Uniform emission, constant wavevector silicon grating surface emitter for beam steering with ultra-sharp instantaneous field-of-view

KUANPING SHANG,1,2,3 CHUAN QIN,1,2 YU ZHANG,1 GUANGYAO LIU,1 XIAN XIAO,1 SHAOQI FENG,1 AND S.J. B. YOO1,4

1Department of Electrical and Computer Engineering, University of California, Davis, 95616, USA
2These authors contributed equally to this work
3kshang@ucdavis.edu
4sbyoo@ucdavis.edu

Abstract: We report on uniform emission intensity profile, uniform propagation constant silicon gratings for beam steering application with ultra-sharp instantaneous field-of-view (IFOV). To achieve uniform emission intensity across relatively long emission length, we designed a custom grating with varying Si₃N₄ width and duty cycle while maintaining a uniform propagation constant for relatively narrow divergence emission pattern. We designed and fabricated the custom Si₃N₄/Si grating with the varying Si₃N₄ width/duty cycle together with the reference Si₃N₄/Si grating with a constant 50:50 duty cycle. The custom grating demonstrated the beam steering angle value of 6.6° by sweeping wavelength between 1530 nm and 1575 nm with the emission length over 1 mm. The measured IFOV based on the 3-dB beamwidth values of the far field patterns for the TE polarization are 0.10° and 0.75° for the custom grating and for the reference grating, respectively. The custom grating also indicates mode-selective behavior due to the perturbation of propagation constant for input modes other than TE polarization. The measured TE-mode to TM-mode suppression ratio for the custom grating is approximately 8.2 dB peak-to-peak measured at far field.

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1. Introduction

Optical phased arrays (OPAs) are attracting strong interest in numerous optical beam-steering applications [1–4], such as free-space optical interconnect, sensing, data communication [5], and light detection and ranging (LIDAR) [6]. For beam-steering OPAs displaying far-field patterns with sharp IFOV, the surface emission grating with long effective coupling length and uniform emission angle becomes necessary [7]. In addition, uniform emission intensity is also important for multi-tiling of such OPAs. Typical silicon-photonic gratings exhibit emission lengths shorter than a few hundred micrometers due to the relatively high refractive index contrast between the silicon core and the SiO₂ cladding [8, 9]. We use the emission rate to describe the emission intensity strength per unit length of the grating. One way to reduce the surface emission rate is to employ shallow etch depths on silicon [10]. However, the fabrication of gratings with ultra-shallow etching process becomes very difficult. To further reduce the emission rate and increase the effective coupling length of the gratings, another approach is to integrate other materials with lower refractive index compared to silicon.

In this work, we propose the uniform emission intensity profile and constant wavevector silicon gratings with integration of silicon nitride (Si₃N₄) as the low index material overlay for ultra-sharp IFOV surface emission grating application. Si₃N₄ based optical devices are also attractive because of its relatively low propagation loss [11] and fabrication compatibility to silicon [12]. Pure silicon nitride-based gratings [13, 14] can also achieve low emission rate with small IFOV. However, they require additional low-loss coupling solutions to integrate with silicon photonics. Therefore, we engineer the emission rate for a longer effective coupling length, while maintaining the uniform propagation constant throughout the grating by varying both the width and the duty cycle of the Si₃N₄ overlay layer. As a result, the mode with uniform propagation constant forms a clear far field pattern with narrow beamwidth, while the other modes scatter as background without introducing additional side lobes. This property of the custom grating also serves as a mode selection mechanism, which is useful to filter emissions from undesired polarization rotations due to perturbations in the waveguide.

2. Design

The proposed custom grating comprises a 60-nm thick Si₃N₄ layer as the overlay material on the 500-nm thick silicon layer as the waveguide with SiO₂ cladding. Figure 1 shows the schematic of the custom grating structure. The width of the silicon waveguide is 500 nm throughout the grating to maintain weak emission. On top of the silicon layer, the Si₃N₄ overlay layer employs various widths and duty cycles, to balance the power emission rate and to increase the effective coupling length. The design of silicon guiding core is compatible with future integration with a hybrid InP/Si phase tuner [10], provides sufficient room for
index-variations by Si$_3$N$_4$ overlays, and prevents the potential cross-coupling between the adjacent grating-waveguides for future grating-waveguide-array LIDAR applications involving ultra-long (> 2 mm) and ultra-dense (2 µm spacing) grating array waveguides. The period $\Lambda$ of the grating is 574 nm. The incident angle $\theta_i$ is 90°. The output medium is air whose refractive index value $n_0$ equals 1.0. According to Eq. (1) of Ref [15], the corresponding center output angle is 13° at 1550 nm wavelength ($\lambda$) when $m = 1$, where $n_i$ is the effective refractive index of the grating.

