Optical fiber-to-chip assembly process for ultra-low loss photonic devices based on silicon nitride for space applications

A. Brimont[1], **D. Zurita**[1], **V. C. Duarte**[2], **T. Mengual**[2], **B. Chmielak**[3], **S. Suckow**[3], **A. Giesecke**[3], **M. A. Piqueras**[2], **P. Sanchis**[1]
[1]Nanophotonics Technology Center, Universitat Politècnica de València,
Camino de Vera s/n, 46022 Valencia, Spain
[2]DAS Photonics, Camino de Vera s/n, 46022 Valencia, Spain
[3]AMO GmbH, Otto-Blumenthal-Str. 25, 52074 Aachen, Germany

e-mail: pabsanki@ntc.upv.es

ABSTRACT

In this work, we demonstrate an efficient fiber array-to-chip assembly process with a high number of input/output ports. The proposed approach is based on using a pre-alignment coupling structure to separately align the input and output ports. The assembling process has been experimentally validated in photonic integrated circuits fabricated with an ultra-low-loss waveguide technology based on silicon nitride, which features propagation losses as low as 9.5 dB/m. The developed technology is expected to extend the use of integrated photonics for space applications.

Keywords: silicon nitride, fiber-to-chip coupling, assembling, packaging.

1. INTRODUCTION

Photonic technologies may become key enablers to satisfy the flexibility, size, weight and power performance requirements for space applications [1]. The ability of photonics to handle high data rates, high frequencies and fast reconfigurability is critical for applications such as synthetic aperture radar space systems for next generation earth observation missions [2,3]. Photonics is a promising option for implementing beamforming networks based on true time-delay switching matrices [4,5]. When implementing true-time delay beamformers the signals are delayed instead of being phase shifted. This allows to have the correct phase shift for each frequency, and therefore, avoiding beam squinting and showing a broadband operation [6]. This type of beamforming also has the capability of performing multi-beam operation [7]. However, the use of photonics is currently restricted to a few demonstrations in non-critical equipment, due to their perceived immaturity compared to RF. One of the critical points is the mandatory need of an ultra-low loss photonic platform for minimizing the optical power budget and an efficient assembling process for optical fiber interconnection. In this work, an efficient fiber array-to-chip assembly process is proposed and demonstrated for interfacing ultra-loss photonic integrated circuits (PICs). The ultra-low loss PIC platform based on silicon nitride is firstly detailed. Then, the proposed assembly process is described and experimentally validated.

2. ULTRA-LOW LOSS PIC PLATFORM

The proposed PIC platform is based on the ultra-low loss photonic waveguide shown in Fig. 1(a). The core consists on a 2.8 µm wide and 100 nm high silicon nitride (Si_3N_4) waveguide, located on top of a 6 µm thick silicon dioxide (SiO_2) buffer layer that separates it from the silicon (Si) substrate. The waveguide core is covered by a 1.6 µm thick low temperature oxide (LTO) cladding layer. The simulated mode profile for TE polarization is shown in Fig. 1(b).

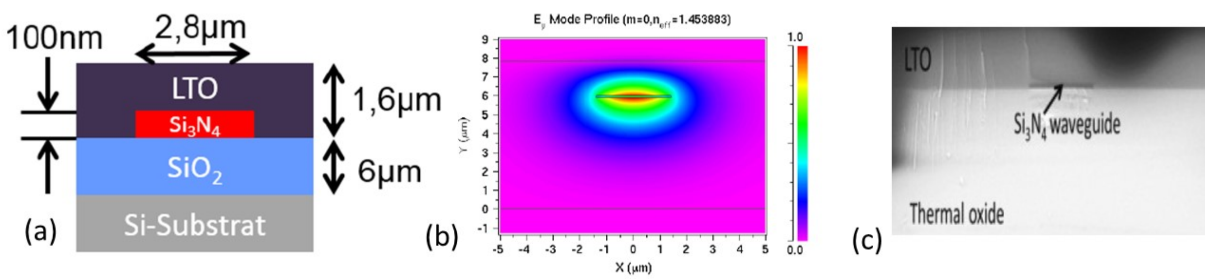

Figure 1.(a) Ultra-low loss photonic waveguide cross-section, (b) simulated mode profile for TE polarization and (c) fabricated waveguide.

