Gold Grating Coupler for Silicon-on-Insulator Waveguides with 34 % Coupling Efficiency

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Abstract: *Gold gratings are proposed for efficient coupling between optical fibers and silicon-on-insulator (SOI) waveguides. They are compact and very easy to fabricate using a processing scheme based on lift-off. In this paper, a gold grating coupler is demonstrated with 34 % coupling efficiency at a wavelength of 1.55 µm. The measurement results are in good agreement with simulation results.*

Introduction

Silicon-on-Insulator (SOI) is emerging as a very interesting platform for integrated nanophotonics due to the high refractive index contrast between the silicon core and the oxide cladding. One of the drawbacks of the high index contrast is the large mismatch in mode size and shape between the fundamental mode of SOI waveguides and the mode of optical fibers. This makes efficient coupling from fiber to waveguide difficult to achieve. Grating couplers defined by etching a grating a few tens of nanometer into the high index silicon waveguide layer offer a very elegant solution to this problem [1]. Their compactness (10 *µm* x 10 *µm*), efficiency, large optical bandwidth and very good alignement tolerances make them suitable for many applications such as rapid testing of photonic circuits on wafer-scale and packaging of photonic circuit chips with optical in- and outputs.

With conventional SOI grating couplers, a coupling efficiency of 33 % [2] from fiber to waveguide has been demonstrated and several approaches are being investigated to improve this value. In particular, introducing a bottom gold mirror has been proven to improve the coupling efficieny up to 69 % [3] and apodizing the grating in combination with local deposition of a poly-silicon overlay is expected to improve the coupling efficiency even more [4]. However, all of these approaches require a number of extra processing steps and make fabrication rather challenging. In contrast, the metal grating couplers proposed here are very easy to fabricate and demonstrate high efficiencies comparable to the coupling efficiencies of current state-of-the art SOI grating coupler devices.

Device layout and operation principle

A scheme of the metal grating coupler for SOI waveguides is depicted in Fig. 1. It consists of a metal grating on top of the silicon waveguide layer of an SOI layer structure. The optical fiber is slightly tilted with respect to the vertical axis in order to prevent a large second order reflection.

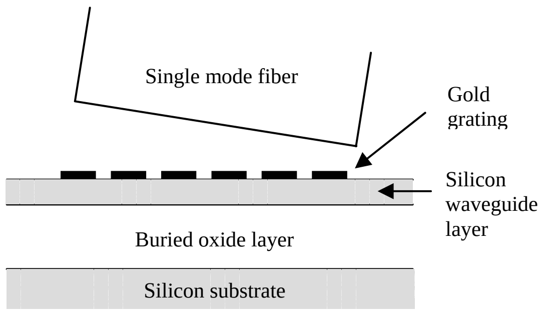

Fig. 1: Device layout and principle: gold grating on top of an SOI waveguide. Light from the single mode fiber incident on the grating is diffracted by the grating into the silicon waveguide layer.

At a wavelength of 1.55 µm, there is a very high refractive index contrast between the metal teeth and their surroundings. In the case of gold, the refractive index contrast between gold and silicon equals $\Delta n = n_{Si}-n_{Au} = 2.9 + 10.8j$. Thus, light incident on the grating is strongly scattered. This property can be exploited for the design of efficient, broadband and compact grating couplers. Moreover, due to the very high index contrast, only a very thin layer of gold suffices to achieve high coupling efficiency, as will be shown in the next section.

Simulation Results

For the design of gold grating couplers, we use CAMFR, a two-dimensional fully vectorial simulation-tool based on eigenmode expansion and mode propagation with perfectly matched layer (PML) boundary conditions [5]. We consider 1-D gratings in 2-D simulations and concentrate on TE polarization (electric field parallel to the grating lines).

Simulation is performed for an SOI layer structure with 220 nm top silicon layer and 2 µm buried oxide layer thickness. The refractive index data for gold is taken from [6]. An index matching glue is present between the optical fiber and the grating coupler so that reflections at the fiber facet are avoided. The waveguide mode is incident from the left and is normalized to the input power. The top and bottom boundaries of the simulation area have PML to avoid parasitic reflections.

In a first step reflection and transmission of the entire structure is calculated. Afterwards, the diffracted field is calculated from which the power flux and overlap with a fiber mode can be calculated. The fraction of the input power that couples to the fiber mode is defined as the coupling efficiency. To this end, the fiber mode is modelled as a Gaussian distribution with a full width at half maximum (FWHM) of 5.2 μm.

Fig. 2 plots the coupling efficiency as a function of wavelength for a gold grating with period 610 nm, filling factor 50 % and thickness of the metal layer 20 nm. The coupling efficiency is 40 % and the 1dB bandwidth exceeds 40 nm. A field plot illustrates the strong diffraction by the grating in the direction of the fiber. This is shown in Fig. 3. We note that the coupling efficiency can be further improved by optimizing the grating parameters and the parameters of the SOI layer structure. However, the above mentioned values were taken as they correspond to the geometric parameters of the prototype device that was fabricated. Fabrication is discussed in the next section.

