Highly efficient circular holes added a-Si:H grating coupler with metal mirror for 3D optical interconnects

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Abstract: *A monolithically fabricated apodized a-Si:H grating coupler with metal mirror was demonstrated. The minimum groove length for the apodized grating was more than 100 nm and measured coupling efficiency was 70%.*

Keywords: *grating coupler, amorphous silicon waveguide, metal mirror*

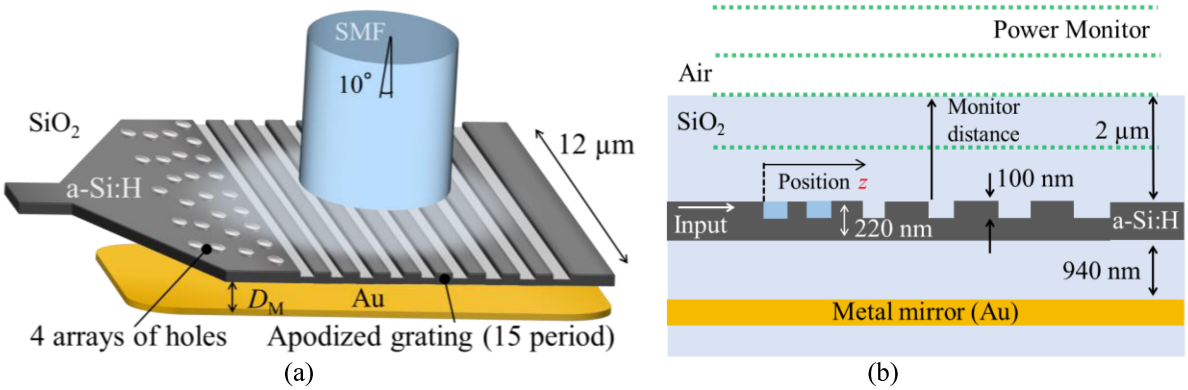
I. Introduction

Grating couplers have been studied for the coupling between Si photonic waveguides and vertical single-mode fibers (SMFs) [1]. Through the grating coupler, spot size of the sub-μm waveguide can be converted to that of um-order fibers. Further, the grating coupler can be located anywhere on the surface of the chip since it can achieved vertical off-chip coupling without cleaving the chip. The coupling efficiency of the grating coupler is determined by following key factors; first, the beam profile of the radiated light should match with that of the SMFs. Second, the portion of the radiated light facing upward is needed to be maximized instead of downward radiation. There have been many novel structures for the efficient coupling including apodization of gratings [2,3], and DBR or metal mirrors under the grating coupler in order to maximize the upward radiated light [4,5]. Recently, Y. Ding et al. reported a grating coupler which introduced both the apodization of grating and the metal mirror but the peak coupling efficiency was limited by 81% and needed an additional wafer for flip chip bonding in order to introduce a metal mirror under the grating coupler [6].

We have proposed to use deposited a-Si:H multi-layered waveguides for optical interconnects and demonstrated highly efficient inter-layer grating couplers with metal mirrors [7, 8]. By applying the fabrication process used in Ref [7], monolithic integration of Si waveguides above the metal mirrors can be realized. In this paper, design procedures and experimental results of a-Si:H apodized grating coupler with a metal mirror will be presented.

II. Technical Work Preparation

The grating coupler was designed for the coupling between SMFs (SMF-28, Corning Inc.) and a-Si:H waveguides. The width of the grating region was set to be 12 μm and then it was connected to 500-nm a-Si:H wire waveguide through 1-mm-long linearly tapered mode-converter. As mentioned earlier, the grating was apodized in order to shape the radiated beam profile by tuning the duty ratio and grating periods. Typically, the groove lengths of the first few grating periods are needed to be rather short which are tens of nm for the gradual increase in beam profile. However, those groove lengths are not preferable if we consider the fabrication tolerance or RIE lag effects. Figure 1(a) illustrates



(a) (b)

Fig. 1 (a) Schematics of grating coupler with holes. (b) Simulation model for grating design.

