# Processing free space optical beams with a silicon photonic mesh

*(Student Paper)*

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## ABSTRACT

Photonic integrated meshes made of tuneable interferometers enable us to implement functions programmable on demand and are being envisioned as the optical counterpart of electronic field programmable gate arrays. Several examples of photonics processors capable of performing arbitrary linear operations have been recently proposed, and are expected to find applications in different areas, from the on-chip processing of telecom signals to microwave photonics, and from quantum optics to neural networks. In this work, we use a reconfigurable mesh of silicon photonic Mach-Zehnder Interferometers (MZIs) to manipulate free-space optical beams. Among the variety of functionalities that can be implemented, we demonstrate beam steering, beam coupling from a free space optical source to a single mode waveguide and automatic identification of the direction of arrival of a beam from a free space source.

**Keywords**: silicon photonics, reconfigurable photonic integrated circuits, free space optics

## 1. INTRODUCTION

Photonic integrated circuits (PICs) consisting of generic programmable architectures that can be reconfigured during operation are emerging as a promising approach for advanced processing of optical signals. Examples of programmable PICs and optical processors have been recently proposed in different application fields, including microwave photonics [1], mode manipulation in telecommunications [2], quantum [3] and neural networks [4].

Silicon photonics (SiP) is a promising photonic platform for the realization of large scale integration of photonic processors, not only because of the high degree of device miniaturization, but also because of the possibility to integrate fast and power-efficient tuning elements and on-chip monitor photodetectors, which are necessary for robust reconfiguration and control of the photonic architecture. Recently, we demonstrated that a SiP mesh of Mach-Zehnder Interferometers (MZIs) can self-configure to perform automatic reconstruction and unscrambling of guided modes which have been strongly mixed during the transmission through a multimode waveguide. In this work, we demonstrate that the same architecture can be effectively used to manipulate free-space optical beams. A number of optical functions are implemented, including beam steering, beaming back to the source, and identification and coupling of a free space beam coming from an arbitrary direction.

## 2. SILICON PHOTONIC MESH

The photonic integrated circuit (PIC) consists of a triangular mesh of Mach-Zehnder Interferometers (MZIs) arranged as in the scheme of Fig. 1a, which was fabricated on a standard 220 nm SiP platform by using 500 nm wide channel waveguides (see Fig. 2a). The four ports labelled as RPi consist of an array of radiating elements (grating couplers) with a mutual spacing of 127 μm to either couple a free-space optical beam into the photonic chip or to radiate a guided-wave signal out to the free space. All the balanced MZIs integrate 3 dB directional couplers with a gap of 300 nm and a length of 40 μm. Two phase shifters are integrated in each MZI by using TiN metal strips (1 μm x 100 μm) to implement amplitude- and phase-tuneable couplers. At the output port of each MZI, on-chip photodetectors (here realized through CLIPP transparent detectors by using the same TiN used for thermal tuners) are used to locally monitor the switching state of each MZI and implement automatic tuning and stabilization procedures.

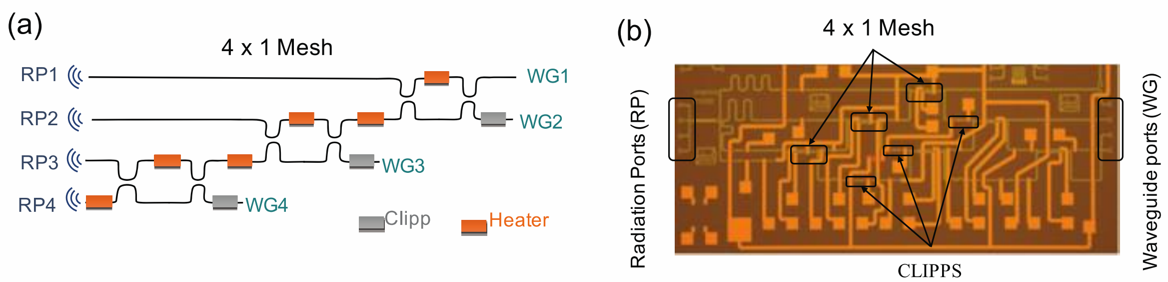

Figure 1: (a) Schematic representation of a 4 x 1 triangular mesh and (b) its implementation on a conventional silicon photonic platform. The overall footprint of the circuit is 3.7 mm by 1.5mm.

