High efficiency silicon nitride surface grating couplers

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Abstract: High efficiency surface grating couplers for silicon nitride waveguides have been designed, fabricated, and characterized. Coupling efficiencies exceeding 60 % are reported at a wavelength of 1.31 µm, as well as angular and wavelength -3 dB tolerances of 4° and 50 nm, respectively. When the wavelength is increased from 1310 nm to 1450 nm the coupling efficiency progressively decreases but remains above 20 % at 1450 nm. The influence of the duty ratio of the grating has also been investigated: maximum coupling efficiency was obtained at 50 % duty ratio.

OCIS codes: (130.0130) Integrated optics, (230.0230) Optical devices, (230.1950) Diffraction grating, (050.2770) Gratings

References and links

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#86018 - $15.00 USD Received 1 Aug 2007; revised 29 Oct 2007; accepted 31 Oct 2007; published 4 Jan 2008

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1. Introduction

Silicon-based photonic integrated circuits (PICs) find applications in an increasing number of fields, such as optical interconnects and optical telecommunication devices (switches, modulators, filters, add-drops, polarizers, photodetectors, etc) [1-4], and in biological and environmental sensing [5-7]. Silicon On Insulator (SOI) substrates are an attractive platform to realize PICs, since the high index contrast ($\Delta n \approx 2$) between silicon and its oxide guarantees a strong light confinement and leads to high integration. However, this strong confinement has the drawback that the devices are highly sensitive to fabrication imperfections like interface roughness [8-10]. Silicon nitride (Si_3N_4) has a lower refractive index than silicon, but still higher than silicon oxide ($\Delta n \approx 0.5$). Therefore, its use as high index material can allow the implementation of photonic devices less sensitive to surface roughness and with higher tolerances to dimensional deviations during fabrication, while remaining low cost and keeping a reasonable level of integration [11, 12]. The development of efficient and reliable PICs significantly depends on the ability to couple a large amount of light into submicron waveguides. Among the solutions proposed so far, surface grating couplers are particularly attractive [13, 14], since they allow high coupling efficiency and light injection anywhere on the wafer surface without the need to cleave the photonic dies.

Hereafter, we firstly present the design and fabrication of high efficiency surface grating couplers for silicon nitride photonic structures, before reporting experimental results: coupling efficiency, wavelength and angle tolerances, as well as coupling length and duty ratio effect.

2. Design and fabrication

The schematic view of the surface grating coupler structure is depicted in Fig. 1(a). It consists of a silicon substrate, a silicon oxide bottom cladding layer, a 300 nm thick silicon nitride layer and a SiO_2 top cladding layer. The grating coupler is either fully etched down to the bottom cladding or partially etched, leaving a 50 nm thick silicon nitride layer (250 nm etching depth). A resonant coupling between the guided TE mode in the silicon nitride layer and a diffraction order of the grating is obtained when the following phase matching condition is fulfilled:

$$k_0 n_{inc} \sin(\theta_{inc}) + p\frac{2\pi}{\Lambda} = \beta \tag{1}$$

where $k_0 = 2\pi/\lambda$, λ is the wavelength, n_{inc} is the refractive index of the top cladding layer, θ_{inc} is the incidence angle, p is the diffraction order (here $p = +1$), Λ is the grating period, $\beta = k_0\, n_{eff}$ is the real part of the propagation constant, and n_{eff} is the effective index of the guided mode in the corrugated waveguide. The coupling efficiency strongly depends on the bottom and top cladding layer thicknesses. The approach used for the related optimization is firstly based on a differential analysis allowing the determination of the optical field under the grating for the input plane wave case [15]. Then, beam propagation method modeling is used

#86018 - $15.00 USD Received 1 Aug 2007; revised 29 Oct 2007; accepted 31 Oct 2007; published 4 Jan 2008

to calculate the diffracted field propagating in the corrugated waveguide for a 3-D Gaussian incident beam illuminating the grating [16].

