Design of a Focusing Multi-Wavelength Grating Coupler on a SiN Photonic Integrated Circuit

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Abstract

We describe a design approach for multi-wavelength grating couplers that emit a near-Gaussian beam that is focused at several millimeters above the chip. To obtain this intensity profile at multiple wavelengths, we optimize the filling factors over the grating, which is based on optimized single-wavelength grating couplers . We design such a grating coupler on a SiN technology platform which can operate at wavelengths of 635 nm, 780 nm and 850 nm. The beams are emitted in the same direction and focus to a near-Gaussian distribution with a diameter of 27.6 µm, 30.0 µm and 32.4 µm, respectively.

Monolithically integrating a coupler on a photonic integrated circuit that can emit or receive free-space beams focussed at a long working distance, enables further miniaturization of optical devices by reducing the need for external optics such as lenses or gratings. Integrated grating couplers are widely used to couple light out of a chip into e.g an optical fiber. However, their emittance angle is highly wavelength sensitive [1] and the output beam is highly divergent due to their small size. This limits focusing beams to the same target far away from a chip at multiple wavelengths from the same grating. This is relevant for e.g. a number of optical sensing and free-space communication applications.

Previously, we published an algorithm to design a Computer-Generated Waveguide Holograms (CGWH) – a "pixelized" grating coupler - that can focus light from an on-chip waveguide to a distance of 10 mm above the chip at a wavelength of 1300, 1450 and 1600 nm [2]. Near-vertical focusing for single- [3] and multi-wavelength CGWH was demonstrated. However a large part of the light passed the holograms without being transmitted due to a low scattering strength used. Using a low strength the waveguide grating emits its light fairly uniformly. In this paper, we describe how to use the concepts of optimizing the local scattering strength in single-wavelength grating couplers to obtain the emission of a near-Gaussian intensity profile for a multi-wavelength coupler. We have designed grating couplers in the SiN platform as shown in Figure 1 using a double strip waveguide. By using the SiN photonic integration platform, we enable the advancement of many optical sensing applications in the visible regime.

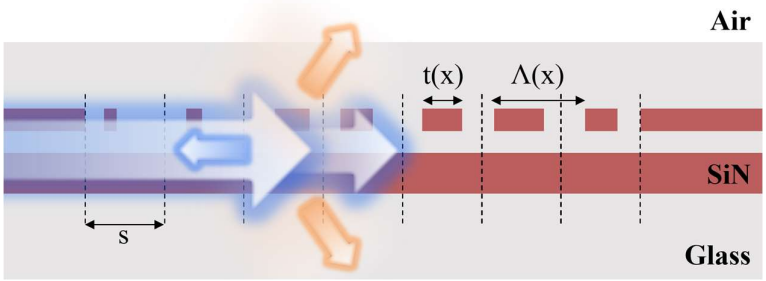

Figure 1 Schematic of our grating coupler. Each cell (dashed lines) contains one and exceptionally two grating lines, the sum of their widths is t(x) and the period with their neighbour is Λ. The arrows show how a grating line scatters some light of the guided mode back-, up- or downward.

Analytical Model of Grating Couplers

When a guided mode in a grating coupler passes a scatterer, a part of its light will be reflected in the waveguide or emitted up- or downward (Figure 1). We can represent the strength of these events by the coupling strengths α_{refl}, α_{up} and α_{dow} , respectively. They depend on many factors of the grating coupler: the period Λ, the filling factor ff (equal to t/s in Fig. 1), the layer properties and the etch depth.

The effect of the coupling strengths on the power of the guided mode $A(x)$ over the propagation length x can be mathematically expressed as

$$\frac{dA(x)}{dz} = -2\alpha(x)A(x) \tag{1}$$

where $\alpha = \sum\alpha_{refl} + \alpha_{up} + \alpha_{down}$ and the factor 2 is conventionally added. So, the guided power in a grating coupler exponentially decays from A_0 at its starting point x_0

$$A(x) = A_0 \exp\left(-2\int_{x_0}^{x}\alpha(x)dx\right) \tag{2}$$

Since the radiated power $B(x)$ represents the leaked guided light, it is given by

$$B(x) = -\frac{dA(x)}{dx} = 2\alpha(x)A_0 \exp\left(-2\int_{x_0}^{x}\alpha(x)dx\right) \tag{3}$$

