Piezoelectric Programmable Optical Mode Conversion in a Photonic Integrated Circuit

Hugo Larocque,[1,*] Mark Dong,[1,2] Andrew Leenheer,[3] Gerald Gilbert,[4] Matt Eichenfield,[3] Dirk Englund[1]

[1] *Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *The MITRE Corporation, 202 Burlington Road, Bedford, MA 01730, USA*
[3] *Sandia National Laboratories, P.O. Box 5800 Albuquerque, NM, 87185, USA*
[4] *The MITRE Corporation, 200 Forrestal Road, Princeton, NJ 08540, USA*

[*] *hlarocqu@mit.edu*

Abstract: Waveguide-based optical mode conversion requires wavelength-scale patterning of the waveguide's optical properties. We implement a programmable version of this patterning with piezoelectrically actuated photonics.

Photonic programmable circuits are a key component in applications requiring scalable platforms for optical transformations. Interconnected sets of integrated Mach-Zehnder (MZ) interferometers, known as MZ meshes, are the current system of choice for implementing such transformations due to their approachable architecture and simple programming [1]. However, further scaling of these MZ systems can be hindered by varying performance metrics in each interferometer due to fabrication errors and by the significant amount of dead space separating single-mode waveguides in the mesh. To address this issue, proposals relying on transformations applied in a single multimode waveguide as opposed to multiple single-mode waveguides have been put forward [2, 3]. Approaches directly coupling the eigenmodes of the waveguide require highly structured perturbations of the waveguide's optical properties [2]. Though such programmable perturbations are achievable, they are often realized with external optical control [4, 5], thereby potentially adding significant overhead on the resources enabling mode conversion when compared to the electronic control typically used in state-of-the-art MZ meshes.

Here, we address these problems by introducing an electronically actuated eigenmode converter. We implement such a device in piezoelectrically programmable silicon nitride visible photonics relying on a 200 mm CMOS fabrication process [6]. As shown in Fig. 1(a), this platform relies on silicon nitride (Si_3N_4) waveguide and piezoelectric aluminum nitride (AlN) layers. Metal layers enclose the AlN to form a capacitive element and are periodically patterned such as to apply a structured electric field within it. The resulting electric field correspondingly induces a structured strain profile in the piezoelectric layer. In conjunction with patterned release holes enabling an undercut of the piezo-waveguide stack, the resulting strain profile along with some geometric deformations carry over to the waveguide, thereby inducing a mode-coupling perturbation. For this demonstration, we focused on coupling the TE0 and TE1 modes of a 150 nm thick and 1.4 μm wide waveguide. Finite element method (FEM) simulations in Fig. 1(b) show the mechanical displacement and the x-component of the normal strain, ε_{xx}, experienced by a period of the actuated device along with the profile of the interacting modes. As shown in Fig. 1(c),

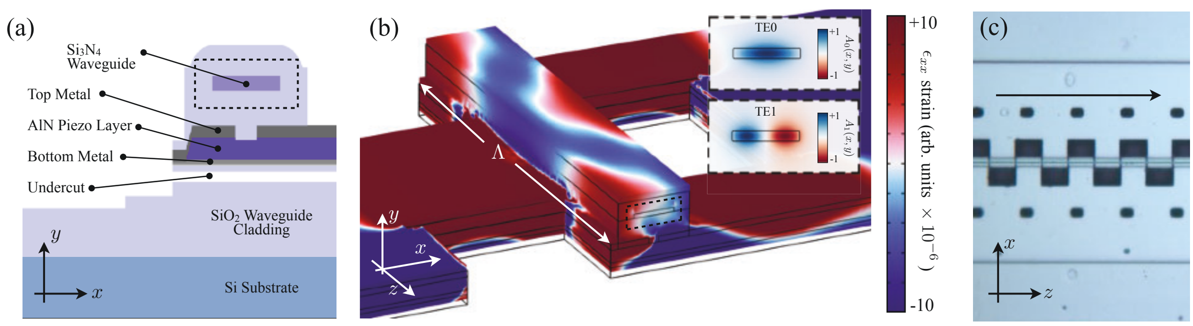

Fig. 1. (a) Material stack of the platform used for piezoelectric patterning of optical waveguides. (b) FEM simulation of the ε_{xx} strain (color-coded) and displacement (50x scale factor) induced in the waveguide by 10 V. Inset : Normalized FEM profiles of the x-component of the electric field for the TE0(1), $A_{0(1)}(x, y)$, waveguide modes. (c) Optical micrograph of the fabricated mode converter.

we expect this period from coupled mode theory to be given by $\Lambda = \lambda/\Delta n$, where λ is the optical wavelength and $\Delta n = n_{\mathrm{TE0}} - n_{\mathrm{TE1}}$ is the effective index difference between the interacting modes.

