Horizontal slot waveguide-based efficient fiber couplers suitable for silicon photonics

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Abstract. *In this paper, simulation results of high performance grating and inverted taper fiber couplers for horizontal slot waveguides are reported. Maximum 48% and 61% coupling efficiencies are achieved for positive and negative detuned gratings, respectively. Furthermore, 93% coupling efficiency is achieved for the horizontal inverted taper-based coupler.*

Introduction

Silicon-on-Insulator is emerging as a very suitable technology to develop silicon-based photonic integrated circuits. This technology is 100% CMOS compatible, allowing the development of planar optical devices and making possible to achieve very large scale integration (VLSI). However, nonlinear effects in silicon are inefficient. Materials which have superior optical properties, such as alloys of Group III and V elements, are commonly used to make lasers and active devices. These materials are regrettably not CMOS compatible. Slot waveguides have recently been proposed for silicon photonics devices [1]. The main advantages of slot waveguides is the possibility of filling the slot region with an active optical material thus enabling modulation, switching, sensing and many other applications which are not feasible with silicon material. In this paper, we design efficient fiber couplers for horizontal slot waveguides.

Horizontal slot waveguides

The use of silicon nanocrystal (Si-nc) embedded in silica (SiO_2) is one of the most promising approaches to exploit nonlinear effects by means of silicon slot waveguides. In the slot waveguide (see Fig. 1), the light is highly confined in a very small region (slot region) of a low index contrast material (n_s) sandwiched between two high index contrast layers (n_H). Vertical and horizontal slot waveguide configurations, as depicted in Fig. 1, have been recently studied [2]. Optimum parameters of the slot waveguide have been obtained in order to achieve minimum effective area in the slot region thus enhancing the nonlinear effects [2]. However, the horizontal slot waveguide planar geometry offers an easier fabrication compared to the vertical geometry [2]. Regarding the horizontal slot waveguide, light confinement in the slot is achieved for TM polarization, whose main electric field component is in the y-axis direction (see Fig. 1b). Considering that the slot is formed by Si-nc/SiO_2 (n_s=1.6 for λ=1550 nm), it was obtained that the optimum slot waveguide parameters for enhanced nonlinear performance are w=350 nm, h=200 nm and w_s=50 nm λ=1550 nm [3].

Horizontal slot waveguide-based fiber couplers

In Fig. 2 it can be seen both grating coupler and inverted taper slot waveguide-based proposed fiber couplers.

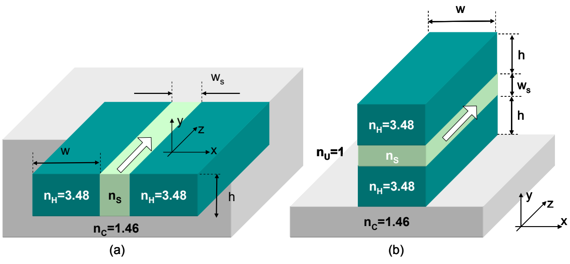

Fig. 1.- (a) Vertical and (b) horizontal silicon based slot waveguide configurations.

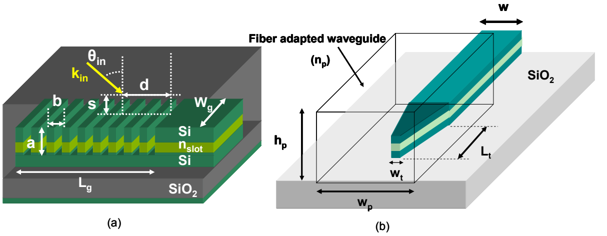

Fig. 2.- (a) Grating coupler and (b) inverted taper horizontal slot waveguide-based fiber couplers.

With respect to the grating coupler in Fig. 2a, the entire grating coupler is surrounded by a silica layer. The slot thickness is 50 nm. The main grating design parameters are the grating period (b), the etching depth (a), the grating width (W_g) and the grating length (L_g). The fiber core is slightly tilted (θ_{in}) to minimize the effect of second order diffraction. The fiber core is also vertically separated from the grating by a distance s, and horizontally by a distance d. The inverted taper-based coupling structure (Fig 2b) is based on a horizontal slot waveguide, on top of a silica cladding layer, which is tapered down by the inverted taper. A fiber-adapted waveguide on top of the inverted taper is used [4] to efficiently guide light from the taper to the fiber (see Fig. 2b). This waveguide can be made by means of a polymer with a refractive index n_p=1.6 equal to the Si-nc/SiO_2 refractive index. The main design parameters are the taper length (L_t), the taper tip width (w_t), and the dimensions of the fiber-adapted waveguide (w_p, h_p).

