

Subwavelength grating couplers for efficient light coupling into silicon nanomembrane based photonic devices

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ABSTRACT

We demonstrate efficient coupling of light into silicon nanomembrane (SiNM) based photonic devices using a subwavelength grating (SWG) coupler. Our designed $17.1 \mu\text{m} \times 10 \mu\text{m}$ grating couplers are fabricated at the input and the output of $8 \text{ mm} \times 2.5 \mu\text{m}$ SiNM waveguides on a glass substrate. A high coupling efficiency of 39.2% is achieved at a wavelength of 1555.56 nm. The 1-dB and 3-dB bandwidths are measured to be 29 nm and 57 nm, respectively. Peak efficiency variation of 0.26 dB is observed from a measurement of 5 grating pairs. Such grating couplers open limitless possibilities for the development of high performance nanomembrane based photonic devices.

Keywords: Silicon nanomembranes, silicon-on-insulator, flexible photonics, subwavelength grating couplers.

1. INTRODUCTION

Over the last decade, thin single crystal nanomembranes have found growing attention, owing to certain unique characteristics [1 - 12]. Among all transferrable single crystal semiconductors, silicon nanomembrane (SiNM) is one of the most promising materials because it possesses not only high carrier mobility and mechanical durability, but also optical transparency in the near infrared region, thus making it suitable for developing high performance flexible optoelectronic devices. Suitable nanomembrane transfer schemes have been developed, and good progress in terms of developing electronic devices has been demonstrated [4, 5, 13, 14, 15]. In contrast to the rapid progress in SiNM based electronics, very little progress has been made on in-plane flexible photonics. Light coupling into these devices was based on butt coupling, which is very difficult to realize on different substrates. A universal light coupling scheme is needed that can efficiently package nanomembrane based devices on any substrate.

In this work, we report the utilization of subwavelength grating couplers (SWGs) for coupling light efficiently into transferred SiNM based photonic devices. Compared to conventional grating couplers, SWG couplers can be fabricated along with photonic circuits and do not require any additional photolithography steps [16-19]. We demonstrate a coupling efficiency of 39.2 % at a peak wavelength of 1555.56 nm, with 1dB and 3dB bandwidths of 29 nm and 57 nm,

respectively. Utilization of such a coupler can rapidly push flexible photonics technology forward, thus opening avenues for a wide range of useful devices.

2. DESIGN AND FABRICATION

A schematic of an SWG coupler is shown in Fig. 1. It consists of an array of periodic rectangular air trenches in a 250 nm thick SiNM which is transferred onto a glass substrate with a SU-8 bottom cladding layer. An Effective Material Theory (EMT) [17, 20], is utilized to approximate the subwavelength section as a uniform material with refractive index n_{sub} . Using an open source simulation package CAMFR, which is based on eigenmode expansion, a best combination of grating period Λ_G and n_{sub} are searched in order to obtain the highest power efficiency around 1550 nm. In our design, the filling factor of the grating is fixed at 50%. The calculated optimum Λ_G and n_{sub} are $\Lambda_G=0.690 \mu\text{m}$ and $n_{sub}=2.45$, respectively, corresponding to $L_{sub}=0.345 \mu\text{m}$, $W_{sub}=0.090 \mu\text{m}$, and $\Lambda_{sub}=0.390 \mu\text{m}$.

