High Directivity, Vertical Fiber-to-Chip Coupler with Anisotropically Radiating Grating Teeth

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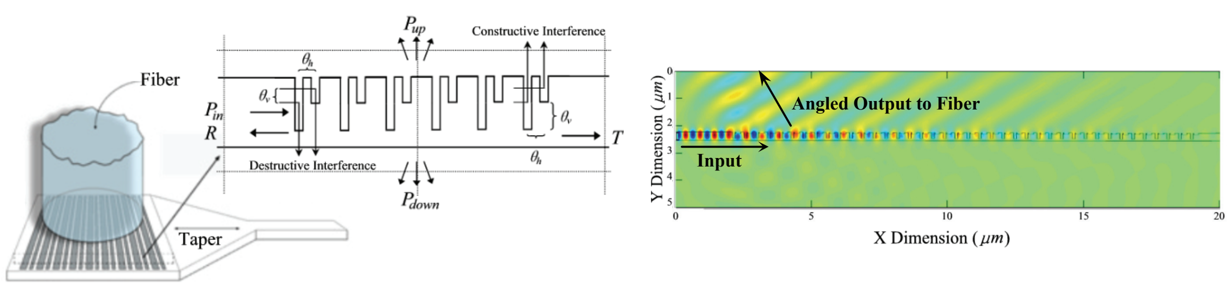
Abstract: Efficient vertical grating-coupler designs are proposed that allow near 50:1 up/down directivity using only two lithographic layers, without top/bottom mirrors, in high-index-contrast silicon waveguides. FDTD simulations predict single-mode-fiber-coupling efficiencies of 75% even for non-apodized gratings.

OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides.

The concept of using periodic structures such as gratings to couple out-of-plane light into waveguides has seen a revived interest recently for high index-contrast (HIC) microphotonics due to the strong HIC scattering that enables all input light to be coupled out vertically over a 10μm grating length, which is close to the mode field diameter of standard single-mode fiber, a necessary condition for efficient coupling to it [1-5]. An efficiently designed vertical coupler enables numerous applications such as wafer scale testing of integrated photonic devices, multiple and flexible placement of I/O ports on photonic chips, and etc. However, one of the key challenges in design is to achieve high coupling efficiency and at the same time provide a practical design for mass fabrication.

We propose in this paper an out-of-plane fiber-to-chip coupler design with a high out-of-plane directivity (preference for upward radiation over downward radiation), achieved by engineering of the tooth shape, through a minimum of lithographic layers (two), and without any need for top or bottom reflector layers required by previous designs [1-3]. We approach the design of the grating coupler from an antenna interference point of view, considered by Flory [6], where the total grating response is due to the grating topology and phase (array pattern), and the radiation pattern of the tooth design (element pattern). We break down the simplest bi-level tooth into a set of antenna diffraction centers to gain insight into efficient tooth design. By phasing the diffraction centers appropriately, highly directional diffraction due to a single tooth can be made to occur. Based on this concept, we formulated a set of requirements for the achievement of perfect asymmetric radiation. A tooth configuration was designed with two separate but equally strongly diffracting subelements in order to arrive at a high directivity contrast with the appropriately chosen phase relationships between the teeth embedded in the HIC waveguides.

By modeling each sub-tooth as a point scatterer, $\Delta\theta_{upward}$ is defined as the phase difference between radiation scattered upward by the both sub-teeth and $\Delta\theta_{downward}$ is that for radiation scattered downward, then $\Delta\theta_{upward} = \theta_v - \theta_h$ and $\Delta\theta_{downward} = \theta_v + \theta_h$ (see Fig. 1a). For reflection back into the waveguide based on this tooth model, the relevant phase is $\Delta\theta_{refl} = 2\theta_h$. A necessary condition for complete constructive interference upwards, as well as total cancellation for the downward wave and reflection, is that $\theta_h = \theta_v = \pi/2$. This basic model requires that diffraction centers be spaced by $\lambda/4$ in order to accumulate a phase difference of $\pi/2$ to achieve complete asymmetric radiation. Within this condition, it is to be understood that in parts an appropriate mode effective index is assigned to scale the wavelength, the radiation taking at least in part a guided-wave path. Since the radiated waves actually travel in slab



(a) (b)

Fig. 1. Physical structure of proposed two-level high-directivity grating coupler: a) Layout and cross-section of coupler, showing grating simulation setup and phase relationships in blown-up detail, b) radiation field plot from FDTD simulation illustrating coupling angle of about –30°.

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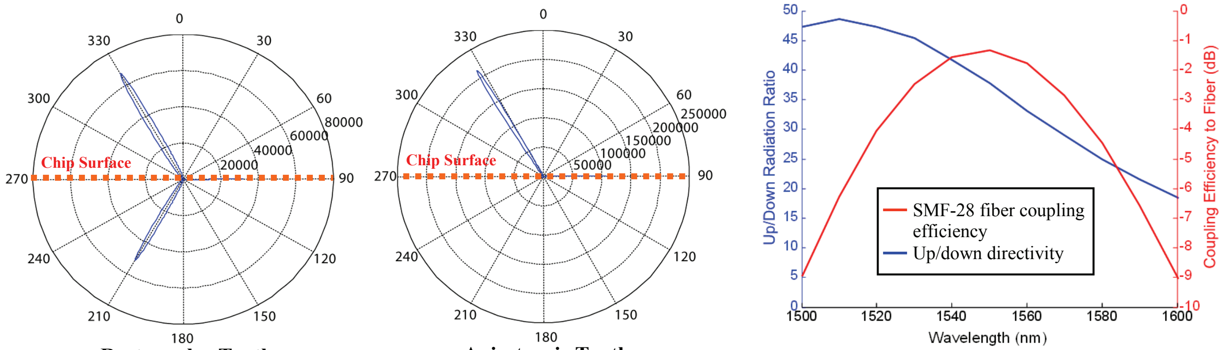