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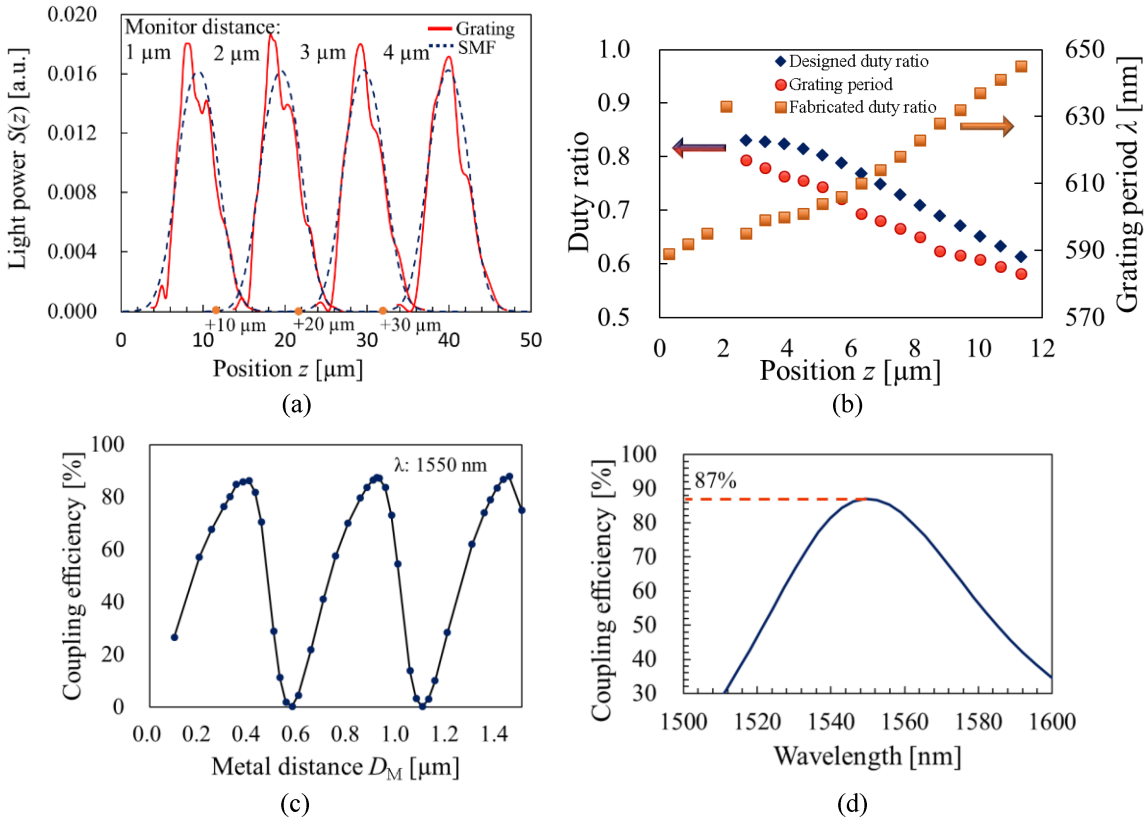

Fig. 2 (a) Radiated beam profile from the apodized grating and SMF. (b) Duty ratio and grating period of apodized grating coupler, blue diamonds: designed duty ratio, red circles: fabricated duty ratio, orange rectangles: grating period. (c) D_M and (d) wavelength dependence of the coupling efficiency.

the apodized grating coupler with the metal mirror. The grating consisted of 4 arrays of holes instead of the short grooves followed by 15 line-space gratings. By introducing 150 nm (diameter) holes, the minimum groove length of more than 100 nm was available. The grating depth of 100 nm was used in this work.

In order to design the apodized grating, we monitored the radiated beam profile while adjusting the duty ratio and period of the grating so it could match with mode profile of SMF. The simulation model used here is shown in Fig. 1(b). The monitors were located at every 1-μm distance in order to determine whether the radiation angle was constant in each position. Figure 2.(a) shows the radiated beam profile of the designed apodized grating coupler with metal mirror and mode profile of SMF with an angle of 10 degree. The both profiles were roughly correspond to each other at the monitor distance within 1~4 μm

The designed duty ratio and the grating period of apodized grating are shown in Fig. 2(b). For the holes, the apodization was applied by controlling the distance of neighboring holes in the same array which was ranged from 400 nm to 460 nm. Also, the grating periods were gradually increased according to the propagation direction to maintain the constant radiation angle. The grating period at the last hole-array was exceptionally long for the smooth connection between holes and line-space grating.