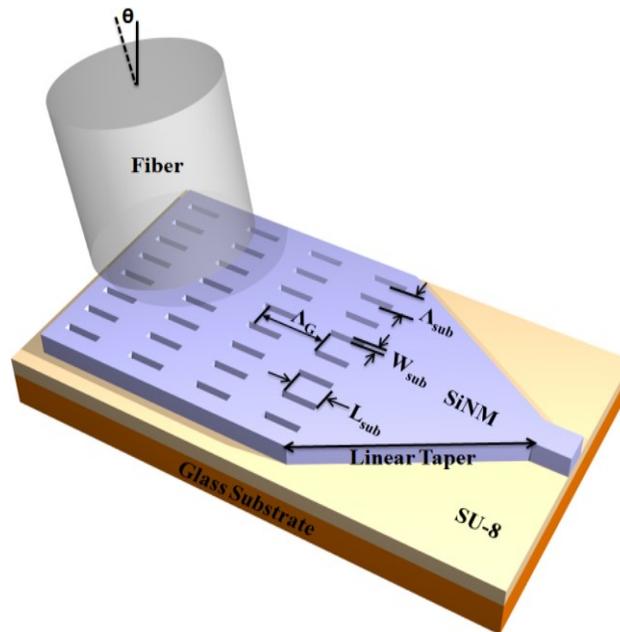


Fig. 1. Schematic of the subwavelength grating (SWG) coupler on a transferred SiNM.

A home-made bonding tool is utilized to first bond a 2cm x 2cm SOI (silicon-on-insulator, 675 μm handle, 3 μm BOX, 250 nm device layer) onto a 1mm thick glass slide. Before bonding, the SOI and glass slide are spin coated with 5 μm thick SU-8 layer. After pre-baking, the SOI chip is brought into contact with the glass slide and pressure is applied. Next, the sample is heated to the glass transition temperature of SU-8 to enable reflow. Next, SU-8 is fully cured by exposing it to UV radiation. After bonding, the silicon handle is removed by deep reactive ion etching (DRIE). To control the thermal budget, the silicon handle is mechanically polished down to $\sim 100 \mu\text{m}$ prior to DRIE, to shorten the etching time. The inductively coupled plasma (ICP) power and the etching time are carefully tuned to achieve an optimized heat dissipation:etch rate trade-off condition. The silicon etch rate of this recipe is around 2.7 $\mu\text{m}/\text{cycle}$. The 3 μm BOX acts as an etch stop layer, which is later removed by hydrofluoric (HF) acid etching. A picture of the

transferred SiNM on glass is shown in Fig. 1. The designed SWG coupler is fabricated at the input and the output of an 8 mm long, 2.5 μm wide SiNM waveguide using electron beam lithography (JEOL JBX-6000). A pair of linear waveguide tapers, each with a length of 500 μm , is incorporated to bridge the 10 μm wide grating region to the waveguide. An SEM of the fabricated SiNM SWG coupler is shown in Fig. 2(b). A schematic of the fabricated structure is shown in the inset. The final SU-8 layer thickness is measured to be 8.22 μm . Our design enables fabrication of the coupler and the photonic device in a single step.

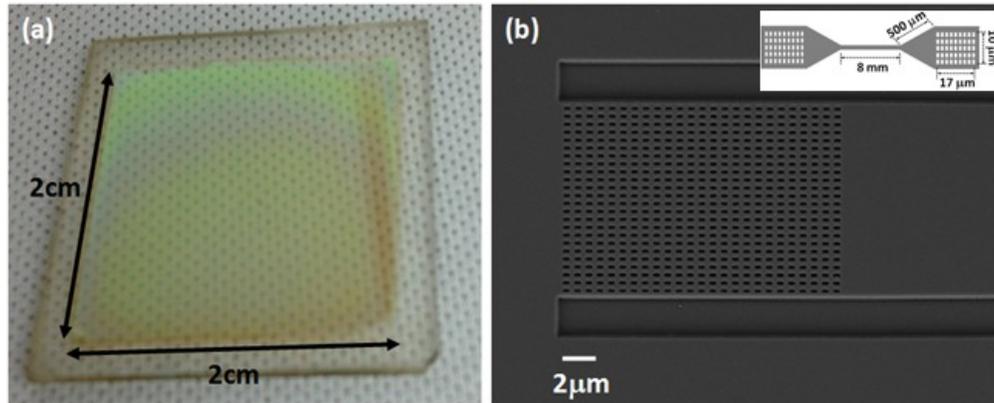


Fig. 2. (a) Optical microscope image of a 2cm x 2cm 250nm thick SiNM transferred onto a 1mm thick glass substrate. (b) Scanning electron microscope (SEM) image of the fabricated subwavelength grating coupler (SWG) on the transferred SiNM. A schematic of the fabricated structure is shown in the inset.