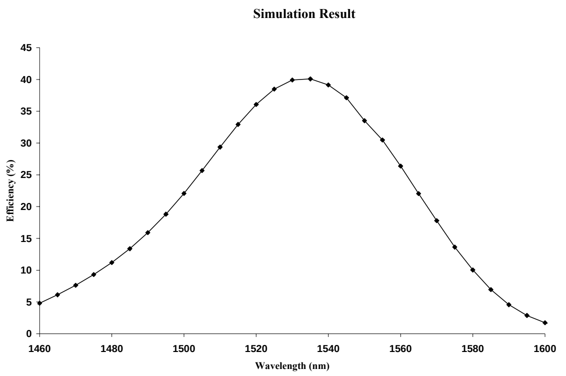

Fig. 2: Simulation of coupling efficiency as a function of wavelength of a gold grating coupler with the following grating parameters: period = 610 nm, filling factor = 50 %, height = 20 nm.

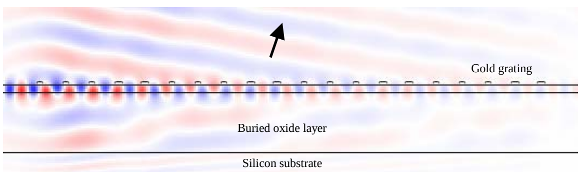

Fig. 3: Field plot of a gold grating coupler on top of an SOI waveguide. The mode guided by the top silicon layer from is incident from the left and is diffracted in the direction of the fiber.

Fabrication

Gold grating couplers are very easy to fabricate. We fabricated a prototype as follows. First, PMMA was spun on an SOI sample containing 10 μm wide and 7 mm long SOI waveguides with standard SOI grating couplers at both ends of the waveguides. The waveguides and couplers were fabricated using Deep UV-lithography (DUV) and inductively coupled plasma etching (ICP). With the electron beam of a Nova 600 Dualbeam (FEI) system, a 610 nm period grating was defined in the PMMA on top of the SOI waveguides. Then, gold was evaporated followed by a lift-off in acetone. A SEM-picture of a fabricated gold grating coupler device is depicted in Fig. 4. The final device is 12 μm x 10 μm.

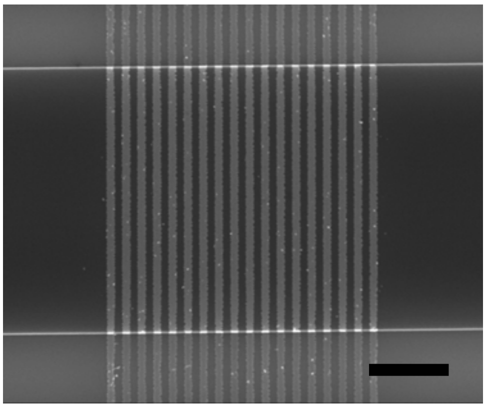

Fig. 4: Top view of the fabricated gold grating coupler on top of an SOI waveguide. Reference bar length = 3 micron.

Measurement results

The fabricated gold grating coupler was optically characterized using the following experimental set-up. An input single mode fiber connected to a tuneable laser source was positioned over the gold grating coupler. An output single mode fiber connected to a photodetector was positioned over the SOI grating coupler. Polarization wheels were used to control polarization. After an active alignation procedure whereby the fiber positions were optimized in order to obtain maximal transmission at a wavelength of 1.55 μm, the tuneable laser source was swept from 1.5 μm to 1.6 μm and the photodetector data were recorded. The same procedure was followed for a reference measurement in which the SOI grating couplers on both ends of a waveguide were used both for incoupling and outcoupling.

From these measurements, the fiber-to-waveguide coupling efficiency of the gold grating coupler can be calculated. The result is plotted in Fig. 5. To this end, a fiber-to-waveguide coupling efficiency of 34 % has been measured at a wavelength of 1.55 μm and a 1dB bandwidth of 35 nm. This result is in good agreement with the simulation results plotted in Fig. 2.

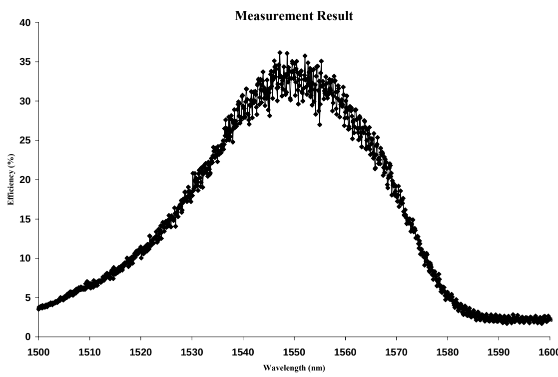

Fig. 5: Experimentally obtained coupling efficiency of a gold grating coupler on top of an SOI waveguide as a function of wavelength.

Conclusion

In this paper, a gold grating coupler was introduced for efficient and broadband coupling between SOI waveguides and optical fibers. A compact gold grating coupler was designed by simulation using eigen-mode-expansion and fabricated using an easy processing scheme based on e-beam writing and lift-off. The fabricated device demonstrated 34 % coupling efficiency at a central wavelength of 1.55 μm. The measurement results are in good agreement with the simulation results for the fabricated structure.

Acknowledgments

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