Rectangular Tooth Grating Design (a) Anisotropic Tooth Grating Design (b)

Fig. 2. Directivity and efficiency of a non-apodized example of proposed bi-level grating fiber-coupler: a) Polar plots for radiated power from standard, rectangular-tooth (left) and phase-matched, bi-level-tooth (right) grating structure with shoot off angle of -30°, b) up/down radiated power ratio and coupling efficiency to SMF-28 fiber for phase-matched grating.

waveguide media, phases θ_h and θ_v accumulate due to propagation at different speeds depending on the medium and guidance properties. The phase-matching conditions may be solved as long as $\Delta\lambda_v = \Delta\lambda_h = \lambda_v/4$. With only 2 free parameters, fortuitously all 3 equations are satisfied, and reflection is eliminated at the same time.

An example coupler device was designed for target wavelengths around 1550nm. Designs of the coupler have a silicon waveguide and SiO_2 cladding. The performance of the waveguide grating designs was simulated using the two-dimensional finite difference time domain (2D-FDTD) method [7], with appropriate mode overlap integrals taken to find transmission/reflection efficiencies, upward vs. downward transmission ratios, polar radiation patterns, as well as the coupling efficiencies to a standard SMF-28 fiber. For designs in SOI, input power can be radiated over a short grating length of 18μm due to the high index contrast. From simulation, total radiated power upwards towards the fiber is over 90% of the total input power, while the reflection is kept below 5% and downward radiation at 2%. Figure 2b shows that the maximum up to down radiated power ratio reaches 50:1 (98% directionality), with about 35:1 (97.2% directionality) at the target wavelength of 1550nm, where directionality is defined as $P_{up}/(P_{up} + P_{down})$. Fig. 2b shows also a coupling efficiency of 74% to a 10.4μm diameter single-mode fiber using overlap integrals at 1550nm (the 3dB bandwidth is approximately 60nm, as usual in HIC gratings).

To compare directionality of the phased-matched coupler with that of uniform gratings, we see from the polar radiation plots in Figure 2a that lobes of radiated power split near-symmetrically for the uniform grating (with standard single-level teeth) while the present phase-matched, bi-level grating produces a highly unidirectional concentration of radiation. An angling of the output to about -30° (i.e. non-vertical) was chosen for output coupling in order to substantially eliminate reflection due to 2nd-order grating coupling. Regarding direction, a negative radiation angle (larger grating k-vector) minimizes the loss due to the 2nd-order backward coupling, since the 2nd-order excited mode k-vector is shifted beyond the range of backward k-vectors that support radiation.

In this presentation, we describe the design of an out-of-plane fiber-to-chip coupler from an antenna theory point of view, by breaking down the design into an array pattern due to the grating, and an element pattern due to the individual grating teeth, the latter being used to achieve the directivity. Simulations show that with appropriate tooth designs, a ~50:1 directivity can be achieved in a silicon-waveguide system with only two lithographic layers, and no need for top or bottom mirrors as used previously [1-3]. We also address some departures from a perturbative viewpoint that need to be taken for the design of HIC devices to be successful. A uniform (non-apodized) grating simulation predicts 75% coupling efficiency to a fiber, but it should be possible to extend this concept to apodized grating designs, known to be better matched to the fiber mode [2], to achieve efficiencies approaching 100%. A variant of this grating coupler concept has been reduced to a complete 3D design for experimental demonstration as part of a collaborative effort, and the fabrication and experimental results are being evaluated.

References

[1] Taillaert, D. et al., *IEEE Journal of Quantum Electronics* **38**, 949 (July 2002).
[2] Taillaert, D. et al., *Optics Letters* **29**, 2749 (December 2004).
[3] Van Laere, F. et al., "Compact grating couplers between optical fibers and Silicon-on-Insulator photonic wire waveguides with 69% coupling efficiency," presented at *Optical Fiber Communication Conference*, Anaheim, CA, March 5-10, 2006, paper PDP15.
[4] Gunn, C. "CMOS Photonics for High-Speed Interconnects," *IEEE Micro*, vol. 26, no. 2, pp. 58-66, Mar/Apr, 2006.
[5] Wang, B. et al., "Stratified Waveguide Grating Coupler for Normal Fiber Incidence," *Optics Letters*, vol. 30, pp. 845-847, April 2005.
[6] Flory, C. A. "Analysis of Directional Grating-Coupled Radiation in Waveguide Structures," *IEEE Journal of Quantum Electronics*, vol.40, pp. 949-957, July 2004.
[7] Manolatou C., "Passive Components for Dense Optical Integration Based on High Index-Contrast", *Ph.D. Thesis*, MIT, June 2001.