High-performance surface grating couplers for fiber-chip and free-space coupling

A. Sánchez-Postigo[1*], M. Barona-Ruiz[1], P. Ginel-Moreno[1,2], J. H. Schmid[3], A. Ortega-Moñux[1], J. G. Wangüemert-Pérez[1], J. M. Luque-González[1], R. Halir[1], P. Cheben[3], Í. Molina-Fernández[1]

[1]Telecommunication Research Institute (TELMA), Universidad de Málaga, E.T.S. Ingeniería de Telecomunicación, Bulevar Louis Pasteur 35, 29010 Málaga, Spain
[2]Currently with AG Photonics S.L., Málaga, Spain
[3]Quantum and Nanotechnologies Research Centre, National Research Council Canada 1200 Montreal Rd., Ottawa ON K1A 0R6, Canada
[*]Corresponding author: asp@ic.uma.es

Abstract: Surface grating couplers are key components in silicon photonics, as they act as efficient fiber-chip and free-space optical interfaces. Here we review some of our latest advances in these devices, including fiber-chip zero-order grating couplers achieving the highest coupling efficiency–bandwidth product reported to date, single-beam fiber-chip couplers with -0.2 dB coupling loss, single-beam optical antennas yielding nearly 100% directionality and ultra-fast beam steering, and apodized-imaging fiber-chip couplers that focus the radiated light at millimeter-scale distances above the chip surface.

Silicon-on-insulator (SOI) is a well-established platform for photonics integration due to its high index contrast, which enables ultra-compact optical devices, and its compatibility with CMOS processes [1]. However, the mode size mismatch between single-mode optical fibers and silicon waveguides makes efficient fiber-chip coupling challenging. Surface grating couplers are waveguides with such a periodic perturbation that the supported mode is diffracted off-chip as a free-propagating wave. This radiated field can be intercepted by an optical fiber, conveniently positioned above the chip at specific height and inclination angle. Furthermore, surface grating couplers can be used as optical antennas for free-space optical communications and beam steering applications, e.g. light detection and ranging (LiDAR) [2]. In this invited talk, we review some of our latest advances in the field of surface grating couplers.

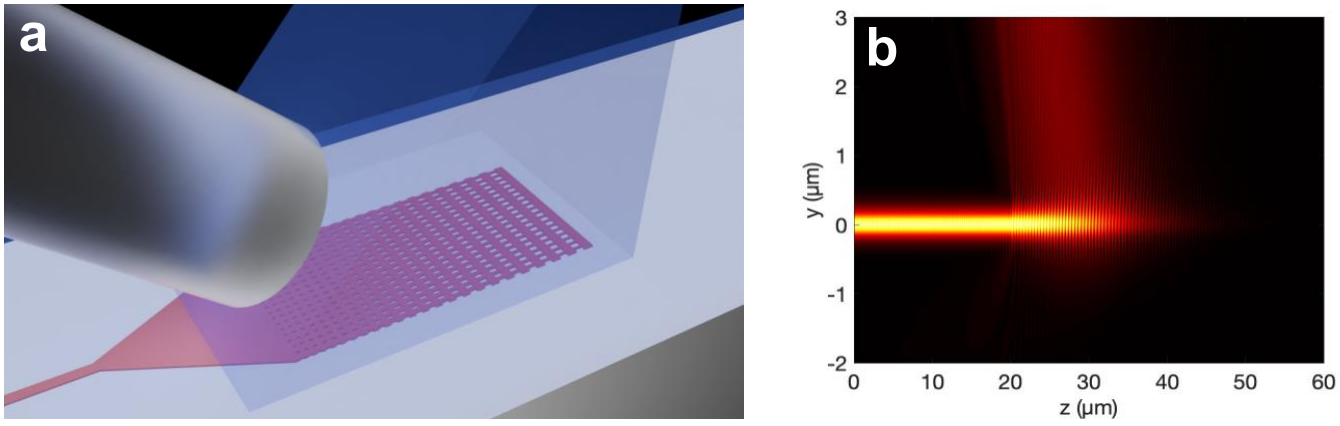

Figure 1. (a) Schematic representation of a single-beam, prism-assisted, silicon nitride–cladding surface fiber-chip grating coupler. (b) Simulated electric field propagation (TE polarization) at a wavelength of 1550 nm.

First, by substituting the diffractive grating structure with a subwavelength grating (SWG) metamaterial and positioning a tilted silicon prism on top, zeroth order radiation is enabled, leading to zero-order grating couplers with a coupling loss below 1 dB at a central wavelength of 1550 nm and a 1-dB bandwidth exceeding 90 nm. This coupler experimentally achieved the highest coupling efficiency–bandwidth product yet reported (>75 nm) [3]. Moreover, by utilizing novel, low-dispersive SWG topologies, we theoretically predict a 3.5-fold bandwidth enhancement without affecting the coupling efficiency.

For applications requiring even higher coupling efficiency, such as those in quantum technologies, we propose silicon nitride–cladding, prism-assisted grating couplers operating in the single-beam diffraction regime (see Fig. 1). In these devices, a unidirectional field is radiated toward the optical fiber. Our simulations show an unprecedented coupling efficiency of -0.2 dB to a reduced-cladding single-mode optical fiber. We also leverage single-beam operation to develop millimeter-long optical antennas with a radiation efficiency of -0.1 dB. By tuning the wavelength, a scan velocity up to 0.37°/nm is achieved, which constitutes a 2.5-fold improvement over similar silicon antennas [4].

Finally, we introduce a silicon grating-coupling concept that employs a carefully designed subwavelength structure to focus a near-Gaussian field onto an optical fiber positioned at a millimeter-scale height above the chip.

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