Using the measured SU-8 layer thickness, calculations are performed for TE polarization since that is the polarization of interest for several interesting photonic crystal waveguide and other active devices we are working on. The calculated back reflection (black curve), coupling efficiency to air (red curve), and coupling efficiency into a single mode fiber tilted at a 10° angle with respect to the normal (blue curve) is shown as a function of wavelength in Fig. 3. At a

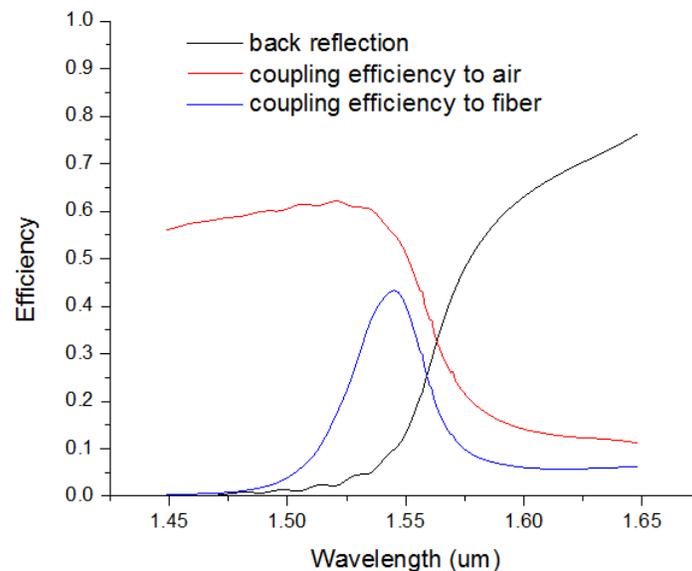


Fig. 3. Simulated back reflection (black), coupling efficiency to air (red) and coupling efficiency to a fiber positioned at 10° with respect to surface normal of the designed SWG coupler (blue) as a function of wavelength of operation. A peak fiber coupling efficiency of 42 % is achieved at a wavelength of 1549nm.

wavelength of 1550nm, a peak upward power efficiency of 54%, corresponding to a 42% coupling efficiency into a single mode fiber, is achieved.

3. DEVICE CHARACTERIZATION

TE polarized light from a broadband amplified spontaneous emission (ASE) source is coupled into the 8 mm long, 2.5 μm wide SiNM waveguide via the grating couplers. The input and output fibers are mounted on two 10° wedges, which are mounted on two xyz stages. The input fiber is a polarization maintaining (PM) fiber whose polarization is controlled via a waveplate-based polarization controller (PC). The output fiber is a conventional single mode fiber with a core diameter of 9 μm . The tilt angle can be adjusted from 0° ~ 20°. For this design, both the input and output fibers are tilted $\sim 9.4^\circ$ from normal incidence. For this structure, the transmission spectrum is first measured on an optical spectrum analyzer (OSA), and then the coupling efficiency is extracted from the loss data by assuming equal coupling efficiencies for both gratings. It can be seen from Fig. 4 that the peak efficiency measured for a single grating coupler is 39.2 % (-4.07 dB) at 1555.56 nm, and the 1 dB and 3dB bandwidths are 29nm and 57nm, respectively. In order to show repeatability, measurements are also performed on a set of 5 pairs of grating couplers, and a maximum deviation in peak efficiency of -0.26dB is obtained.

