Silicon photonic mode demultiplexer enabled by on-chip beamforming

David González-Andrade[1,*], Xavier Le Roux[1], Thi Thuy Duong Dinh[1], Dorian Oser[1,2], Diego Pérez-Galacho[3], Eric Cassan[1], Delphine Marris-Morini[1], Laurent Vivien[1] and Carlos Alonso-Ramos[1]

[1]Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 10 Bd. Thomas Gobert, Palaiseau, 91120, France
[2]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, 2600 GA, The Netherland
[3]ITEAM Research Institute, Universitat Politècnica de València, Camino de Vera s/n, Valencia, 46022, Spain
[*] david.gonzalez-andrade@c2n.upsaclay.fr

Mode-division multiplexing has a great potential to increase the bandwidth and data rates of emerging communication systems. Here, we propose a novel silicon photonic mode multiplexer exploiting on-chip free-space-like propagating optical beams to achieve TE_0 and TE_1 mode demultiplexing with a 1 dB bandwidth of 100 nm and crosstalk lower than -42 dB in a 200 nm bandwidth for both fundamental and first-order modes.
Keywords**:** *silicon photonics, silicon-on-insulator, mode-division multiplexing, leaky mode, slab waveguide*

INTRODUCTION

Silicon photonic devices are becoming a cornerstone of modern communication systems. The possibility to integrate multiple components on a single chip allows a significant reduction in the size, energy consumption and cost of optical modules and interconnects [1]. Among the different material platforms, silicon-on-insulator provides a high refractive index contrast and compatibility with complementary metal-oxide-semiconductor (CMOS) processes, resulting in cost-effective mass production [2]. Optical interconnects based on SOI have attracted much attention as a solution to address the ever-increasing demand for broader bandwidth and higher data rates of new services. Different advanced multiplexing technologies have been employed to scale the transmission capacity, such as wavelength-, polarization- and time-division multiplexing [3-5]. Recently, mode-division multiplexing (MDM) has been proposed to further increase aggregate bandwidth and data rates by transmitting information encoded in different spatial modes at the same wavelength and polarization [6].

The mode multiplexer/demultiplexer (MUX/DEMUX) is the fundamental device at the core of any MDM system. Its main function is to convert fundamental modes into higher-order modes and combine them into a single multimode waveguide (MUX operation), or vice versa (DEMUX operation). Several SOI device configurations have been reported for MDM, including asymmetric Y-junctions [7], tapered or adiabatic couplers [8], asymmetric directional couplers [9], ring resonators [10], multimode interference (MMI) couplers [11] and topology-optimized devices [12]. However, in all these photonic devices light is guided within a spatially bounded structure, restricting both the region and the field distribution with which light propagates (i.e., propagation of light wave is limited to a set of modes confined to a waveguide). Radiation of electromagnetic fields within a chip offers interesting opportunities to overcome the stringent design rules and limited on-chip reconfigurability of fixed layout-guided interconnects, opening new venues for on-chip wireless optical communications [13,14]. Contrary to diffractive gratings, of which a considerable number have been demonstrated for out-of-plane light coupling [15], only a few works have addressed radiation from a channel waveguide into an adjacent slab [14,16]. Still, these devices are intended for wavelength-division multiplexing as they rely on frequency-scanning focus of the beam within the slab.

In this work, we expand on this concept and propose a silicon photonic mode demultiplexer based on in-slab beam forming. Optical tunneling effect is exploited in order to couple the fundamental and firs-order transverse-electric (TE) modes from a waveguide to and adjacent slab. The slab acts as a free-space-like propagation region where the different beams are vertically confined and focused on a specific position. Our simulation results show coupling efficiencies of 97%, and 83%, as well as 1 dB bandwidths of 124 nm and 107 nm, for TE_0 and TE_1 mode demultiplexing, respectively.