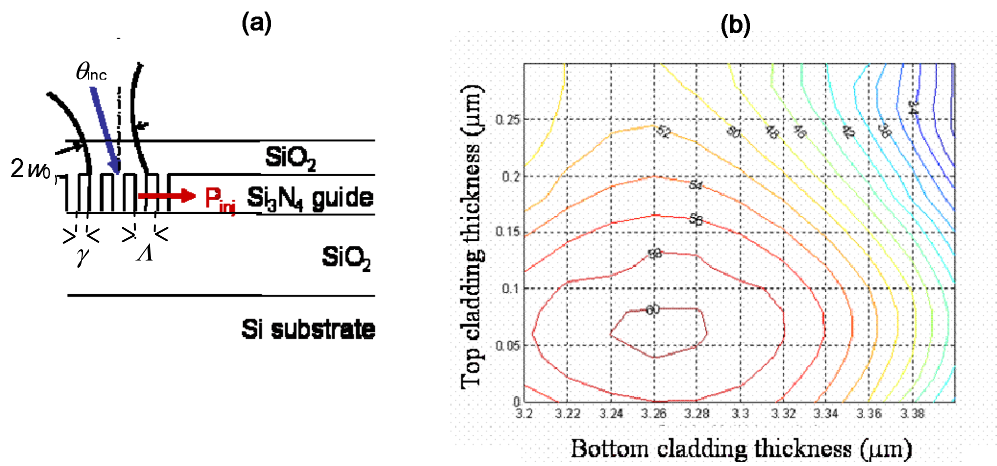

Fig. 1. (a). Grating coupler diagram: The silicon nitride layer thickness is 300 nm, the period is 1µm, the etching depth is 300 nm and the duty ratio is 50%. (b) Theoretical results of coupling efficiency (percentage) as a function of top and bottom cladding thicknesses for a 1.31 µm wavelength.

Using this approach, the theoretical results of the coupling efficiency as a function of the top and bottom cladding layer thicknesses for an incident wavelength of 1.31 µm are presented in Fig. 1(b) for a fully etched grating coupler. The 1,31 µm wavelength leads to a grating period of 1 µm for a 50 % duty ratio. Refractive indices of silicon oxide and silicon nitride are 1,45 and 1,95, respectively. A maximal coupling efficiency of about 60 % is predicted for bottom and top cladding thicknesses of 3.26 µm and 60 nm, respectively. As a result of an interference effect, this maximum is periodically obtained as a function of top and bottom cladding thicknesses [17]:

$$e_{bottom} = [3.26 + 0.46\, m]\ \mu m \quad (2.a)$$

$$e_{top} = [0.06 + 0.47\, q]\ \mu m \quad (2.b)$$

where m and q are integers. To evaluate the impact of the cladding layer and of the etching depth of the gratings on their performances, four different configurations have been studied. Partially etched (250 nm etching depth) and fully etched (300 nm etching depth) structures have been fabricated, and tested before and after the top cladding layer deposit.

To fabricate the structures, a 3.26 µm thick bottom cladding layer was thermally grown on a 4 inch silicon wafer and then, a 300 nm thick silicon nitride layer was deposited by low pressure chemical vapor deposition (LPCVD). The grating coupler was defined in the silicon nitride layer using e-beam lithography followed by a reactive ion etching (RIE) step. A top cladding thickness of 60 nm, corresponding to the case where $q = 0$ in Eq. (2.b), is not enough to obtain a smooth top surface. Thus, the structure was covered by a 530 nm ($q = 1$) thick silicon oxide top cladding by TEOS based LPCVD. An anti-reflection (AR) coating consisting of a 150 nm silicon nitride layer covered by a 50 nm silicon oxide layer was deposited on the back side of the silicon wafer by PECVD. The AR coating prevents reflections from the back side of the wafer inside of the sample.

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3. Experimental results

The characterization is carried out using a tunable laser from 1250 nm to 1500 nm. The polarization is fixed to couple the TE mode. The laser beam is focused on the grating coupler at an angle close to the predicted resonance and with a beam diameter at $1/e^2$ of about 30 µm. The coupling efficiency of the grating coupler is defined as:

$$\eta = \frac{P_{\text{inc}} - \left(P_{\text{t}} + P_{\text{r}}\right)}{P_{\text{inc}}} \tag{3}$$

where P_{inc} is the incident power, and P_{t} and P_{r} denote the power transmitted and reflected by the grating, respectively. The measurement of these three powers permits to estimate accurately the power guided along the grating, i.e. the numerator of Eq. (3).

