High Efficiency Nonuniform Grating Coupler by Utilizing the Lag Effect in the Dry Etching Process

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Abstract: Utilizing the lag effect in dry etching, a nonuniform silicon-on-insulator grating coupler is designed and fabricated. Over 80% (>-1dB) coupling efficiency is theoretically obtained and experimental coupling efficiency of 55% is achieved for TE polarization.

OCIS codes: (130.3120) Integrated optics devices; (050.2770) Gratings

1. Introduction

Great efforts have been devoted to silicon photonics, driven by both academia and industry. The compatibility with the standard microelectronics COMS technology and the large refractive-index contrast between silicon core and underlying oxide, make the silicon-on-insulator (SOI) system promising for mass production of large scale and dense integration of photonic circuits. However, together with the great benefits, there are still some issues to be solved. One of them is the coupling problem due to the huge mode mismatch between an on-chip silicon nanowire waveguide and an external single-mode fiber.

Grating coupler has been widely demonstrated to solve the coupling problem by several groups [1-4]. Although grating coupler has many advantages, such as relaxed alignment tolerance, multi-functionality and capability of on-wafer testing, it has not been competitive for the coupling efficiency, typically, with a maximum of 35% (-4.5dB) for a standard SOI grating coupler [1]. In order to improve the coupling efficiency, advanced structures like bottom reflector [2] and silicon overlay [3] were proposed to reduce the downward leakage of light through the substrate at the expense of increased fabrication complexity. Another way is to improve the mode match between the upward light and the Gaussian-profile fiber mode by carefully designing the nonuniform gratings to fit specific leakage parameter distribution [1]. A theoretical study showed that maximum coupling efficiency of 61% is possible for a nonuniform SOI grating coupler with equal etch depth, however no experimental results have been reported yet.

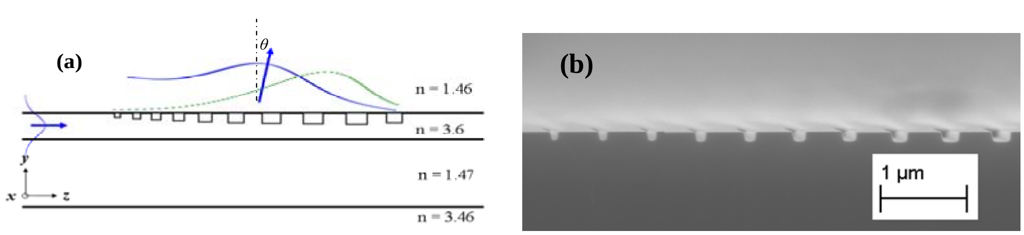

Fig. 1. (a) Schematic structure of a nonuniform SOI grating coupler. Blue lines (solid) represent the input and the output power distributions when light is propagating from waveguide to fiber. Green line (dashed) represents the leakage parameter distribution along the waveguide in order to achieve a Gaussian profile output. (b) Scanning electron micrograph of a part of the nonuniform grating coupler cross section.

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In this work, we theoretically and experimentally demonstrate a nonuniform grating coupler by utilizing the lag effect [5] in the inductively coupled plasma reactive ion etching (ICP-RIE) process. Fig. 1 shows the schematic structure of the presented nonuniform grating coupler, as well as a scanning electron microscope (SEM) image of a part of a sample's cross section. The tilt angle θ of the output light is set to be 15°, due to the limitation of our characterization platform. Lag effect describes the dependence of etch rate on feature size in dry etching process. In result, the wider the etch width is, the deeper the etch depth is obtained. Although the etching nonuniformity caused by lag effect is usually detrimental for most applications, it can offer benefits in nonuniform grating coupler design as it extends the variation range of the leakage parameter. Hence, it is possible to fit the leakage parameter distribution better by using reasonable etching grooves. Furthermore, lag effect will help to achieve more smooth transition from blank waveguide to the grating zone, leading to less reflection.

2. Design and experimental results

The SOI structure was fabricated by using plasma enhanced chemical vapor deposition (PECVD) technique developed at the Royal Institute of Technology, Sweden [6]. A 297 nm thick amorphous silicon (n=3.6) layer was deposited on a buried oxide (n=1.47) layer, whose thickness was optimized to be 2.97 µm (measured thickness is 2.995 µm). Material loss of amorphous silicon is usually larger than that of crystalline silicon, but the fact that it can be deposited with accurate thickness control offers flexibility for device design, especially during the prototype validation period.

In order to investigate the lag effect, we use Raith 150 electron beam lithography (EBL) system to define a series of line patterns with different widths ranging from 60 nm to 450 nm. The dose for each line was carefully tuned to get best performance. The patterns on ZEP520 resist were then transferred into the SOI structure by ICP-RIE etching. Using SEM, the etch width and etch depth for each groove can be measured from the cross section of a test sample. As shown in Fig. 2, the lag effect is obvious especially when the etch width is smaller than 300 nm. We also show the fitted expression, which is used in the following design and simulation.

