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Design and Characterization of a Top Cladding for Silicon-on-Insulator Grating Coupler *

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An effective top cladding for silicon-on-insulator grating coupler is designed and the validity of the design is confirmed experimentally. The proposed double-layer silicon oxide/silicon nitride (SiO_2/Si_3N_4) cladding demonstrates antireflection properties and affects a coupling strength of the grating structure. A coupling efficiency of 65% is obtained after cladding layer deposition.

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Silicon on insulator (SOI) shows great promise as a material for photonic integrated circuits. However, this trend faces a key challenge to couple light between optical fibers and nanophotonic waveguides because of the large mode mismatch. Coupling is therefore crucial for practical device operation in most applications. There are several approaches to reduce the coupling loss between the rib mode and fibers. Waveguide grating couplers demonstrate many advantages, which include the simplicity of fabrication without facet polishing, flexibility of placement of the optical interface anywhere on the chip surface, and compatibility with wafer scale testing before dicing.

There are two main factors limiting the coupling efficiency of grating couplers. One is the directionality of gratings; a significant part of the light power leaks towards the substrate because of grating diffraction. The use of a bottom reflector based on a metallic layer[1] or distributed Bragg mirror[2] significantly increases the fiber to chip coupling efficiency. The directionality can also be improved by applying an additional silicon overlay.[3–5] A design of grating coupler with a back hole and reflection metal layer on the top was proposed by our group.[6] Another factor limiting the coupling efficiency is the mismatch between the diffracted field and the Gaussian fiber mode profiles since the field profile is exponentially decaying. A number of approaches using a nonuniform grating coupler were demonstrated to tailor the coupling strength of the grating structure to the mode profile of the fiber.[7–9]

In Ref. [10] we demonstrated a high efficiency and broad bandwidth SOI grating coupler. In this Letter, we present a sophisticated design of a double-layer silicon oxide/silicon nitride (SiO_2/Si_3N_4) top cladding for a grating coupler. We achieve high coupling efficiency by means of minimizing back reflection into the silicon waveguide and tailoring the coupling strength. This device can be fabricated in a CMOS line with standard processes and it requires less process steps than for integrating a bottom mirror or making a grating nonuniform.

Inserting a top cladding layer onto the silicon is a simple way to increase the coupling efficiency and usually an index-match layer of silicon oxide is used for this purpose. However, its refractive index (1.46) is too small to act as an efficient single-layer antireflection coating (ARC) on silicon since a single dielectric film on a dielectric substrate will yield zero reflectance if the film is an optical quarter-wavelength thickness, and its refractive index is equal to the square root of the substrate index. From the theory of optical coatings it is known that double-layer ARC has much better antireflection properties than single-layer coating. Double-layer ARCs can be used to provide a broader region of low reflectance than that afforded by single-layer coatings or to give zero reflectance with materials, which cannot be used for the purpose as single-layer coatings. Two types of such coatings are available. In one case, the optical thicknesses of the layers are integral multiples of one-quarter wavelength, in the other type, the thicknesses of the layers are not related by integral multiples of a quarter wavelength.

The reflection losses at the grating-fiber interface will be eliminated if the refractive index of the top layer is equal to the effective index of the fiber. With a double-layer coating design this condition can be fulfilled while the refractive index of the second layer is adjusted to provide good antireflection properties for the whole structure. In fact, the coating is not as

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simple as one usually dealt with when considering an ARC for a substrate with a given refractive index for operation at a reference wavelength. When designing the top cladding for the grating coupler, besides sub-wavelength relief structure of the grating, we should take into account a buried oxide layer and a silicon substrate.

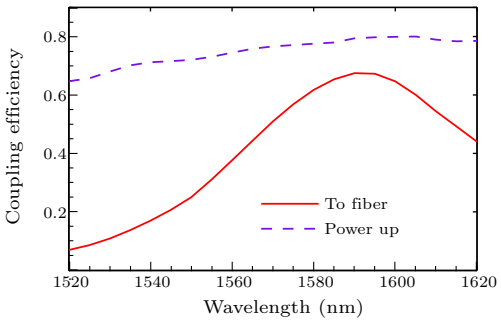


Fig. 1. Calculated coupling efficiency to the fiber and upwards radiated power.

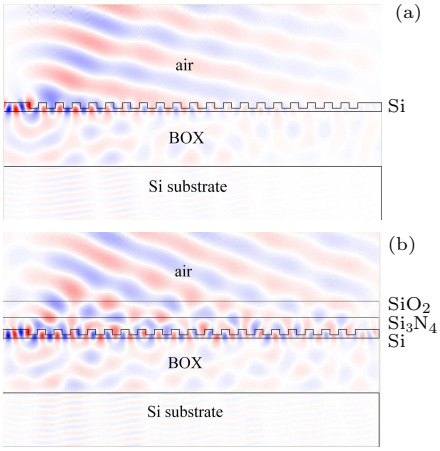


Fig. 2. Field plot comparison of the standard grating coupler design (a) and the grating coupler structure with top cladding (b).

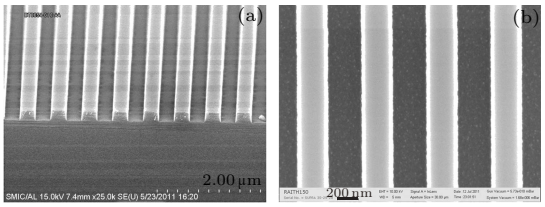


Fig. 3. Oblique (a) and top-view (b) SEM images of the SOI grating coupler before coating deposition.

