or out of the chip can also be seen.

### A. *Gain (SOA)*

The gain section consists of two cascaded SOAs with length 500 µm and 750 µm respectively. One side of the waveguide is connected to a loop mirror and the other output is directed to the facet of the chip. The SOAs have separated bond pads and can be separately current driven. In this measurement we connected them to one currents source, so the total current is divided over the two SOAs. The optical output power of two gain sections are measured using an integrating sphere sensor instead of a lensed fiber. The sensor is placed directly in front of the output of the waveguide, where it collects the total output power. The measurement result is shown in Fig. 6. The maximum measured output power is 10 mW, at a current of 225 mA, where 20 mW was desired.

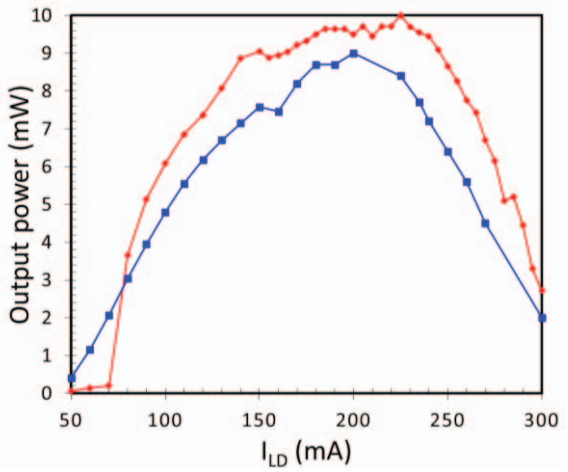

Fig. 6: Measured optical output power versus driving current of two different SOAs both with the combination of 750 µm and 500 µm (blue: SOA with 500 µm at the mirror and 750 µm in direction of the facet, red: SOA with 750 µm at the mirror and 500 µm at the end of facet). The driving current is divided over the two gain sections of the SOA. The light is collected by an integrating sphere detector. Maximum optical power is 10 mW.

### B. *Modulator*

The RF-PCB to drive and terminate the modulators has been designed and is in fabrication. We will start the characterization of the modulators when the PCBs are available. Desired performance >10 GHz, with $V_\pi$ <4 V.

### C. *Photodiode*

The fabricated PIN diodes have a length of 30 and 50 µm respectively, where the first one is measured. A lensed fiber has been used to couple the light into the waveguide of the detector. The polarization of the light has been changed to give maximum detector current. The measured output current versus output power of the fiber is shown in Fig. 7, for two distances between the lensed fiber and the facet of the chip. The maximum external responsivity is 0.15 A/W , which is lower than the desired 0.7 A/W, probably caused by fiber to chip coupling losses. The measured dark current at a reverse bias of 2 V is less than 100 nA, measurement limited by our current meter. The bandwidth of the detector will be measured when the RF-PCB is available. Desired speed > 10 GHz.

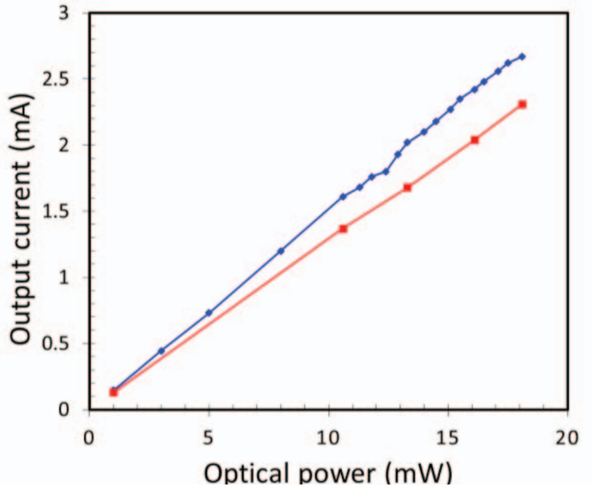

Fig. 7: Measured output current versus optical power at the output of the lensed fiber for two different distances between fiber and chip (blue 3 µm, red 5 µm). The measured diode has a length of 30 µm.

## VI. SUMMARY

The first steps toward a hybrid integrated optical beamforming network has been taken. Both InP and TriPleX have been designed and the InP chip is fabricated. Preliminary measurements have been performed. The maximum optical output power of the gain section is 10 mW, which is slightly lower than the desired 20 mW. The external responsivity of the photodiode is 0.15 A/W which is lower than the desired 0.7 A/W. Improved fiber to chip coupling will probably increase the responsivity. RF measurements will start with the availability of the RF-PCBs. Integration with the TriPleX OBFN will start when the fabrication is finished.

## ACKNOWLEDGMENT

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