Fully-etched apodized fiber-to-chip grating coupler on the SOI platform with -0.78 dB coupling efficiency using photonic crystals and bonded Al mirror

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Fully-etched Apodized Fiber-to-chip Grating Coupler on the SOI Platform with -0.78 dB Coupling Efficiency Using Photonic Crystals and Bonded Al Mirror

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Abstract *We design and fabricate an ultra-high coupling efficiency fully-etched apodized grating coupler on the SOI platform using photonic crystals and bonded aluminum mirror. Ultra-high coupling efficiency of -0.78 dB with a 3 dB bandwidth of 74 nm are demonstrated.*

Introduction

Grating couplers are attractive thanks to their ability to directly couple light from nanowire waveguides to standard single mode fibers (SSMFs). The biggest advantage of grating couplers is that neither chip cleaving nor tapered fibers are required, making wafer-scale testing possible. Traditional grating couplers are uniform, and are shallowly etched in order to introduce a proper scattering strength[1-7]. However, extra processing steps are required on top of waveguide fabrication to fabricate the shallowly-etched scattering slots. Moreover, their coupling efficiency is limited not only by power leakage to the substrate, but also by the intrinsic mode mismatch between those uniform gratings and SSMFs. In order to simplify the fabrication process and achieve ultra-high coupling efficiency, fully-etched apodized grating couplers are preferred[3, 4].

Table 1 summarizes the performances of state-of-the-art fully-etched and shallowly-etched grating couplers that have been demonstrated over the past few years. For fully etched grating couplers, the highest coupling efficiency (CE) is about -1.65 dB with 3 dB bandwidth of 69 nm[8]. In terms of shallowly-etched grating couplers, the highest coupling efficiency of -0.64 dB was demonstrated by using an aluminum (Al) mirror, which is realized by etching through the silicon substrate followed by Al deposition[7]. However, the optimum thickness of the lower cladding (i.e. buried oxide (BOX) layer), which is critical for maximizing the coupling efficiency, might not correspond to that of commercial silicon-on-insulator (SOI) wafers.

In this paper, we demonstrate an ultra-high coupling efficiency fully-etched grating coupler on the SOI platform using photonic crystals (PhCs) and a bonded Al mirror. The advantage of the bonding method is that both upper and lower cladding thicknesses can be precisely optimized. With optimum upper and lower SiO_2 cladding thicknesses, -0.78 dB coupling efficiency with a wide 3 dB coupling bandwidth of 74 nm are achieved. Such coupling efficiency is, to the best of our knowledge, the highest coupling efficiency ever reported for fully etched grating couplers.

Tab 1: Summary of published experimental results for grating couplers

Fully-etched			Shallowly-etched		
CE (dB)	3 dB BW (nm)	Ref.	CE (dB)	3 dB BW (nm)	Ref.
-3.76	68	[9]	-1.6	65	[2]
-3.7	60	[10]	-1.9	70	[3]
-4.6	83	[11]	-1.2	48	[4]
-2.3	60	[12]	-1.6	80	[5]
-1.65	60	[8]	-1.5	54	[6]
-0.78	74	This work	-0.62	67	[7]

Principle and design

The proposed grating coupler is based on flip-chip bonding of a silica-clad fully etched silicon PhC grating coupler on a silicon carrier wafer, as schematically depicted in Fig. 1. The thickness of the top silicon device layer is 250 nm. Artificial materials are introduced for the scattering units, with refractive indices n_i and lengths of scattering units l_i changed along the grating[8]. SiO_2 is used as upper and lower cladding material with thicknesses of h_u and h_d, respectively. A 100 nm Al mirror is introduced below the lower cladding. Another layer of SiO_2 is introduced beneath the Al mirror and is

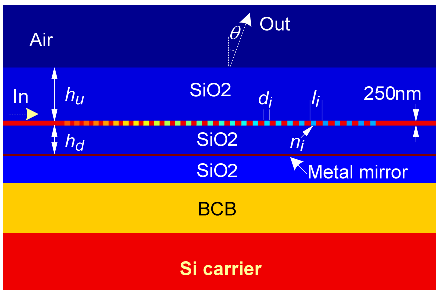

Fig. 1: Schematic structure of the proposed grating coupler.

