High efficiency diffractive grating couplers for interfacing a single mode optical fiber with a nanophotonic silicon-on-insulator waveguide circuit

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High efficiency diffractive grating structures to interface a single mode optical fiber and a nanophotonic integrated circuit fabricated on silicon-on-insulator are presented. The diffractive grating structures are designed to be inherently very directional by adding a silicon overlay before grating definition. 55% coupling efficiency at a wavelength of 1.53 μm is experimentally demonstrated on devices fabricated using standard complementary metal-oxide semiconductor technology. By optimizing the grating parameters, we theoretically show that 80% grating coupling efficiency can be obtained for a uniform grating structure. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2905260]

High refractive index contrast optical waveguide structures hold promise for large scale integration of optical functions on a single substrate. This is due to the fact that the high refractive index contrast allows realizing wavelength-scale optical components (e.g., photonic crystal cavities,[1] ring resonators,[2] modulators,[3] etc.) which can be interconnected by nanophotonic integrated waveguides. Silicon-on-insulator (SOI) is emerging as the dominant platform for this integration because the refractive index contrast between the silicon waveguide layer (n_{Si}=3.45 at a wavelength of 1.55 μm) and the underlying buried oxide layer (n_{SiO_2} =1.45) is very high. Moreover, these nanophotonic structures can be defined using state-of-the-art complementary metal-oxide semiconductor (CMOS) technology.[4] While the high omnidirectional refractive index contrast allows realizing wavelength-scale optical functions, the interfacing between a nanophotonic waveguide and a standard single mode fiber is far from trivial due to the large mismatch in dimensions between the 9 μm diameter core of a single mode fiber and the cross section of an integrated high index contrast waveguide, which is typically 0.1 μm^2 for a single mode waveguide at telecommunication wavelengths. In this paper, we present the use of a diffractive grating structure defined in the waveguide layer to efficiently interface with a single mode optical fiber. The operation principle of the device is based on the Bragg diffraction from the grating. The optical fiber is slightly tilted off vertically in order to avoid second order Bragg reflection into the waveguide.[4] While the optical coupling properties of one-dimensional grating structures are very polarization dependent, it was shown that a two-dimensional grating coupling approach allows tackling the issue of the polarization dependent loss of high index contrast photonic integrated circuits by applying a polarization diversity configuration,[5] without the need of integrating a polarization splitter and rotator on the photonic integrated circuit.[6]

The fiber-to-waveguide coupling efficiency is determined by the directionality of the grating, being the ratio of the power that is diffracted upward (P_{up}) to the total diffracted power ($P_{up}+P_{do}$), as shown in Fig. 1. Besides the directionality, the profile of the diffracted field also determines the coupling efficiency because it has to match the Gaussian field profile of the optical fiber as much as possible. For a uniform grating, this diffracted field profile is in good approximation exponentially decaying. Previously, we theoretically and partly experimentally proposed that a bottom mirror can be integrated to redirect the downward diffracted light to obtain a higher directionality[7] and that a higher coupling efficiency can be obtained by making the diffraction grating nonuniform in order to better match the diffracted field profile (which is no longer exponentially decaying) and the Gaussian field profile of the optical fiber.[8] However, one can argue that integrating a bottom mirror (which was achieved by a wafer bonding process) and making a grating nonuniform is not CMOS compatible or is at least very complex. Recently, we proposed to inherently modify the directionality of the diffraction grating by altering the grating design, thereby altering the properties of the (radiating) Bloch modes propagating in the one-dimensional periodic structure.[9] Instead of directly etching the grating into the 220 nm silicon waveguide layer, in the advanced design, a silicon overlay is deposited before grating etching, as shown in Fig. 1. This extra degree of freedom allows the tailoring of the radiation properties of the Bloch modes which propagate in the one-dimensional periodic structure, and thereby opti-

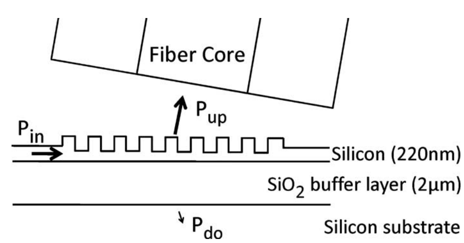

FIG. 1. Proposed diffraction grating layout for efficient fiber-to-waveguide coupling.

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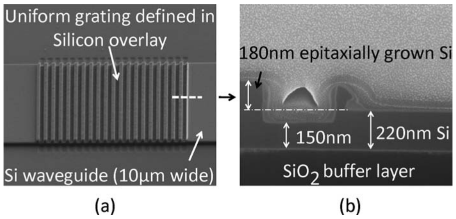

FIG. 2. (a) SEM image of fabricated grating structure on a 10 μm wide SOI waveguide and (b) a FIB cross section of the device revealing epitaxial layer thickness and grating etch depth.