RESULTS

Figure 1 illustrates the geometry and operation principle of the proposed device, which comprises a tapered waveguide that is placed in close proximity to a slab. The light propagates through the input multimode waveguide (width W_I) in the form of fundamental and first-order TE modes. As the light propagates along the taper (length L_T), it progressively couples to the adjacent slab via optical tunneling effect [14]. The angle at which the vertically confined beam propagates within the slab, defined with respect to the y axis, is given by:

$$\theta = \sin^{-1}\left(\frac{n_{eff,W}^{i}}{n_{eff,S}}\right), \tag{1}$$

where $n_{eff,W}^{i}$ is the effective index of the i-th order mode in the waveguide and $n_{eff,S}$ is the effective index of the slab. The separation between waveguide and slab allows to tailor the leakage rate and thus the field profile of the in-slab beam. The DEMUX is designed for SOI with 220-nm-thick silicon, a 3-µm-thick buried oxide (BOX) layer and a 2-µm-thick polymethyl methacrylate (PMMA) upper cladding. The input waveguide has a width of $W_I = 710$ nm to support both fundamental and first-order TE modes within the design wavelength range, i.e., 1450 – 1650 nm. The separation between input waveguide and slab varies from $G_I = 340$ nm to $G_E = 40$ nm to achieve a near-Gaussian field profile. Finally, the width of the input waveguide is reduced from $W_I = 710$ nm to $W_E = 250$ nm along the 20 µm long taper to ensure that all the optical power is radiated from the input waveguide into the slab.

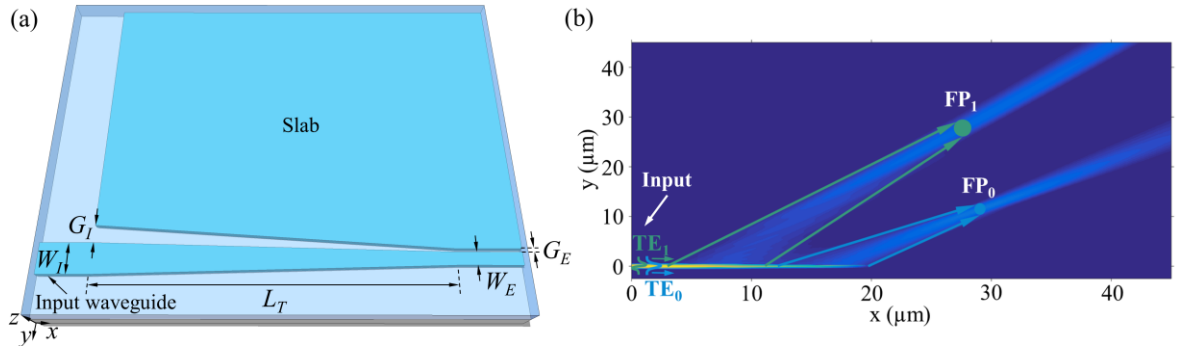

Fig. 1. (a) Schematic representation of the free-space mode multiplexer and its geometrical design parameters. (b) Illustration of the operation principle working as demultiplexer: electric field magnitude (normalized to the maximum) in the XY plane in the middle of the Si layer at 1550 nm. The fundamental and first-order transverse-electric modes that propagate through the input waveguide are coupled into the slab producing two in-slab beams that are focused on different points (i.e., FP_0 and FP_1).

The mode DEMUX was simulated with a three-dimensional finite-difference time-domain (3D FDTD) solver. Figure 1b shows an illustration of the electric field magnitude in the middle of the silicon layer at the center wavelength (i.e., $\lambda_0 = 1550$ nm). It is observed that the TE_1 mode is radiated along the first half of the taper, while the TE_0 mode is radiated towards the end. In this case, the lower modal confinement of TE_1 compared to TE_0 results in a greater evanescent interaction with the slab and, therefore, in a stronger radiation strength at the beginning of the taper. When TE_0 is injected through the input waveguide, the in-slab beam focus on point FP_0 with an angle of 48°. Conversely, when TE_1 is injected, the beam focus on FP_1 with an angle of 36°.

The figure of merit used to evaluate the performance of the device is the coupling efficiency (CE), which is defined similarly to the coupling efficiency employed in fiber-chip grating couplers: $\mathrm{CE} = (1-\rho_R)\cdot\eta_U\cdot\eta_{OL}$, where ρ_R is the reflection coefficient, η_U is the ratio between the power injected in the input waveguide and the power radiated into the slab, and η_{OL} is the overlap integral between the radiated field and a Gaussian-like mode field. For TE_0 mode demultiplexing, a high overlap of 98.7% is achieved between the radiated field and a Gaussian field with $\sigma = 4.7$ µm at FP_0. On the other hand, for TE_1 mode demultiplexing, the overlap is 92.7% between the radiated field and a Gaussian field with $\sigma = 5.9$ µm at FP_1.