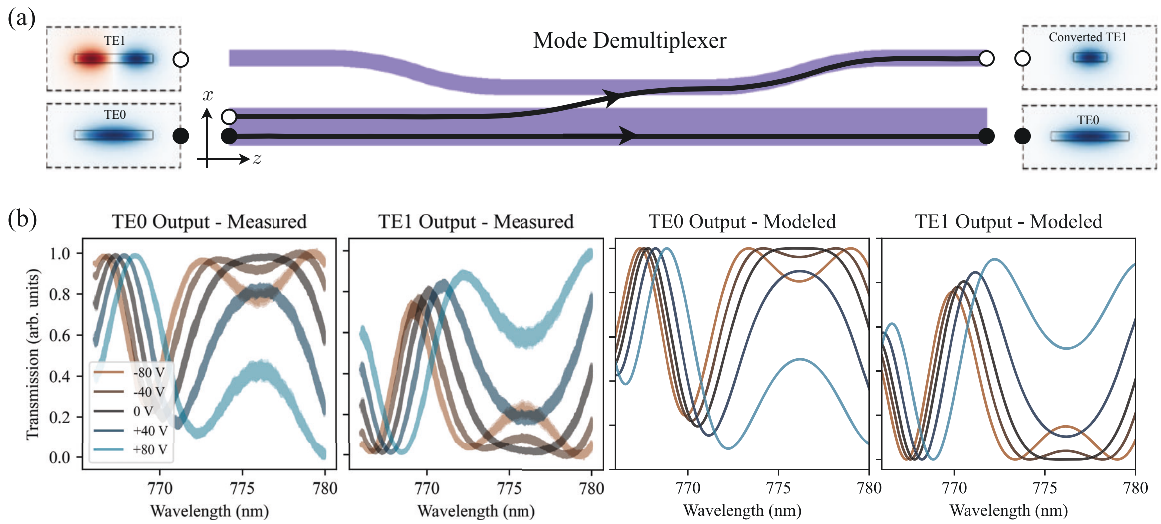

Fig. 2. (a) Schematic of the eigenmode demultiplexer used to measure power contained in the TE0(1) modes. (b) Measured and modeled spectral traces of transmission in the TE0(1) modes, $|c_{0(1)}(\lambda)|^2$, for applied voltages ranging within ± 80 V.

We proceed by sending the TE0 mode through the device with an adiabatic taper connecting a single-mode waveguide to the mode converter. After propagating through the device, we expect the resulting optical field to be given by the superposition $c_0 A_0(x,y) + c_1 A_1(x,y)$, where $c_{0(1)}$ and $A_{0(1)}(x,y)$ are the weight coefficients and spatial profiles of the TE0(1) modes, respectively. We measure these weights with a spatial mode demultiplexer. As shown in Fig. 2(a), the demultiplexer brings in a single-mode waveguide near the multimode region, which is phase-matched to tap out any light contained in the TE1 mode. Figure 2(b) shows the resulting transmission spectra in both output ports. We observe significant variations in transmission with applied voltage at $\lambda = 776$ nm. We model this behavior with coupled mode theory, in which transmission into the TE1 mode is given by:

$$c_1(\lambda) = -i\frac{\kappa}{\sqrt{|\kappa|^2+\delta^2}}\sin\left(\sqrt{|\kappa|^2+\delta^2}L\right), \qquad \delta = \frac{2\pi\Delta n}{\lambda} - \frac{2\pi}{\Lambda}, \qquad \kappa \approx -i\frac{\pi\delta n}{\lambda}, \tag{1}$$

where $L = 6.5$ mm is the length of the mode converter, and δn is the effective index change resulting from the piezoelectric perturbation. Assuming that $\delta = 0$ at $\lambda = 776$ nm, we observe that index changes δn ranging between 4.63×10^{-4} and 5.08×10^{-4} reproduce our measurements. This agreement suggests an effective index modulation of 2.81×10^{-6}/V, which is similar to previous work performed in this piezoelectric platform [6].

In summary, we introduced a programmable optical mode converter relying on piezoelectrically induced mode perturbations. Our approach benefits from a purely electronic actuation mechanism similar to those used in state-of-the-art programmable integrated photonics. This level of control over the modes of a waveguide provides a suitable platform for a variety of applications ranging from coupling to quantum emitters embedded in large solid-state structures, beam shaping, to multimode-based optical machine learning accelerators,

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