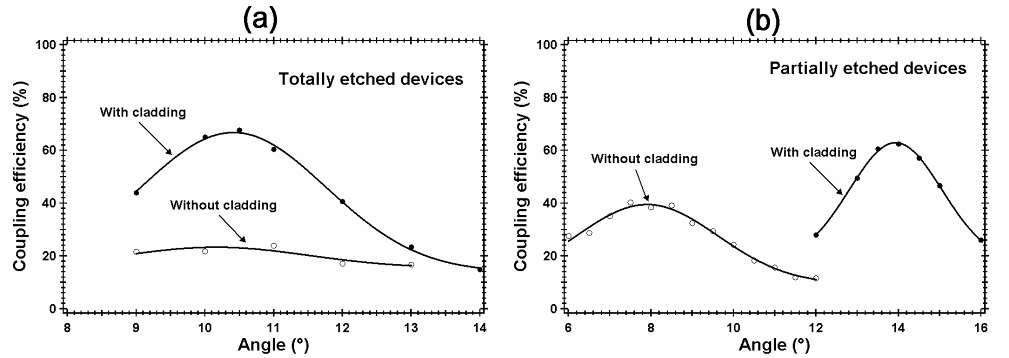

Fig. 2. Coupling efficiency at 1.31 µm as a function of incidence angle for fully (a) and partially (b) etched grating couplers with and without top silicon oxide cladding.

First, the coupling efficiency, as a function of the incidence angle at a 1.31 µm wavelength, is determined for the four different configurations: fully and partially etched structures, with and without top cladding layer. The tested gratings are 40 µm wide. As shown in Fig. 2, the coupling efficiency increases from 23 % to 67 % and from 40 % to 62 % for fully and partially etched structures, respectively, after the top cladding deposition. The higher coupling efficiencies are obtained at resonant angles of 10.5° and 14° for fully and partially etched couplers, respectively. They compete favorably with previously reported coupling efficiencies for SOI gratings, that do not exceed 60% [13, 14]. Furthermore, a fairly large angle tolerance of about 4° at -3 dB is measured. The difference between structures with and without top silica cladding is due to the difference of the refractive index contrast which changes the phase matching condition (1). The coupling efficiency as a function of the wavelength, at a fixed incidence angle, was also measured for both fully and partially etched grating couplers, with and without top cladding. The considered fixed angles correspond to the resonance angles measured in Fig. 2 at 1.31 µm wavelength. The wavelength tolerances are about 50 nm at -3 dB for each structure.

To quantify the maximum coupling efficiency as a function of the wavelength, measurements have been performed where the incidence angle was optimized at each probed wavelength. Figure 3 shows the results for the partially etched structure with top cladding. The resonance angle decreases linearly from 17.5° to 4.2° as the wavelength increases from 1.25 µm to 1.45 µm. The coupling efficiency is higher than 40 % in the range from 1.25 µm to 1.4 µm. Itstill exceeds 20 % at 1.45 µm and remains higher than coupling efficiencies obtained with other classical solutions. Measurements can still be performed above 1.45 µm but the resonance angles become too low to be conveniently reached with our set-up. Surface grating couplers possess therefore a large working spectral range, well suited for the study of broadband devices.

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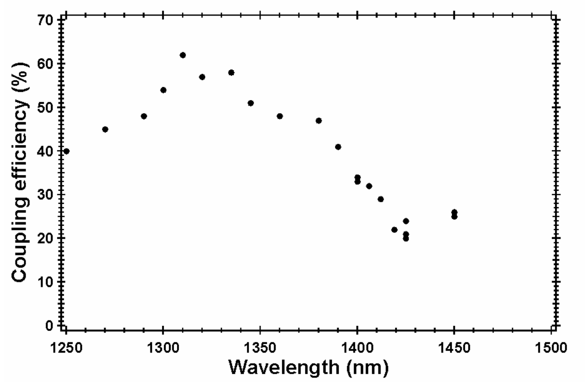

Fig. 3. Optimum coupling efficiency as a function of wavelength in a partially etched grating coupler with top silicon oxide cladding.

The influence of the duty ratio of the grating coupler has also been studied at a wavelength of 1.31 µm for both fully and partially etched structures with top silica cladding. The duty ratio is defined as the width γ of the silicon nitride groove divided by the period Λ of the grating (see Fig. 1(a)). It is varied between 0.2 and 0.8 on a new set of structures with a grating width of 30 µm. The coupling efficiency, coupling length and resonance angle as functions of the duty ratio for the partially etched structures with top cladding are reported in Fig. 4.