As a first step of the design, the leakage parameter and the effective refractive index of an infinite uniform grating are extracted from the Bloch mode's complex propagation constants. For certain groove width, grating period is searched by bisection method so that the output light will have an expected tilt angle according to the well-known Bragg equation. Fig. 2(b) shows the mapping from the etch width to the grating period and the leakage parameter when the groove width changes from 60 nm to 490 nm. According to the mapping, we can assemble a nonuniform grating coupler with a distribution of leakage parameter as shown in Fig. 1(a). Then, the obtained initial structure is optimized by a genetic algorithm to achieve a maximum coupling efficiency. The final design is

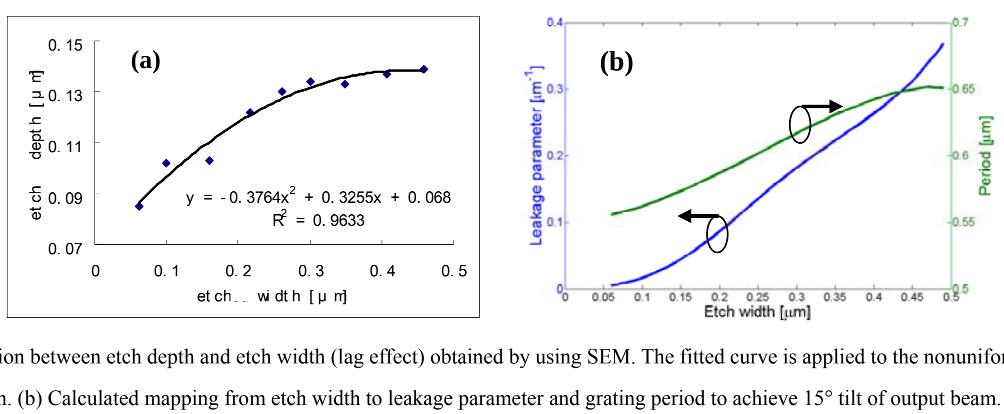

Fig. 2. (a) Relation between etch depth and etch width (lag effect) obtained by using SEM. The fitted curve is applied to the nonuniform grating design. (b) Calculated mapping from etch width to leakage parameter and grating period to achieve 15° tilt of output beam.

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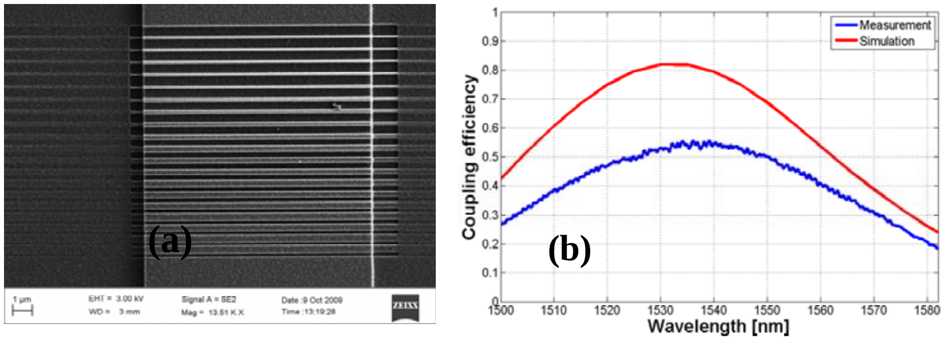

Fig. 3. (a) SEM top view of a nonuniform SOI grating coupler. (b) Theoretically and experimentally obtained waveguide-to-fiber coupling spectrum for TE polarization. Maximum coupling efficiency of 82% and 55% are obtained by simulation and experiment, respectively.

validated by using COMSOL. The simulated coupling spectrum is shown in Fig. 3(b). We can see that as high as 82% coupling efficiency is possible.

Fig. 3(a) shows the SEM top view of a fabricated nonuniform grating coupler. The grating on this device was etched under the same condition as for the sample to get the etch data in Fig. 2(a). Agilent 86082A wavelength domain component analyzer was used to characterize the grating coupler. Fig. 3(b) also shows the measured coupling spectrum for the fabricated nonuniform grating coupler. The coupling efficiency for TE polarization (electrical vector parallel to the grating lines) is obtained via fiber-to-fiber transmission measurement, providing that the propagation loss due to the bridge waveguide between two gratings is small enough to be ignored. In Fig. 3(b), one can find that a maximum coupling efficiency of 55% (about -2.6 dB) is achieved at 1538 nm and the 3dB bandwidth is beyond 70 nm. The shifted peak implies that the etch depth is a bit shallower than expected. The deviation between the simulation and the experiment is mainly due to the accumulated fabrication errors. New data for lag effect will be collected from the present grating coupler. It will help to improve new device's performance.

3. Conclusion

Taking the lag effect into consideration, we have fabricated a nonuniform SOI grating coupler with maximum coupling efficiency of 55%. From our simulation, a nonuniform grating coupler is able to achieve a practical coupling efficiency of more than 80% (> -1dB).

4. References

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