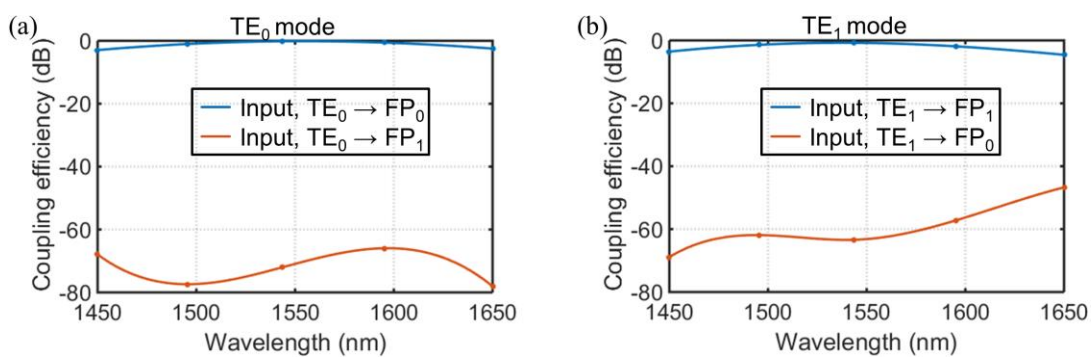

Fig. 2. Calculated coupling efficiency as a function of the wavelength for the mode demultiplexer when (a) TE_0 and (b) TE_1 modes are injected through the input waveguide. Blue curves correspond to the coupling efficiency at desired positions, while orange curves correspond to the coupling efficiency at undesired positions.

The performance of our proposed device is shown in Fig. 2. Blue curves indicate the CE at desired positions, i.e., calculated at FP_0 and FP_1 for TE_0 and TE_1 mode demultiplexing, respectively. In this case, the mode DEMUX yields efficiencies of 97.1% (-0.13 dB) and 82.8% (-0.82 dB) at 1550 nm when TE_0 and TE_1 modes are injected through the input waveguide, respectively. Notably, the device exhibits broad 1 dB bandwidths of 124 nm for TE_0 and 107 nm for TE_1. Orange curves, on the contrary, indicate the CE at undesired positions. The CE at FP_1 is as low as -66 dB when the TE_0 mode is injected through the input waveguide and below -47 dB at FP_0 when the TE_1 mode is injected, both within the entire simulated wavelength range. The crosstalk is, therefore, below -42 dB for both modes in the entire 200 nm simulated bandwidth.

DISCUSSION

In this work, we propose a novel two-mode multiplexer that leverages optical tunneling between a tapered waveguide and an adjacent slab. The device was designed for the silicon-on-insulator platform considering a standard silicon thickness of 220 nm and a PMMA cladding. First-order and fundamental TE modes injected through the input waveguide are radiated sequentially from the taper into the slab due to their different evanescent field interaction. Full 3D FDTD simulations show efficiencies of 97.1%, and 82.8% for TE_0 and TE_1 mode demultiplexing, respectively, at 1550 nm. In addition, a remarkable 1 dB bandwidth of 124 nm is achieved for TE_0, while the 1 dB bandwidth for TE_1 is 107 nm. The proposed device also exhibits a high isolation between the beams in the slab, with values lower than -47 dB for both modes within the 1450 – 1650 nm wavelength range. We believe that these results open promising prospects for emerging applications such as on-chip wireless optical communications.

Acknowledgements: This work has been partially funded by the French Industry Ministry (Nano2022 project under IPCEI program); and the Agence Nationale de la Recherche (ANR-MIRSPEC-17-CE09-0041). The fabrication of the device was performed at the Plateforme de Micro-Nano-Technologie/C2N, which is partially funded by the Conseil General de l'Essonne. This work was partly supported by the French RENATECH network.

References

[1] L. Vivien, L. Pavesi, *Handbook of silicon photonics*, Taylor & Francis, 2016.

[2] D. Thomson, A. Zilkie, J. E. Bowers, T. Komljenovic, G. T. Reed, L. Vivien, D. Marris-Morini, E. Cassan, L. Virot, J.-M. Fédéli, J.-M. Hartmann, J. H. Schmid, D.-X. Xu, F. Boeuf, P. O'Brien, G. Z. Mashanovich, M. Nedeljkovic, *Roadmap on silicon photonics,* J. Opt., vol. 18, no. 7, pp. 073003, 2026.