The Si_3N_4 waveguide core was fabricated by low pressure chemical vapour deposition (LPCVD). The waveguide layer is defined via optical projection lithography with an i-line stepper tool and patterned via reactive ion etching

(RIE). An optimized RIE process is used, which yields steep and smooth sidewalls that are essential for low loss operation. After the etching step, the photoresist mask is removed using oxygen plasma and subsequently the LTO cladding material is deposited via LPCVD. Finally, the wafer is annealed at 1000°C for several hours, which is critical to improve the quality of the LTO layer and so ensuring low-loss operation. Fig. 1(c) shows a scanning electron microscope (SEM) image of the fabricated waveguide. The cut-back method was used to experimentally characterize the propagation losses. To achieve a good statistic, a full wafer featuring photonic waveguides with varying lengths from $1.5\ \mathrm{cm}$ to $109\ \mathrm{cm}$ was fabricated and characterized thoroughly, yielding ultra-low propagation losses of $9.5\ \mathrm{dB/m}$.

3. OPTIMIZATION OF FIBER-TO-CHIP ASSEMBLY PROCESS

2.1 Design of pre-alignment photonic structure for seamless fiber array coupling

A high number of input/output ports are usually required for supporting advanced multi-beam operation for space applications. Therefore, an efficient fiber-to-chip assembly process is necessary. A photonic structure, shown in Fig. 2(a), is proposed to carry out the pre-alignment procedure of the fiber array, which is then slightly moved to the functional ports of the photonic device. Grating couplers optimized for both positive and negative coupling angles ($\pm\ \theta$) are necessary. In such a way, the alignment of the fiber array at the input and output ports can be optimized separately. A configuration of 32 input/output ports is targeted. The proposed photonic structure is based on the interconnection of several ports by using directional couplers featuring a 1:99 splitting ratio. A low coupling ratio is desirable to achieve a similar optical power in all ports, which makes the optimization of the alignment process much more robust. Figure 2(b) shows the normalized output power by considering that the input signal is injected into port number #0 and considering that the optical power at the output ports is extracted by using a directional coupler with a coupling ratio of 1% and 10%. It can be seen that the power is lower for the smallest coupling ratio but turns out to be much more balanced (around $-20\ \mathrm{dBm}$) across each single output ports.