$$n_i \sin \theta_o = n_i \sin \theta_i - m \frac{\lambda}{\Lambda} \quad (1)$$

Fig. 1. (a) The cross section and (b) the schematic of the proposed Si$_3$N$_4$/Si grating with custom duty cycle and Si$_3$N$_4$ width.

The propagation constant of the grating structure depends on the width of the Si$_3$N$_4$ overlay and the duty cycle. To maintain the uniform propagation constant, the Si$_3$N$_4$ layer employs larger duty cycle with narrower Si$_3$N$_4$ at the input end, 0.5 duty cycle with 500 nm width at the output end, and continuous transition in between the two ends. Figure 2(a) illustrates the simulated contour map of the $\delta$ values, where $\delta = \beta - \beta_0$, $\beta_0 = 1.185 \times 10^7$/m, and $\beta$ is the propagation constant for the Si$_3$N$_4$/Si grating with varying duty cycle and Si$_3$N$_4$ width. When the duty cycle or $\delta$ value equals to 0, the propagation constant in the grating equals to that in the silicon waveguide. Figure 2(b) shows the designed duty cycles and width values for the custom grating with maintaining uniform propagation constant. The simulation tool is Lumerical MODE solutionTM.

![Fig. 2(a)](image)

We introduce the coupling constant, $\kappa$ in Eq. (2) [16], to discuss the effective refractive index contrast of the grating, where $n_{\text{eff}1}$, $n_{\text{eff}2}$, and $n_{\text{eff}}$ are the effective refractive index of the
high index sections, the low index sections, and their weighted average values of the grating, respectively.

$$\kappa = \frac{n_{eff2} - n_{eff1}}{n_{eff} \Lambda}$$  \hspace{1cm} (2)

Typically, a wider Si$_3$N$_4$ overlay layer achieves a greater $\kappa$ value as well as a higher emission rate. In addition, Si$_3$N$_4$ overlay duty cycles closer to 0.5 result in stronger emissions. As a result, the proposed custom grating illustrated in Fig. 1 demonstrates its emission rate increasing with the duty cycle approaching 0.5 and the Si$_3$N$_4$ width gradually increasing. The corresponding $\kappa$ values vary from 17.0 cm$^{-1}$ to 28.9 cm$^{-1}$. Figure 3(a) illustrates the simulated emission rate of the custom grating with varying duty cycles (or Si$_3$N$_4$ width values), where the red triangles, blue circles, and black boxes indicate top, bottom, and total emission, respectively. The emission to the top is slightly smaller than that to the bottom, which limits the emission efficiency to be less than 0.5. One way to collect the bottom emission light is to integrate a reflective mirror underneath the grating, such as metal layers or distributed Bragg reflectors [17]. Figure 3(b) shows the simulation of the top emission intensity distribution assuming the input power is 1 mW. The simulation tool is Lumerical FDTD solution$^\text{TM}$. In the custom grating design, the duty cycles and Si$_3$N$_4$ width values were 0.85 and 265 nm at the input end, and 0.5 and 500 nm at the output end. The corresponding emission rate values were $3.3 \times 10^{-4}$ μm$^{-1}$ and $2.2 \times 10^{-4}$ μm$^{-1}$, respectively. In between the two ends, the emission rate increases continuously while remaining the uniform propagation constant.