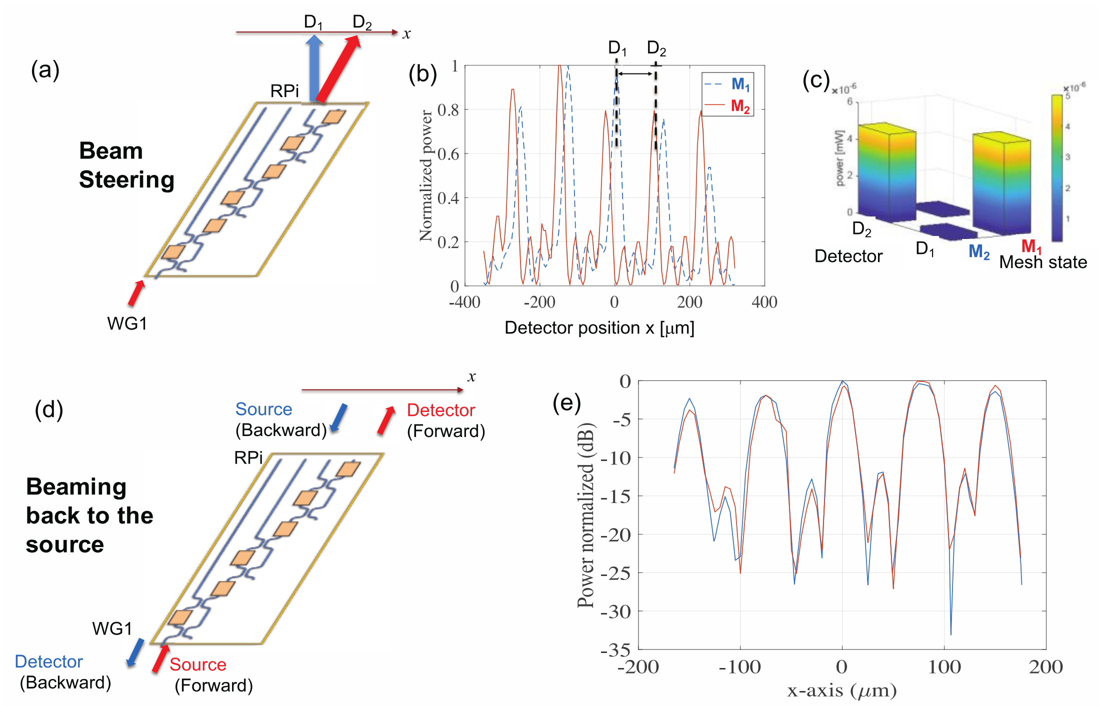

Figure 2: (a) Schematic representation of the beam steering experiment. (b) Free-space radiation pattern measured at the distance of 11 mm from the grating array RPi when the light is coupled to input port WG1 and the mesh is tuned in two different states $M_1$ and $M_2$. (c) Optical power measured by a detector (collimator) placed at positions $D_1$ and $D_2$ when the mesh is configured in states $M_1$ and $M_2$; (d) schematic representation of the "beaming back" experiment: the source and the detector are swapped to observe the behavior of the mesh when the direction of the optical propagation is reversed. (e) Comparison between the field pattern measured by a free-space detector moving along the $x$-axis when the source is coupled to port WG1 (red line) and the optical power measured by a detector coupled to port WG1 when a free space source moves along the x- axis (blue line).

The silicon photonic chip was mounted on an electronic printed circuit board hosting the drivers of the thermal tuners and the electronics for the read-out of the on-chip detectors. More details on the circuit design, fabrication technology and electronic circuit for the automatic control of the mesh can be found in [1]. All the experiments reported in this work were carried out at a wavelength of 1530 nm.

## 3. STEERING, COUPLING AND IDENTIFICATION OF A FREE SPACE OPTICAL BEAM

The SiP mesh was employed to manipulate free space optical beams, and, in detail, the following functionalities were demonstrated:

*(a) Beam steering.* As a first application we used the mesh to demonstrate the steering of a free space optical beam. To this end, we injected into the mesh an optical signal from port WG1 (see Fig. 2a) and we measured the radiation pattern generated by the grating array (RPi) for different tuning states of the mesh. The radiation pattern was measured by sampling the optical field along the transverse x-axis with a probe fiber with a resolution $dx = 5$ μm. Figure 2(b) shows the radiated field at a distance of (11 mm) from the output ports when the mesh is tuned in order to maximize the power received by a first detector $D_1$ (placed in $x = 0$, mesh state $M_1$) and by a second detector $D_2$ ($x = 100$ μm, mesh state $M_2$). The spacing between the maxima of the field pattern (about 150 μm, corresponding to an angular spacing of about 1°) is related to the large physical distance (127 μm) between radiating elements. Figure 2(c) shows the optical power collected by a detector (1 mm fiber collimator spaced 51.5 cm away from the chip) placed at the same angular direction of D1 and D2, when the mesh is tuned in states $M_1$ and $M_2$. Though the steering angle is rather limited, this demonstrate high resolution in the control of the radiation direction.