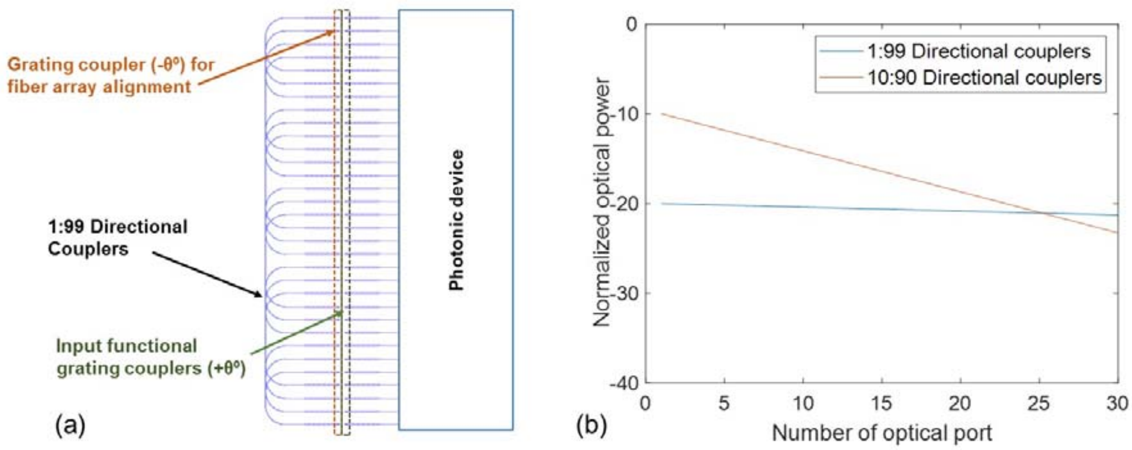

Figure 2.(a) Proposed photonic structure for fiber array pre-alignment. (b) Extracted normalized output power at each optical port by using directional couplers with a 1% and 10% coupling ratio.

2.2 Experimental demonstration of the assembly process

In the proposed approach of an efficient fiber assembly, low-loss grating couplers are a key building block to minimize the overall insertion loss of the assembled PIC. In the original grating coupler structure, coupling losses were as high as 10 dB [2]. Therefore, a new design was developed to reduce coupling losses by about a factor of two (in dB). A more detailed description of the final structure will be reported elsewhere.

An early photonic multiport waveguiding structure was fabricated to experimentally demonstrate the assembly process. The layout consisted of straight waveguides connected with the optimized grating couplers together with the proposed pre-alignment photonic structure. The fiber array is firstly aligned with the row of grating couplers, which couple light with a negative angle. Once aligned, each grating coupler become optically connected to the other ones via the 1:99 directional couplers, allowing us to measure an almost constant $-20\ \mathrm{dBm}$ output power across the grating couplers and seamlessly monitor the alignment process in situ. Once aligned, the fiber array is moved towards the functional grating couplers by a single translation.

Figure 3(a) shows an optical microscope image of the fabricated PIC. The measured spectra fiber-to-fiber at different ports are depicted in Fig. 3(b). Total fiber-to-fiber insertion losses of around 11.9 dB and 13.2 dB were measured, yielding $\approx$ 5.85 to 6.6 dB coupling losses per grating coupler (input/output ports 1-32, 20-13 and 32-1, $\theta > 0$). Grating couplers with a negative coupling angle ($\theta < 0$) were also designed by optimizing the grating period and filling factor. Similar coupling losses around 5.9 dB were experimentally validated. Fig 3(c) and Fig 3(d) show, respectively, the side and perspective views of the setup once the alignment procedure is completed.