3. Fabrication and near field characterization

Figure 4 illustrates the fabrication flow charts for the custom grating. Fabrication steps included projection lithography using ASML$^\text{TM}$ PAS 5500 300 deep-UV stepper on 6-inch silicon-on-insulator (SOI) wafers each with a 500-nm thick silicon layer and a 3-μm thick buried oxide (BOX) cladding layer. The first fabrication step started with the growth of a 60-nm thick Si$_3$N$_4$ layer on the SOI by Low-Pressure Chemical Vapor Deposition (LPCVD) at 800 °C. We defined the duty cycle of the Si$_3$N$_4$ layer through dry etching on a 10-μm wide area using the Inductively Coupled Plasma (ICP) dry etching. Over the dry etched area, we subsequently patterned photoresist to define the width of Si$_3$N$_4$ and proceed with dry etching. Afterward, over the custom Si$_3$N$_4$ grating with varying widths and duty cycles, we fully etched the silicon guiding layer with a constant width value of 500 nm. Finally, we deposited a 2-μm thick Low-Temperature Oxide (LTO) layer by LPCVD as the overcladding, deep etched the facet edge coupler of 100 μm depth for fiber coupling, and diced the wafers.
The grating design included two types of gratings, which are the variable duty cycle grating (custom grating) and the constant duty cycle grating. Figure 5(a) shows the measurement setup using a cleaved multi-mode fiber to collect light from the top and a lensed single mode fiber launching light from the input facet. The length of the grating under test is 2 mm. Figure 5(b) indicates the normalized surface emission of the custom grating and the 0.5 constant duty cycle grating in red and black, respectively. The inset in Fig. 5(a) is the top view SEM image of the Si$_3$N$_4$ assisted silicon grating with custom duty cycles and Si$_3$N$_4$ widths. Overall, the custom grating shows a longer coupling length than the 0.5 constant duty cycle grating. However, the measured emission rate is stronger than the simulated values, which is possibly due to the over-etch into the silicon top surface during the Si$_3$N$_4$ dry etching process, where the large $\kappa$ value between the silicon core and the SiO$_2$ cladding enhances the emission rate. To solve the over-etching issue, one solution is to incorporate the design of partially etched Si$_3$N$_4$ grating instead of fully etched grating.

4. Experimental setup and results for far field measurement

Figure 6(a) shows the far field measurement setup that consists of a lensed fiber with a mode field diameter (MFD) of 2.5 µm coupling light into the silicon waveguide in the grating device and a lens tube with two lenses, fixed onto an infra-red (IR) camera tilted at about 12° in the vertical plane to maximize the collected power of the light coupled out from the surface emission grating coupler. The lens 1 creates a Fourier image which gives the far field pattern on the Fourier plane at one focal length away after the lens 1, and the lens 2 images the Fourier image onto the camera sensor with a 1:1 magnification ratio.

Figure 6(b) shows the far field pattern beam steering at ten different wavelengths between 1530 nm and 1575 nm with a 5-nm step. The intensity peak exhibits a 6.6° steering angle within an entire 45-nm wavelength span, with an average steering angle increment of 0.73°.
for every 5 nm of wavelength scan. The steering angle is centered at 12° from the vertical axis when the input wavelength is at 1550 nm.

The custom grating maintains the uniform propagation constant throughout the device for the TE input mode as designed. For other input modes, the propagation constant is not uniform, and blurs the far field patterns for beam steering. Figures 7 (a) and 7(b) demonstrate the mode selectivity of the regular grating with a constant duty cycle of 0.5, and the custom grating with non-uniform duty cycles, while the insets show the corresponding far field patterns. For the 0.5 constant duty cycle grating, both TE and TM modes result in clear peaks in the far field patterns. The measured 3-dB beam widths at 1550 nm are 0.75° and 0.5° for the TE and the TM modes, respectively. For the custom grating, the TE mode results in a clear peak with the 3-dB beam width of 0.1° at 1550 nm, while the TM mode results in a weak peak due to the non-uniformity of the propagation constant. The measured TE to TM far field peak-to-peak suppression ratio is approximately 8.2 dB for the custom grating.

5. Conclusion

We demonstrated a Si₃N₄ assisted silicon grating with a uniform propagation constant and uniform emission intensity over a 1-mm length grating, which leads to ultra-sharp IFOV in the far field patterns. Based on the Si₃N₄ low refractive index overlay layer, we designed and fabricated the custom grating with maintaining uniform propagation constant throughout the device for the TE mode. By sweeping the launching wavelength between 1530 nm and 1575 nm, we observed the beam steering angle to vary by 6.6°. The total field-of-view (TFOV) of the beam steering is limited by the measurement setup. The measured IFOV based on the 3-dB beam width values of the far field patterns for the TE polarization are 0.1° and 0.75° for
the custom grating and for the reference grating, respectively. The custom grating also indicates mode-selective behavior due to the perturbation of propagation constant for input modes other than TE polarization. The measured TE-mode to TM-mode suppression ratio for the custom grating is approximately 8.2 dB peak-to-peak measured at far field.

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