In addition to the apodization, the distance from the metal mirror to the grating (metal distance, DM) was also critical to the performance of the grating coupler. Therefore, we examined the effect of DM on the coupling efficiency, and the coupling efficiency was varied periodically as shown in Fig. 2(c). The periodic change was resulted from the phase matching condition between the reflected light by the metal mirror and the light passed through the grating [8]. Figure 2(d) shows the wavelength dependence of the coupling efficiency when the DM is 940 nm. The peak coupling efficiency was 87% at 1550 nm. The 1dB bandwidth was 37nm which can cover the C-band and 3dB bandwidth was 71 nm.

III. Fabrication Process and Coupling Efficiency Measurement

The apodized grating coupler with the metal mirror was fabricated based on the design as described in section 2. The initial wafer was 2-inch Si wafer with 3-μm-thick layer of thermal SiO_2. The first step was evaporation of a 100-nm-thick Au film on the SiO_2 and the metal mirror and alignment mark for EB-lithography was formed by lift-off. The Au

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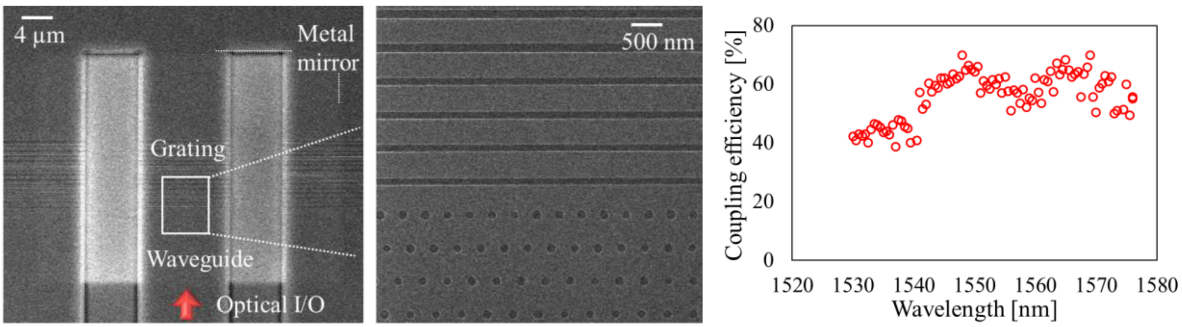

(a) (b)

Fig. 3 (a) Top SEM image of apodized grating and its enlarged image. (b) Measured coupling efficiency of apodized grating coupler with metal mirror

patterns were buried by SiO_2 and then flattened by CMP process. The thickness of SiO_2 was controlled targeting 940 nm and then, 220-nm-thick a-Si:H layer was deposited on the SiO_2 at 300°C. The apodized grating with holes and waveguide patterns were formed by EB lithography and ICP-RIE system. Finally, 2 μm of SiO_2 overcladding layer was deposited and flattened again by CMP process. After the fabrication process, the thickness of DM was confirmed to be 915 nm. Figure 3 shows the top SEM image of the apodized grating. The apodized grating was placed above the metal mirror which can be seen through the waveguide patterns and the grating was located at the center of the metal mirror. The duty ratio of the fabricated apodized grating is plotted in Fig. 2.(b). There was 2~8% difference in the designed and fabricated values of duty ratio.

The measured coupling efficiency of the apodized grating coupler with the metal mirror is shown in Fig. 3(b). The coupling efficiency of the fabricated apodized grating coupler with the metal mirror was calculated by fiber to fiber transmission through a pair of grating couplers. The peak coupling efficiency was 70%, which was smaller than the designed coupling efficiency since the duty ratio of the fabricated grating was slightly different from the target value. Higher coupling efficiency is expected with correct groove-lengths control of apodized grating by adjusting the exposure amount in the EB lithography. Even though, we successfully demonstrated the monolithically integrated a-Si:H grating coupler with the metal mirror which is promising for the realization of 3D optical interconnect.

IV. Conclusions

In this work, a fiber-to-chip a-Si:H grating coupler was monolithically fabricated with a-Si:H multi-stacking method. Metal mirror was added under the a-Si:H grating coupler to improve the coupling efficiency. In order to optimize the mode profile of the radiated light from the grating to the SMF, apodization of grating was demonstrated by shallow etched grooves. 4 arrays of holes were introduced to the grating instead of any grooves shorter than 100 nm were needed. The peak coupling efficiency of 87% was calculated in a simulation and 70% was measured with fabricated grating coupler.

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