bonded to the silicon carrier wafer using a BCB layer. The coupling angle θ is designed to be15º. In the design, the width of the artificial material slots is fixed to be 345 nm, and the scattering strength and coupling angle are tuned by optimizing n_i and l_i. The distributions of n_i and l_i of the grating coupler are designed, as shown in Fig. 2(a), so that a Gaussian output field profile is synthesized from the grating with coupling angle of 15º at 1550 nm. PhCs with triangular lattice can then be used for the artificial material slots, and the hole size can be determined by the effective index approximation[8]. The details of the design method can be found in Ref. 8. According to the effective index approximation, the optimized hole size of the designed grating coupler has a feature size of 70 nm. Considering that such a dimension is beyond the capability of some fabrication methods such as conventional deep ultraviolet (DUV) lithography, alternative optimum designs restricting the feature size to 100 nm and150 nm are also shown in Fig. 2(a). The coupling efficiency of the transverse electric (TE) mode is then investigated by a two-dimensional (2D) eigenmode expansion method (EME) as a function of h_d with h_u set to 1000 nm, as shown in Fig. 2(b). The coupling efficiency depends periodically on h_d, and reaches a local maximum at h_d= 1600 nm. With h_d= 1600 nm, the coupling efficiency is further calculated by changing the upper cladding thickness h_u. One can find that the coupling efficiency is moderately influenced by the upper cladding thickness, and could reach its maximum when h_u=1000 nm. With h_d=1600 nm and h_u=1000 nm,

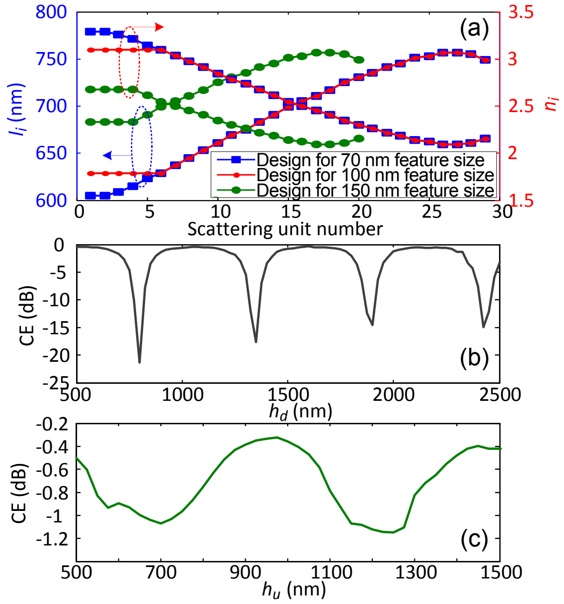

Fig. 2: (a) Designed l_i and n_i distributions of the grating couplers with feature sizes of 70 nm, 100 nm, and 150 nm. Simulated coupling efficiency as a function of (b) lower cladding thickness with h_u=1000 nm, and (c) upper cladding thickness with h_d=1600 nm.

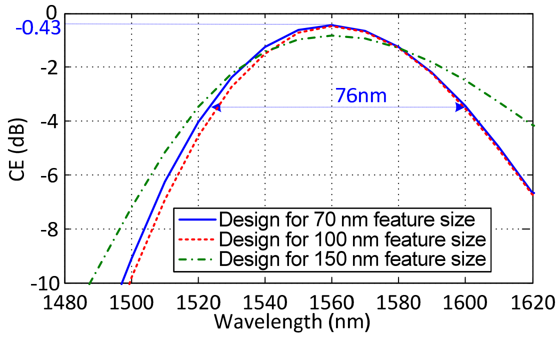

Fig. 3: Simulated coupling efficiency as a function of wavelength for designed grating couplers with different feature sizes.

the coupling efficiency is then calculated as a function of wavelength for the original design with 70 nm feature size, as well as for the designs with restricted feature sizes of 100 nm and 150 nm, as shown in Fig. 3. A highest coupling efficiency of -0.43 dB (corresponding to coupling efficiency of 91%) is predicted for the original design at 1560 nm, with a 3 dB bandwidth of 76 nm. In addition, the 100 nm feature size design shows negligible coupling efficiency degradation and the 150 nm design exhibits only 0.4 dB coupling efficiency degradation, indicating that our design is compatible with most fabrication methods.