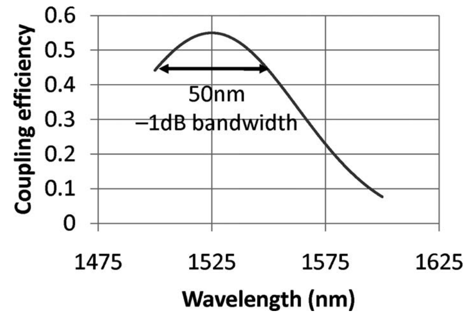

FIG. 3. Experimentally obtained fiber-to-waveguide coupling spectrum showing 55% maximum efficiency and a −1 dB optical bandwidth of 50 nm.

mizing the coupling efficiency of the grating. By assuming a 50% grating duty cycle, 66% coupling efficiency between a single mode optical fiber and a 220 nm thick SOI waveguide layer at a wavelength of 1.55 μm was predicted by using finite difference time domain (FDTD) simulations using a 150 nm silicon overlay thickness, a 610 nm period grating, and a 220 nm grating etch depth. These grating parameters are optimal because they allow the propagation of a radiating Bloch mode at 1.55 μm in the periodic structure, which intrinsically radiates most of the power toward the superstrate and which has an attenuation length (which determines the decay length of the exponentially decaying diffracted field profile) that optimally matches with the 10.4 μm $1/e^2$ diameter of the Gaussian fiber mode profile. In this design, the light is diffracted under an angle of 10° with respect to the surface normal. This 66% fiber coupling efficiency is two to three times higher than those of standard grating structures, where the diffraction grating is directly defined into the silicon waveguide layer.[4] Only by using free space optics to expand the fiber mode size can an efficiency comparable to that presented here be obtained from the standard grating structures, which is at the expense of the optical bandwidth (due to the lower grating strength) and at the expense of the ease of packaging.[10] In this paper, we report on the experimental realization and characterization of these Bloch mode engineered diffraction gratings. We will also show that by allowing a grating duty cycle different from 50%, coupling efficiencies up to 80% can be obtained by further optimizing the Bloch mode radiation properties.

The processing of the diffractive grating structure was performed on a 200 mm SOI wafer, consisting of a 220 nm silicon waveguide layer and a 2000 nm buried oxide layer on a silicon substrate. Standard CMOS technology was used for fabrication. After the deposition of a blanket SiO_2 hard mask, windows are opened in the hard mask, exposing the silicon waveguide layer, in order to locally define the silicon overlay. The silicon overlay is defined by epitaxial silicon growth in a reduced pressure chemical vapor deposition tool by using SiH_4 at 700 °C. After silicon epitaxy, the SiO_2 hard mask is removed and the diffraction grating and optical waveguides are defined by using 193 nm deep UV lithography and dry etching using a low-pressure/high-density $Cl_2/O_2/He/HBr$ chemistry. A scanning electron microscope (SEM) image of the fabricated structures is shown in Fig. 2(a), together with a focused ion beam (FIB) cross section of the device at the first slit of the grating [Fig. 2(b)]. The SEM image shows the high quality silicon overlay on top of a 10 μm wide SOI waveguide. From the cross section, one can conclude that 180 nm of silicon was epitaxially grown on the silicon waveguide layer (while 150 nm was targeted) and the etch depth is 250 nm (220 nm target). The width of the first grating tooth is reduced due to a slight misalignment between the grating mask and the silicon overlay mesa. FDTD simulations show, however, that this has a negligible effect on the device efficiency. Simulation of these experimentally obtained diffractive grating structures shows a theoretical coupling efficiency of 59% for transverse electric polarized light, which is only slightly less than the optimal grating structure efficiency of 66%. The simulated −1 dB optical bandwidth is 55 nm. The diffractive grating structures were experimentally characterized by measuring the fiber-to-fiber transmission efficiency, where the light passes through a 6 mm long photonic wire with two identical diffraction gratings at each side to interface with single mode optical fibers. Index matching fluid was applied between the optical fiber facet and the diffraction grating to avoid reflections at the fiber facets.

The light in the input fiber was linearly polarized with the electric field vector parallel to the grating lines (transverse electric polarization). By assuming that the coupling spectra of both diffraction gratings are identical and neglecting the loss that the light experiences while propagating through the 6 mm long photonic wire, a lower boundary for the grating coupler efficiency is obtained. This coupling spectrum is plotted in Fig. 3, showing a 55% coupling efficiency and a −1 dB optical bandwidth of 50 nm, which is in good agreement with the simulations. This development results in a four to seven times enhancement of the fiber-to-fiber transmission compared to standard gratings, which are directly etched in the silicon waveguide layer.[4]

While the demonstrated grating structures had a 50% duty cycle, for ease of fabrication, much can be gained in terms of efficiency by allowing a grating duty cycle different from this 50%. In order to assess the maximum obtainable efficiency for a uniform grating structure, a particle swarm optimization algorithm was used to optimize the properties of the radiating Bloch modes supported by the grating structure. FDTD simulations show that for a grating structure consisting of a 150 nm overlay, a 250 nm etch depth, a grating period of 710 nm, and a duty cycle of 25% (530 nm wide etched slits) up to 80% coupling efficiency can be obtained. This grating coupler has a −1 dB optical bandwidth of 50 nm and a −3 dB optical bandwidth of 100 nm. Supported by the good correspondence between the experiment and simulation for the structures presented above, it is believed that another important leap in coupling efficiency can be made toward the practical level of −1 dB fiber-to-waveguide coupling efficiency.

In this paper, we presented the experimental characterization of Bloch mode engineered fiber-to-waveguide grating coupler structures. The obtained 55% efficiency is in good agreement with numerical simulations and outperforms standard directly etched grating structures by a factor of 4–7 in terms of fiber-to-fiber transmission efficiency.[4] The structure has several advantages: It is compact and efficient. It does not require a polished waveguide facet for interfacing, thereby paving the way to wafer level testing and packaging of photonic integrated circuits, which can dramatically reduce the cost of the photonic integrated circuit. Moreover, the structure can be defined using standard CMOS technology, i.e., using a 193 nm deep UV lithography on 200 mm SOI wafers, as demonstrated in this paper. Furthermore, we show that by allowing a grating duty cycle different from 50%, the radiation properties of the Bloch modes supported by the grating can be further enhanced to achieve 80% fiber-to-waveguide coupling efficiency.

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