Optimization of an out-of-plane grating coupler using a novel 3D simulation scheme

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We present results of our novel 3D simulation scheme for out-of-plane grating couplers, which can be used for the design of, for example, free-space remote sensor connections, wafers scale inspection methods, or the coupling of active components such as VCSELs into planar photonic integrated circuits (PICs). This method uses a hybrid 2D/3D calculation scheme. An optimization procedure for a grating that couples light into an optical fiber positioned 0.1 mm above the photonic integrated circuit is performed within the tolerances of current CMOS fabrication for silicon-on-insulator technology. The efficiency of our coupler is -5.6dB, which differs from the -4.7dB attained using a 2D approach.

Introduction

This year, the 50th anniversary of the laser is celebrated with *LaserFest* events around the world [1]. Although the first experimental demonstration of the laser by Theodore Maiman passed without much recognition, its unique temporal coherence properties have revolutionized datacommunication systems worldwide. Optical fibers have replaced copper-wire-based networks in long-haul telecommunication systems. However, the use of light as carrier of information is certainly not limited to long-distance communication only. Other fields of applications, such as on-chip interconnects for electronic integrated circuits (IC's), and biosensors for medical point-of-care diagnostics have gained a lot of interest over the last decade [2, 3]. These devices are based on integrated optics, the concept to integrate various photonic components on a single chip, a vision that was already proposed in the late 1960's. Development of integrated optical components has always gone hand-in-hand with development of fabrication processes. Universities have been using a broad range of technologies for photonic integrated circuits (PICs). Of these, silicon-on-insulator technology has emerged as one of the most stable and profitable platforms by using existing CMOS fabrication processes, thereby building on the momentum of silicon electronics. The *ePIXfab* consortium has tailored existing processes for fabrication of nanophotonic devices [4]. Using this technology, passive components such as a 16 channel wavelength division multiplexer [5] and sensors such as temperature sensor [6] or even a label free antibody detection sensor [3] have been demonstrated. However, as silicon has an indirect band gap, generation or detection of light requires additional material. IBM recently presented CMOS fabricated germanium photodetectors [2]. Promising hybrid integration of indium phosphide (InP) sources has been demonstrated, but mass-fabrication like CMOS is not available [7].
The high refractive index contrast of SOI ($\Delta n \sim 2$) allows for a small device footprint, and thus for high functionality per mm^2. However, there is a huge size mismatch between the

mode in optical fiber (∼9 μm) and the mode of a SOI ridge waveguide (∼ 0.5μm), which makes coupling of light into a SOI-PIC difficult. Various methods have been introduced to overcome this problem, such as direct focusing or *end-fire* coupling, tapered couplers, inverted tapered couplers, prism couplers and grating couplers [8, 9]. Of these methods, out-of-plane grating couplers, a technique already introduced in the 70's, are easiest to fabricate, have the most flexibility and relaxed alignment tolerances. They radiate light upwards from the top-surface of the PIC, so that the coupler can have the same dimensions as the optical fiber [10].

The out-of-plane coupler is not only useful for coupling light into a fiber. A near-future candidate as light source for mass-produced silicon PICs is a VCSEL mounted above an out-of-plane coupler with automated pick-and-place equipment [9, 11]. Furthermore, these couplers are very suitable for functional wafer-scale testing of PICs during the fabrication process. In the field of sensing, we expect grating couplers to be used for line-of-sight remote sensing in rough environments. This versatility of applications, in combination with the huge number of design parameters, requires a fast simulation method to calculate the full electromagnetic field at arbitrary position from the grating.

Rigorous simulation methods such as finite difference time domain (FDTD) or Eigenmode expansion (EMM) are required to accurately model the behavior of the high-contrast gratings [12]. In this paper, we extend the method with three-dimensional free-space propagation. The focus of this work is mainly on uniform gratings to demonstrate our novel calculation technique, but the analysis is easily applicable to any type of out-of-plane couplers with 1D gratings.