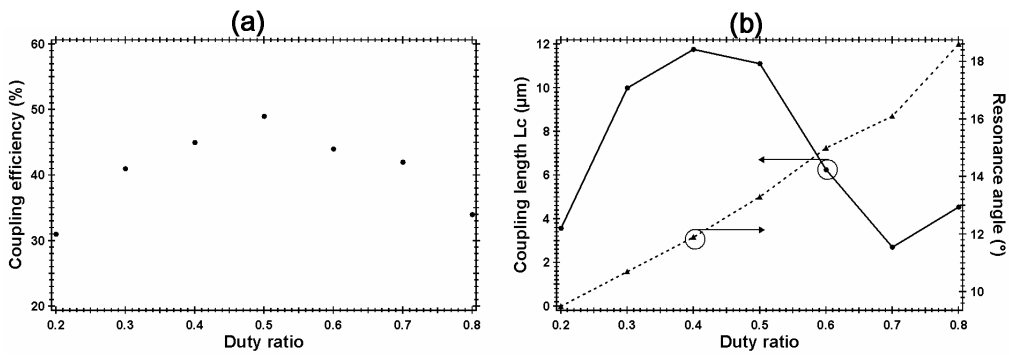

Fig. 4. Coupling efficiency (a) and coupling length (b) as a function of the duty ratio for partially etched grating couplers with top silicon oxide cladding.

The resonance angle is adjusted for each tested duty ratio in order to reach the optimum coupling efficiency. Each grating coupler is in fact associated to a tapered transition to inject the light into a monomode waveguide, and a symmetric structure at the end of the waveguide allows the decoupling of the light. The coupling length L_c is determined using a linear infrared camera, on which the decoupled power is imaged. The decoupled power profile is proportional to $\exp(-z/L_c)$, where z is the coordinate along the grating with its origin at the edge of the grating. The resonance angle was observed to linearly increase with the duty ratio (Fig. 4(b)). This is due to the increase of the effective index which changes the phase matching condition (1). The coupling efficiency reaches a maximum for a duty ratio of 50 % which corresponds to a L_c and a resonance angle of about 11.2 µm and 13.3°, respectively. The maximal coupling efficiency of about 50 % is decreased compared to the results over 60 % reported above for the 40 µm wide gratings. This is due to the fact that here the grating width of 30 µm and the focused beam diameter at $1/e^2$ are equal, and a non negligible amount

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of the focused beam power is therefore not incident on the grating. The maximum coupling efficiency is obtained for an incident laser beam waist w_0 focused on the grating coupler which satisfies the following equation [13]:

$$w_0 = 1.37\, L_c \cos(\theta_{inc}) \tag{4}$$

The measured beam waist of 15 µm corresponds to a coupling length of about 11.25 µm. This value is consistent with the measured coupling length.

7. Conclusion

In conclusion, we have designed, fabricated and characterized high efficiency surface grating couplers for silicon nitride waveguides. The measured coupling efficiencies of these optimized grating couplers are higher than 60 % at a wavelength of 1.31 µm, as was theoretically predicted. Those large values are especially due to the presence of a top silicon oxide cladding layer with optimized thickness. Furthermore, the angular and wavelength tolerances at -3dB are quite large: 4° and 50 nm, respectively. The performance is not significantly altered if the gratings are only partially etched, leaving 50 nm of the silicon nitride layer. Moreover, the coupling efficiency at the resonance angle is still above 20 % at a wavelength of 1450 nm, which is quite interesting for the study of broadband devices. The influence of the duty ratio of the grating has also been investigated. We have shown that the coupling length and the coupling efficiency are maximized for a specific duty ratio, of about 0.4 and 0.5, respectively.

Acknowledgments

This work has been done within the FP6-IST-SABIO project (026554), funded by the European Commission. The authors would like to acknowledge Suzanne Laval from IEF/CNRS for fruitful discussions. K. B. Gylfason acknowledges support of the Steinmaur Foundation, Lichtenstein.

#86018 - $15.00 USD Received 1 Aug 2007; revised 29 Oct 2007; accepted 31 Oct 2007; published 4 Jan 2008