*(b) Beaming back to the source.* We also investigated the behaviour of the mesh when the direction of the optical propagation is reversed, that is when the source and the receiver are swapped. A free space beam coming from a collimator (beam waist 1 mm) at a distance of 6.5 mm from the mesh was used to shine the light on the grating array RPi while a photodiode was coupled to port WG1 (blue arrows in Fig. 2d). The blue curve in Fig. 2(e) shows the optical power at the photodiode (WG1) when the position of the collimator (free space beam) is shifted along the $x$-axis. The red curve is the power collected by the sliding collimator (receiver) when a light source is coupled to port WG1 and the grating array is used as a radiating antenna (red arrows in Fig. 2e). The good matching between the forward and backward behaviour demonstrate the capability of the mesh to beam the

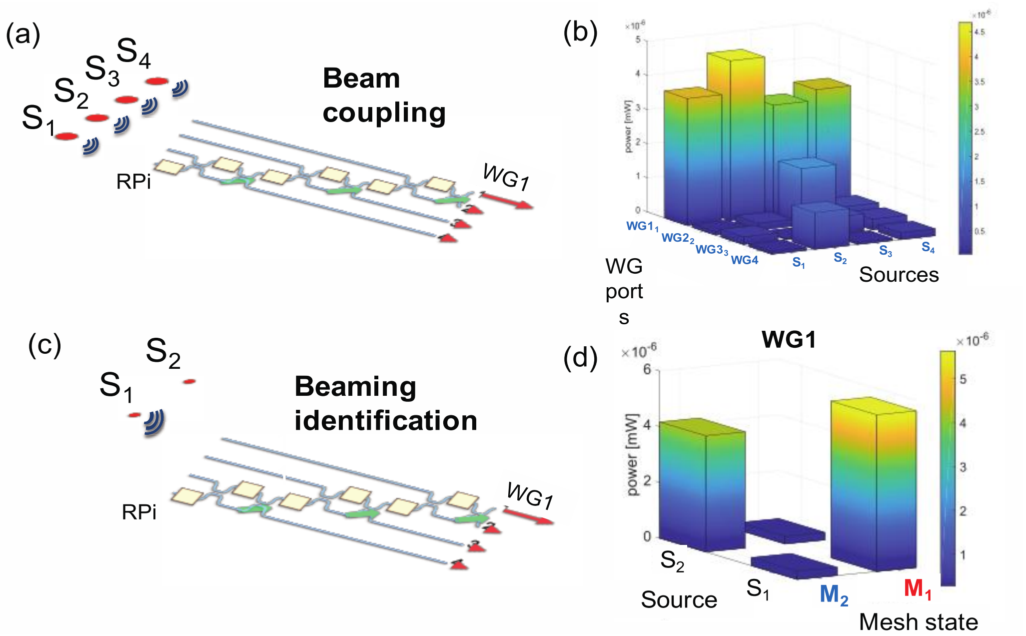

Figure 3: (a) Schematic representation of the beam coupling experiment. (b) Optical power coupled at the waveguide ports ($WG_1$-$WG_4$) when the mesh is configured to couple the light from an arbitrary free space source ($S_1$-$S_4$) to port WG1. (c) Schematic representation of the beam identification experiment. (d) Optical power coupled at port WG1 when the mesh automatically self-configures to maximize the power coming from an unknown source ($S_1$ or $S_2$).

field back toward a free-space source along an arbitrary direction, this operation not being achievable with a conventional mirror.

*(c) Beam coupling and source identification.* The high angular resolution of the mesh can be exploited to couple into a single-mode optical waveguide a free-space beam coming from an arbitrary direction of arrival, while minimizing the coupling from other directions. To demonstrate this concept, four free space optical beams ($S_1$-$S_4$) were simultaneously shone on the grating array RPi by using an array of 4 fibers spaced by $d$ = 127 μm at a distance of 5.5 mm from the mesh (see Fig. 3a). When a beam for a given fiber impinges on the grating array, the mesh automatically self-configures by following a progressive tuning scheme [2] in order to maximize the transmission to port WG1. Figure 3(b) show the power coupled to the waveguide ports WGi when the mesh is configured to couple the light from $S_1$- $S_4$ to WG1. This feature implies that the mesh can automatically identify the direction from which a beam is arriving. In Fig. 3(c)-(d) a beam is coming from a source whose position is not known (it can either be $S_1$ or $S_2$). The mesh automatically self-configures to maximize the coupling to WG1 and once convergence is achieved, the phase shifts (voltages) are applied to the thermal tuners of the MZIs of the mesh identify the position of the source.

## 4. CONCLUSION

We demonstrate manipulation of free-space optical beams by using a 4x1 self-configuring SiP mesh. The performance of the mesh in steering, coupling and identifying free-space beams can be improved by optimizing the design of the radiating elements, whose number can be scaled up without impairing the progressive self-configuration procedure employed for the tuning of the mesh. Applications are envisioned to more advanced free-space optical processing, including phase front reconstruction, beaming through scattering media and chip-to-chip free space communications.

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