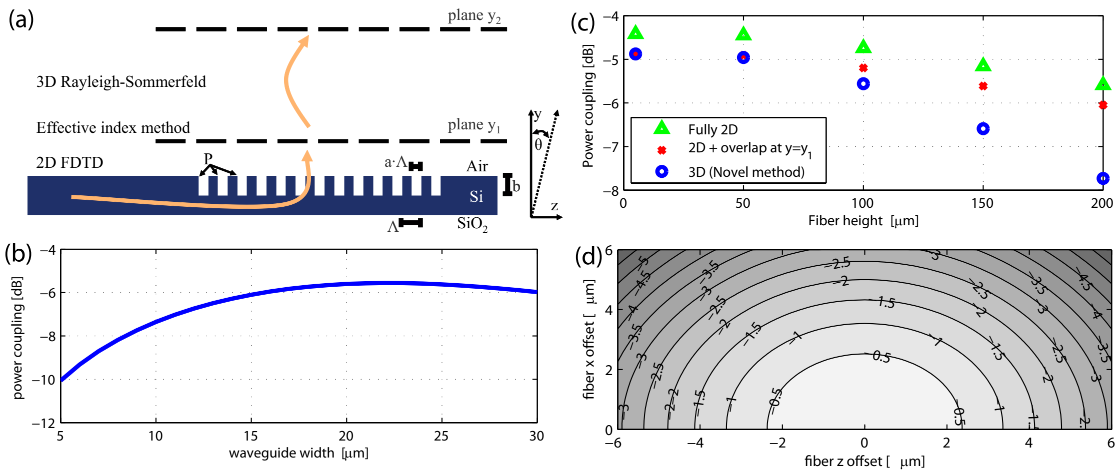

Figure 1: (a) Schematics of the grating coupler. The grating period Λ, the fill factor *a* and the etch depth *b* are indicated. The numerical methods for the different steps of the simulation approach are given on the left-hand-side of the figure. (b-d) Power coupling between the fundamental waveguide-mode and the fiber-mode, i.e. the power flux trough the optical fiber devided by the power flux trough the waveguide incident on the grating. (b) Variation of the width (in the x-direction) of the grating coupler waveguide. (c) Comparison between a 3D simulation performed using our new approach and 2D simulations. The distance of the PIC to the fiber (e.g. the fiber y-position) is plotted along the horizontal axis. For each y-position, the z-position and tilt of the fiber are optimized for maximum coupling. (d) Variation of the position of the fiber with respect to the grating coupler. The power coupling [dB] is plotted with respect to the power coupling at the optimal position of the fiber.

Theory and simulation method

An out-of-plane grating coupler couples light from a high refractive index waveguide upwards via the air into, for example, an optical fiber. Figure 1a shows a schematic of an out-of-plane grating coupler. The behavior of the coupler can intuitively be understood by considering all the tall-short interfaces on the left edge of the grating grooves as ”point-sources” which have a phase difference dictated by the propagation speed of the light trough the waveguide (a few of such ”point sources” are indicated by P in Fig. 1a). The fields emitted by these point-sources constructively interfere to a plane wave radiating under a certain angle θ_q w.r.t. the y-axis. The relation between this angle and the waveguide properties is given by [10]:

$$n_3 \sin(\theta_q) = n_{\text{eff}} - q \cdot \lambda_0/\Lambda, \tag{1}$$

where n_3 is the refractive index of the upper medium (air in Fig. 1a), n_{eff} is the effective index of the light propagating trough the grating, q is the coupling order, λ_0 is the wavelength of the light in vacuum and Λ is the grating period. For perfect vertical coupling, $\theta_q = 0$, Eq. (1) describes the second order resonance of a distributed Bragg reflector (DBR) [12], which very efficiently reflects the forward propagating light in the waveguide backwards, rather than radiating it upwards.
We suggest a novel combination of numerical methods, see Fig. 1a, which are detailed in [13]. The electromagnetic field up to plane (y_1) just ($\sim$ 1 wavelength) above the coupler is calculated using 2D FDTD simulations and the lateral profile is obtained using the effective index method (EIM). Propagation from this plane upwards is performed using the 3D Rayleigh-Sommerfeld diffraction formula [14].

Results

Using the method presented in the previous section, we designed an out-of-plane grating coupler for coupling to a single-mode optical fiber positioned 102 μm above a PIC. We considered a SOI layer stack as usually used in the *ePIXfab* consortium, which is a 220 nm high silicon guiding layer, on top of a 2 μm SiO_2 buried oxide (BOX) layer, on top of a silicon substrate. In this layer stack, only TE modes exist. The minimal feature (groove or line) size of *ePIXfab* is 120 nm [15]. The first step in our design flow is a parameter scan in grating period Λ and etch depth b, with the fill-factor a = 50 % and the waveguide width W = 22 μm kept constant. The scansteps of both Λ and b are 20 nm. The grating always has 60 periods, because there is almost no light left in the waveguide after this number of periods. For each grating, the fiber position and fiber tilt are optimized for maximal coupling. The second step we performed was a scan in the fill-factor a with scansteps of 20 nm. The maximum power coupling between the fundamental mode of the waveguide and the mode of the single-mode fiber is found with grating parameters (Λ = 580 nm, b = 20 nm, a = 50 %) and a fiber tilt of 5.2°. The final design step is a scan in the width W of the waveguide in scansteps of 1 μm. This design step is presented in Fig 1b. One can see that the optimal width is W = 22 μm. Here, a three-dimensional description of the problem is clearly necessary.
Figure 1c compares the 3D result with a purely 2D result for a fiber positioned at various heights above the grating. The triangles denote a fully 2D approach. The crosses corrected the 2D approach with the 2D overlap integral of the field radiated from the grating

at position $y = y_1$ and the field at the end-facet of the fiber. This method neglects the lateral spreading of the electromagnetic field while propagating trough the air. The circles denote the 3D result, which we calculated with our new method. The difference between a fully 2D approach and a 3D approach for a fiber at position y = 102 μm is $\sim$1 dB.
An alternative approach is to describe the propagation of light from the fiber facet to a plane just above the coupler, which can be done analytically for Gaussian beams [12]. However the method proposed here gives much more flexibility which is necessary when the light is coupled to a electromagnetic field that cannot be propagated analytically.
Figure 1d shows the alignment tolerance of the grating coupler. The axes of the figure represent fiber offsets from the optimal position in z- and x-directions. The area with a maximum transmission loss of -1 dB has a diameter of 6.8 μm and is almost circular.

Conclusion

In this paper, we presented the design of an out-of-plane grating coupler for coupling to a single-mode fiber positioned 0.1 mm above the grating. The coupler is compatible with CMOS fabrication for photonic components based on SOI technology. The results where obtained using a novel simulation scheme, that considers the free-space propagation three-dimensionally. The power coupling efficiency is -5.6 dB and the alignment tolerance of the fiber is 6.8 μm. We foresee a broad range of applications for grating couplers, and the method as presented here fulfills this versatile need.

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