Grating coupler design

The grating has been designed employing 2D-FDTD simulations. The parameters optimization is based on maximum coupling efficiency for λ=1550 nm and TM polarization. The grating is 20 period long (L_g=20b). The grating width is chosen as W_g=12μm. The fiber is considered vertically separated from the grating by a distance s=1.5μm. A tilt angle of $\theta_{in}=\pm 8^o$ is chosen for negative and positive detuned gratings. As usual in conventional SOI grating coupler designs [5-6], the filling factor is initially ff=50%. Tab. 1 shows the obtained optimum simulation parameters. 48% coupling efficiency can be achieved for the positive detuned grating coupler. On the other hand, it 61% coupling efficiency can be achieved for the negative detuned grating coupler. For these optimum parameters, the spectral response of the grating coupler has also been calculated. Fig. 3 shows the obtained spectral response. A 35 nm 1 dB-bandwidth spectral response is achieved in both cases.

Parameters @ λ=1550 nm and TM polarization			
Positive detuned grating θ_{in}=8º		Negative detuned grating θ_{in}=-8º	
b	807 nm	*b*	670 nm
a	265 nm	*a*	265 nm
d	3.83 μm	*d*	3.83 μm
t_{BOX}	2.2 μm	t_{BOX}	2.3 μm

Table 1.- Optimum design parameters of the grating coupler.

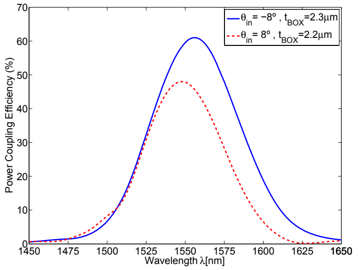

Fig. 3.- Spectral response of the grating couplers with optimum parameters shown in Tab. 1.

Sensitivity to fabrication and alignment tolerances of the structure has also been analyzed. Regarding fabrication tolerances, it is obtained that the coupling efficiency is almost constant for etching depth variations of ±10 nm or filling factor changes of ±5 %. For alignment tolerances, it is obtained that the coupling efficiency is also almost constant for tilt angle variations of ±2º or horizontal fiber position changes of ±3 μm.

Inverted taper design

The inverted taper-based fiber coupler has been analyzed employing 3D BPM simulations. Parameters have been optimized to achieve maximum coupling efficiency for λ=1550 nm and TM polarization. To simplify the design, the dimensions of the fiber-adapted waveguide have been chosen as $w_p=h_p=3$ μm. For these waveguide dimensions, it has been evaluated the mode mismatch between the fundamental mode of the waveguide and the fiber in the fiber-SiO_2 waveguide interface. To do this, overlap integral [5] between the fiber and the waveguide fundamental modes has been analyzed as a function of the fiber mode field diameter (MFD). It was obtained that if a standard single mode fiber with MFD=2.5μm is chosen, 98% coupling efficiency is achieved at the fiber interface. The design can be optimized for coupling to higher MFD optical fibers by changing the dimensions of the SiO_2 waveguide. For this waveguide section, the mode mismatch in the inverted taper tip interface has also been evaluated by using the overlap integral. Fig. 4a shows the simulation results of the power coupling efficiency as a function of the inverted taper tip width. It can be seen that if a taper tip width of w_t=40nm is chosen, the power coupling efficiency at the taper tip interface increases up to 95%.
Using the taper tip width of w_t=40 nm and the SiO_2 dimensions of $w_p=h_p=3$ μm, the taper length has been optimized by employing 3D BPM simulations. In Fig. 4b, it can be seen the simulation results of the coupling efficiency as a function of the taper length for $w_p=h_p=3$ μm and w_t=40 nm. It is obtained that the coupling efficiency remains almost constant for inverted taper lengths longer than 150 μm. For a taper length of

L_t=150 μm a maximum coupling efficiency of 95% is obtained. The final coupling efficiency would then be 93% for TM polarization and λ=1550 nm.

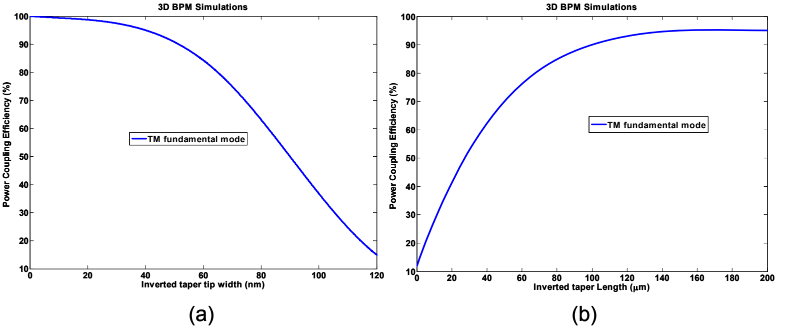

Fig. 4.- (a) Power coupling efficiency as a function of the inverted taper tip width taking into account a SiO_2 waveguide of w_p=h_p=3 μm. (b) Power coupling efficiency as a function of the taper length for a taper tip width of w_t=40 nm.

Conclusion

In conclusion, 48% and 61% coupling efficiencies and a 35 nm-bandwidth spectral response can be obtained for positive and negative detuned slot waveguide-based grating couplers, respectively. On the other hand, coupling efficiency higher than 90% may be achieved with slot waveguide-based inverted taper couplers.

Acknowledgments

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