Device fabrication and characterization

In order to validate our design, the device was fabricated on a commercial SOI sample with top silicon thickness of 250 nm and BOX of 3 µm. The fabrication process is shown in Fig. 4. A single step of standard SOI processing, including e-beam lithography and inductively coupled plasma (ICP) etching was first used to fabricate the grating coupler and silicon nanowire waveguide simultaneously (see Fig. 4(a)). An 800 nm thick layer of SiO_2 was then deposited on top of the grating coupler (see Fig. 4(b)). Considering the surface is not flat after SiO_2 deposition, another 800 nm borophosphosilicate

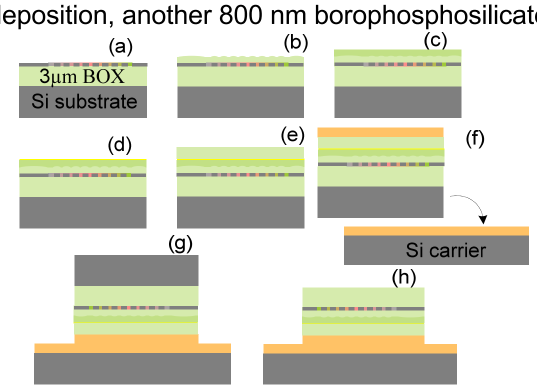

Fig. 4: Fabrication process of the grating coupler with bonded Al mirror. (a) Grating coupler fabrication based on standard e-beam lithography and ICP etching. (b) SiO_2 deposition. (c) BPSG deposition and annealing. (d) Metallic mirror deposition. (e) SiO_2 deposition. (f) BCB spinning for both sample and carrier wafer. (g) Bonding. (h) Si substrate removal.

glass (BPSG) was deposited (see Fig. 4(c)) and annealed at 950ºC for 30 minutes in nitrogen. Afterwards, 100 nm Al was deposited on top of the BPSG (see Fig. 4(d)). Then, about 2 μm benzocyclobutene (BCB) was spun on both the sample and silicon carrier wafer (see Fig. 4(e)). The sample was then flip-bonded on the silicon carrier wafer (see Fig. 4(f)) and thermally cured in an oven (see Fig. 4(g)). Finally the substrate of the chip was removed by ICP fast etching (see Fig. 4(h)) stopping on the BOX layer.

Fig. 5(a) and 5(b) show details of the fabricated device. In order to test the coupling efficiency, two identical grating couplers were fabricated with a 700 μm long single-mode straight waveguide introduced in between. The waveguide width was tapered from 12 μm for the grating couplers to 450 nm for the single mode straight waveguide with 500 μm tapering length. The propagation loss of the single mode silicon waveguide was measured to be 2 dB/cm by the cut-back method. Fig. 5(c) shows the measured coupling efficiency as a function of wavelength for the designed grating coupler with the bonded Al mirror. The coupling efficiency for the same grating coupler fabricated on the same type of SOI wafer but without Al mirror is also shown. A significant improvement provided by the bonded mirror is confirmed. Thanks to the Al mirror and both optimized upper and lower SiO_2 thicknesses, a highest coupling efficiency of only -0.78 dB with 3 dB bandwidth of 74 nm were obtained, which are in very good agreement with the design. In addition, the tolerance to fabrication error was also investigated by changing the size of all the holes. A diameter change of the holes dD_{hole} of 8 nm resulted in

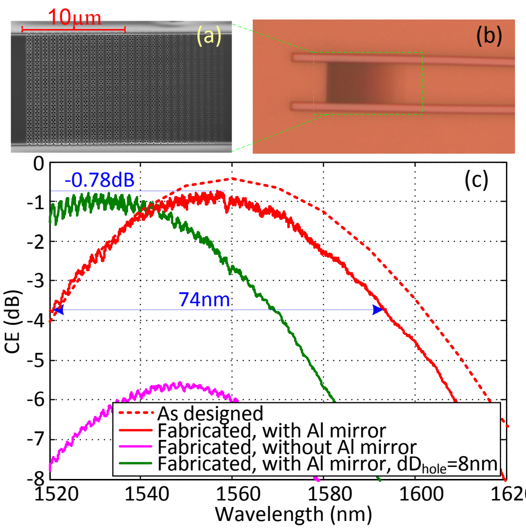

Fig. 5: (a) Scanning electron microscopy (SEM) image and (b) optical microscopy image of the fabricated grating coupler. (c) Measured coupling efficiency for the fabricated coupler with Al mirror with and without 8 nm hole size change, as well as for the same grating coupler fabricated on the same type of SOI wafer without Al mirror.

peak coupling wavelength shift of only 23 nm without peak coupling efficiency degradation. Such coupling wavelength shift could be compensated by adjusting the coupling angle.

Conclusions

We have designed and demonstrated a fully-etched fiber-to-chip grating coupler using PhCs and bonded Al mirror. A record high coupling efficiency of -0.78 dB with 3 dB bandwidth of 74 nm were measured.

Acknowledgement

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