The designing principle of any coating consists in varying both the refractive index and the thickness of each layer. The selection of coating material depends mainly on the refractive index of the material and the production method to be applied. As the number of CMOS compatible materials is limited, in the present work we focus on a pair SiO_2/Si_3N_4. In Ref. [11] an effective SiO_2/SiN ARC deposited by plasma enhanced chemical vapor deposition (PECVD) is proposed to improve the efficiency of silicon solar cells. PECVD allows tailoring refractive index n of both SiN and SiO_2 films by adjusting deposition parameters, where the most used one is the gas flow ratio of the precursor gases.

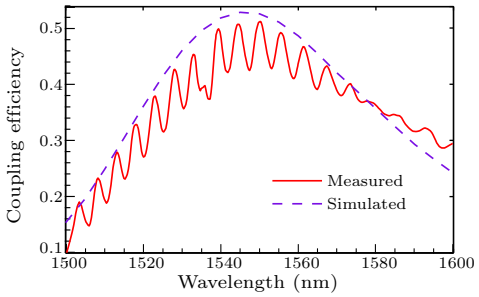


Fig. 4. Measured coupling efficiency of the uncoated grating coupler and comparison with the simulation result.

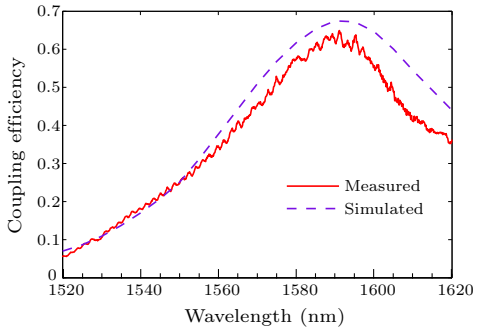


Fig. 5. Comparison of simulated and measured coupling efficiencies of the grating coupler with the top cladding.

The goal of all thin-film design techniques is to obtain an optimal solution. In this study, an optimal top cladding is defined as the one where the coupling efficiency of a grating coupler with the coating is as high as possible in a given wavelength region. From the above we have the specified refractive indices for each layer and the design procedure is only to vary a thickness of the layers to yield an optimal solution.

We simulate and optimize the grating coupler performance using the eigenmode expansion technique with perfectly matched boundary layers as implemented in the software package CAMFR. The transverse electric (TE) polarization, i.e. the electric field is parallel to the grating, is assumed and the target wavelength is 1550 nm. The incident light diffracts into a 10.4 μm wide Gaussian profile (i.e. a single mode fiber) tilted 8° off the vertical axis. The grating coupler is based on a standard SOI wafer with a silicon top layer of 340 nm and a buried oxide layer of 2 μm, the optimized grating period of 610 nm, the etching depth of 200 nm and the filling factor 0.5. For better alignment to the fibers the number of grating periods is chosen to be 20. The refractive indices used in the computation are as follows: for silicon 3.476, Si_3N_4 2.03, SiO_2 1.444, index matching layer (IML) 1.46 and air 1.0.

A SiO_2/Si_3N_4 stack is inserted on the top of a grating and the design was optimized. The coupling

efficiency of 67.5% is obtained numerically with thicknesses 590 nm for SiO_2 and 450 nm for Si_3N_4, respectively. Coupling efficiency as functions of wavelength and total upwards coupled power is shown in Fig. 1. A top cladding layer also influences the coupling strength since the effective index of a grating coupler is changed. The strength is reduced but the asymmetry of the grating structure is increased (which can improve the directionality) and we have a longer coupling length of the grating. The field plot of the optimized grating coupler structure with and without the top cladding is shown in Fig. 2.

Standard CMOS technology was used for fabrication of the sample, cladding was deposited by PECVD. The fabricated grating coupler before cladding deposition is presented in Fig. 3. In order to avoid the mode transition loss produced by the tapered mode size converters, the two grating couplers were connected directly by a 12 μm wide multimode SOI waveguide with the length of 950 μm.

During the device characterization, we first measured the coupler-to-coupler transmission in the wavelength range 1500–1600 nm. Careful alignment of grating couplers is needed to achieve a higher coupling efficiency. For example, the two fibers and the waveguide should be adjusted to be strictly coaxial. The position of the fiber over the grating is also critical to achieve high efficiency. The polarization of the input light is controlled by a tunable fiber polarizer in order to obtain the best input condition. After the coupler was measured, we replaced the tilted fibers with a single mode fiber in comparable length. The fiber was connected at the end of the polarization controller. Lastly, the transmission from the fiber was measured as the reference spectrum. The difference between the coupler-to-coupler transmission and the fiber-to-fiber transmission is the coupling-induced loss of the two couplers. The coupling efficiency of one coupler can be determined as the square root of this value because the input and output coupling efficiencies to fiber are the same.

The maximum measured transmission for the coupler in the absence of cladding is approximately −3.3 dB or 47%. The relationship between coupling efficiency and wavelength is shown in Fig. 4. It is revealed that the fringes on a curve are due to interference of the fundamental and second-order modes supported in the wide waveguide, narrower fringes correspond to interference within the Fabry-Perot cavity formed by two grating couplers. The coupling efficiency is increased to 1.9 dB or 65% when applying the top cladding. The coupling efficiency as a function of wavelength is shown in Fig. 5. The central wavelength is shifted since the effective index of the guided mode was changed after cladding deposition. The second-order mode as well as Fabry-Perot interference are suppressed as the result of a lower index contrast after coating deposition so we have a smoother curve. Slight discrepancy between the measurement and simulation results can be explained by variation of light polarization during the measurement procedure but the results are in good agreement.

The highest demonstrated fiber coupling efficiency for grating couplers fabricated in a CMOS line is 1.6 dB.[5] However, our design requires less process steps which makes it competitive.

In conclusion, we have presented the optimized design of top cladding for SOI grating couplers. The coupling efficiency of 65% is demonstrated experimentally, which is in good agreement with the numerical simulations and shows a potential of our approach for coupling efficiency improvement.

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