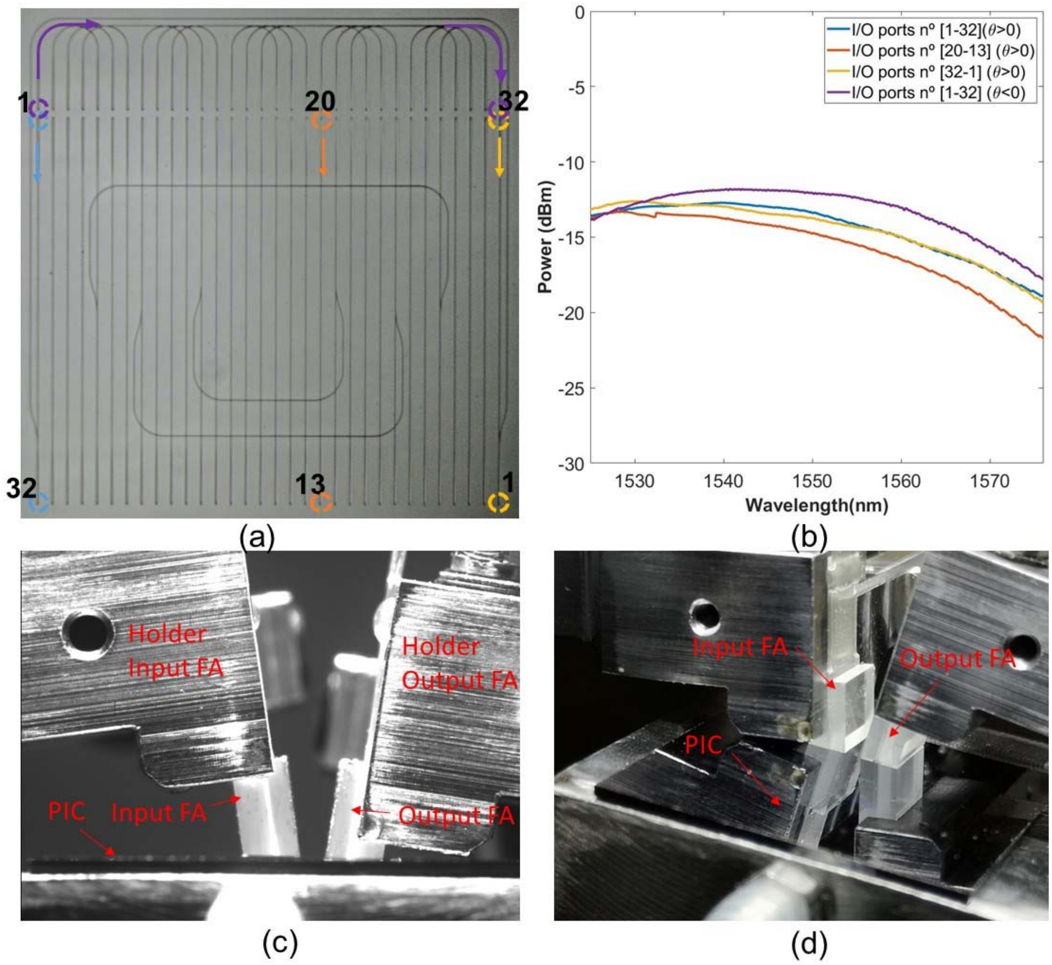

Figure 3. (a) Optical microscope image of the PIC, (b) measured fiber-to-fiber spectra once aligned at different I/O ports, (c) side-view of the I/O fiber arrays and their respective holders and (d) perspective view the I/O fiber arrays and their respective holders.

3. CONCLUSIONS

A fiber array-to-chip assembly process to optically interconnect ultra-low loss photonic integrated circuits with a high number of input/output ports has been demonstrated. The proposed approach is based on using pre-alignment photonic structures to ease the alignment process, hence allowing us to reduce the assembly time and cost. Low loss grating couplers have also been developed and demonstrated. The obtained results are a significant step forward towards the integration of photonic technologies for space applications.

ACKNOWLEDGEMENTS

This work was supported by EU-funded H2020 project RETINA under grant agreement n° 821943.

REFERENCES

[1] C. Ciminelli, F. Dell'Olio and M. N. Armenise: Photonics in Space: Advanced Photonic Devices and Systems, World Scientific, 2016.

[2] M. A. Piqueras, *et al.*: Photonic Front-End for the next-generation of space SAR applications, pp. 1152-1155, *in Proc. 45th European Microwave Conference (EuMC)*, Paris, France, Sep. 2015.

[3] http://www.retinah2020.eu/

[4] M. A. Piqueras, *et al.*: Optically beamformed beam-switched adaptive antennas for fixed and mobile broad-band wireless access networks, *IEEE Trans. Microw. Theory Tech.*, vol. 54, pp. 887–899, 2006.

[5] Y. Liu, *et al.*: Ultra-Low-Loss Silicon Nitride Optical Beamforming Network for Wideband Wireless Applications, *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24. pp. 1-10, 2018

[6] V. C. Duarte, M. V. Drummond and R. N. Nogueira: Photonic true-time delay beamforming system for a phased array antenna receiver, pp. 1-5, *SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)*, Porto de Galinhas, 2015.

[7] V.C. Duarte, J. G. Prata, C. F. Ribeiro, *et al.*: Modular coherent photonic-aided payload receiver for communications satellites, *Nat. Commun.*, vol. 10, pp. 1984, 2019.