[3] Z. Liu, J. Zhang, X. Li, L. Wang, J. Li, C. Xue, J. An, B. Cheng, *25 × 50 Gbps wavelength division multiplexing silicon photonics receiver chip based on a silicon nanowire-arrayed waveguide grating*, Photon. Res., vol. 7, no. 6, pp. 659-663, 2019.

[4] C. R. Doerr, P. J. Winzer, Y.-K. Chen, S. Chandrasekhar, M. S. Rasras, L. Chen, T.-Y. Liow, K.-W. Ang, G.-Q. Lo, *Monolithic polarization and phase diversity coherent receiver in silicon*, J. Lightwave Tehcnol., vol. 28, no. 4, pp. 520-525, 2009.

[5] Y. Ding, H. Hu, M. Galili, J. Xu, L. Liu, M. Pu, H. C. H. Mulvad, L. K. Oxenløwe, C. Peucheret, P. Jeppesen, X. Zhang, D. Huang, H. Ou, *Generation of a 640 Gbit/s NRZ OTDM signal using a silicon microring resonator*, Opt. Express, vol. 19, no. 7, pp. 6471-6477, 2011.

[6] C. Li, D. Liu, D. Dai, *Multimode silicon photonics*, Nanophotonics, vol. 8, no. 2, pp. 227-247, 2019.

[7] W. Chen, P. Wang, T. Yang, G. Wang, T. Dai, Y Zhang, L. Zhou, X. Jiang, and J. Yang, *Silicon three-mode (de)multiplexer based on cascaded asymmetric Y junctions*, Opt. Lett., vol. 41, no. 12, pp. 2851-2854, 2016.

[8] D. Guo, T. Chu, *Silicon mode (de) multiplexers with parameters optimized using shortcuts to adiabaticity*, Opt. Express, vol. 25, no. 8, pp. 9160-9170, 2017.

[9] J. Wang, P. Chen, S. Chen, Y. Shi, D. Dai, *Improved 8-channel silicon mode demultiplexer with grating polarizers*, Opt. Express, vol. 22, no. 11, pp. 12799-12807, 2014.

[10] B. A. Dorin, N. Y. Winnie, *Two-mode division multiplexing in a silicon-on-insulator ring resonator*, Opt. Express, vol. 24, no. 4, pp. 4547-4558, 2014.

[11] D. González-Andrade, J. G. Wangüemert-Pérez, A. V. Velasco, A. Ortega-Moñux, A. Herrero-Bermello, I. Molina-Fernández, R. Halir, P. Cheben, *Ultra-broadband mode converter and multiplexer based on sub-wavelength structures*, vol. 10, no. 2, pp. 2201010, 2018.

[12] L. F. Frellsen, Y. Ding, O. Sigmund, L. H. Frandsen, *Topology optimized mode multiplexing in silicon-on-insulator photonic wire waveguides*, Opt. Express, vol. 24, no. 15, pp. 16866-16873, 2016.

[13] C. García-Meca, S. Lechago, A. Brimont, A. Griol, S. Mas, L Sánchez, L. Bellieres, N. S. Losilla, J. Martí, *On-chip Wireless silicon photonics: from reconfigurable interconnects to lab-on-chip devices*, Light Sci. Appl., vol. 6, no. 9, pp. e17053, 2017.

[14] D. Headland, W. Withayachumnankul, M. Fujita, T. Nagatsuma, *Gratingless integrated tunneling multiplexer for terahertz waves*, Optica, vol. 8, no. 5, pp. 621-629, 2021.

[15] D. González-Andrade, D. Pérez-Galacho, M. Montesinos-Ballester, X: Le Roux, E. Cassan, D. Marris-Morini, P. Cheben, N. Vulliet, S. Monfray, F. Boeuf, L. Vivien, A. V. Velasco, C. Alonso-Ramos, *Dual-band fiber-chip grating coupler in a 300 mm silicon-on-insulator platform and 193 nm deep-UV lithography*, Opt. Lett., vol. 46, no. 3, pp. 617-620, 2021.

[16] A. Hadij-ElHouati, A. Ortega-Moñux, J. G. Wangüemert-Pérez, R. Halir, S. Wang, J. H. Schmid, P. Cheben, Í. Molina-Fernández, *Low-loss off-axis curved waveguide grating demultiplexer*, Opt. Lett., vol. 46, no. 19, pp. 4821-4824, 2021.