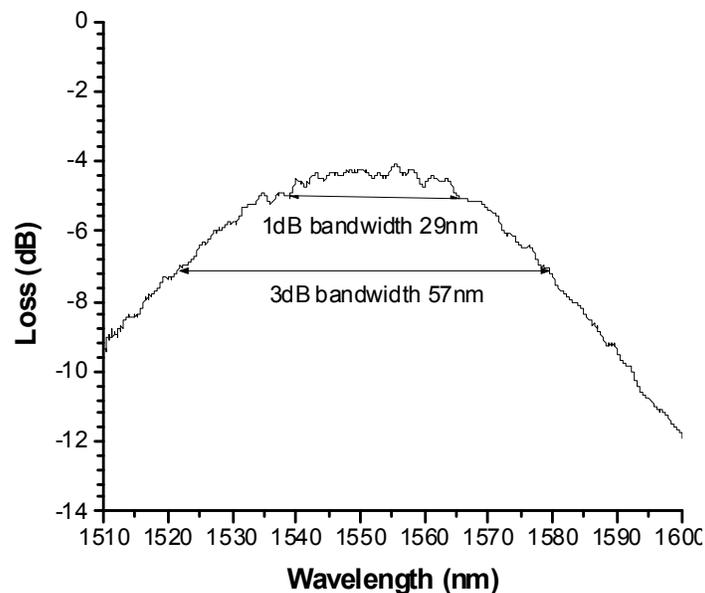


Fig. 4. Measured transmission spectrum of the grating coupler fabricated on SiNM on glass substrate. Peak efficiency of 39.17% (-4.07dB) is obtained at a wavelength of 1555.56nm. The 1 dB and 3 dB bandwidths are 29 nm and 57 nm, respectively.

We also evaluated the effect of bottom cladding thickness on the efficiency, as shown in Fig. 5. The SU-8 layer thickness is varied from 7 μm to 9 μm in the simulations. Due to the fact that the constructive and destructive interference between the upward diffracted beam and the downward diffracted beam reflected upwards at the SU-8/glass interface is a periodic function of the

cladding layer thickness, it is essential to have an optical bottom layer thickness. Our measurement point is indicated as a red dot in the figure. Better control of the SU-8 layer thickness will further increase the efficiency. Nevertheless, the 'worst-case' scenario of 53% coupling efficiency to air is still better than other demonstrated coupling methods [13, 21]. Due to the absence of a precise SiNM bonding tool, the SU-8 layer thickness cannot be controlled precisely. However, by utilizing a specialized bonding tool with a pressure monitoring system for the SiNM transfer process, the SU-8 layer thickness can be controlled accurately.

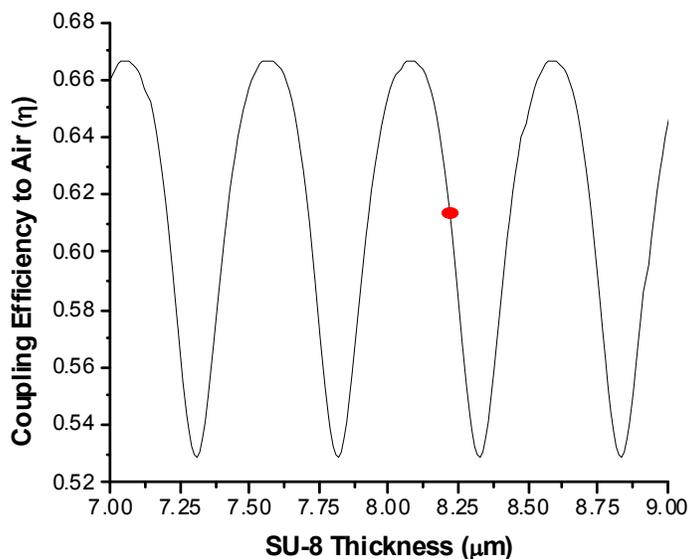


Fig. 5. Simulation showing the effect of SU-8 layer thickness variation from 7 μ m to 9 μ m on the coupling efficiency to air. A periodic efficiency fluctuation between 53% to 67% is produced. The red dot indicates our fabricated result.

4. CONCLUSIONS

In conclusion, we have developed a subwavelength grating (SWG) coupler consisting of an array of periodic trenches in SiNM transferred on glass substrate and demonstrated 39.17 % (-4.07 dB) coupling efficiency into an 8 mm long, 2.5 μ m long silicon waveguide. A coupling efficiency deviation of -0.26 dB is observed from a measurement of 5 grating pairs, indicating acceptable uniformity. The 1 dB and 3 dB bandwidths are measured to be 29 nm and 57 nm, respectively. Better coupling efficiency can be obtained by further improving the SiNM transfer process. This demonstration opens vast possibilities for the development of high performance hybrid photonic components using nanomembrane technology.

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