However, this $B(x)$ represents the local scattering of light. The total reflection/emission is only strong if the contributions of all the scatterers constructively interfere with each other. For a grating with period Λ, the light constructively interferes if

$$k_{out,x}\,\Lambda = k_{guided,x}\,\Lambda + 2\pi\, m \tag{4}$$

with $k_{ou\ ,x}$ and $k_{out,x}$ the wave vector contributions in the x direction of the guided and output mode and m is the diffraction order. We can rewrite Eq. (4) to determine the period Λ needed to emit a beam upward above the chip (in the air) with an angle θ

$$\Lambda = \frac{m\lambda_0}{n_{eff} - \sin\theta} \tag{5}$$

where λ is the wavelength in vacuum and n_{eff} the effective refractive index of the waveguide.

To obtain a Gaussian emission profile, we can derive from Eq. (1) and (3) how the profile of the required coupling strength should look like [4]

$$\alpha_{required}(x) = \frac{B(x)}{2\left[A_0 - \int_{x_0}^{x}B(t)dt\right]} \tag{6}$$

Designing multi-wavelength grating couplers

As our target, we want our coupler to emit a Gaussian beam with a spot size of 164, 200 and 218 um at the wavelengths of 635, 780 and 850 nm, respectively, and focus it to a 30 µm-narrow Gaussian beam 5 mm above the chip. Figure 2b shows the required coupling strengths $\alpha_{required}$. To determine how α depends on the filling factor ff and the period Λ, we simulate utilizing Lumerical's Finite-Difference Time-Domain (FDTD) method a series of 100 um-long grating couplers. We determine α by fitting the exponential decay of the guided mode's power (Eq. (2)). We then optimized the layer thicknesses of the grating coupler (Fig. 1) such that $\alpha(ff,\Lambda)$ can sufficiently reach $\alpha_{required}$.

Figure 2(a) shows the resulting profile $\alpha(ff,\Lambda)$. For most periods, α changes slowly with Λ. But around $\Lambda = 390\,nm$, suddenly a second maximum occurs with α reaching a very low value. This line closely matches the analytically expected condition

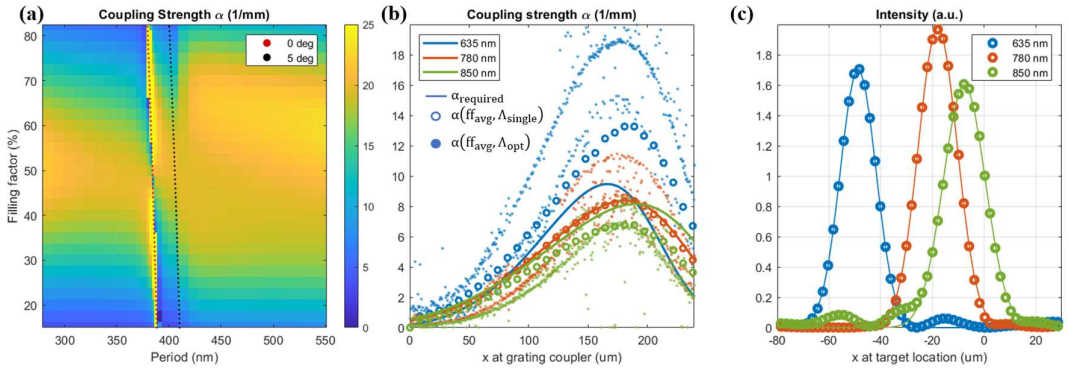

Figure 2 Optimization of the multi-wavelength coupler. (a) Influence of the filling factor and period on the coupling strength at 635 nm. The dots indicate the grating parameters required to emit a beam with an angle of 0 or 5°. Note the colour scale is saturated. The coupling strength can be as high as 83 1/mm around the 0° line. **(b)** Required coupling strength (lines) vs after taking the average of ff_{single} whilst assuming Λ_{single} (circles) and after also optimizing the period Λ (dots) to focus the light at multiple wavelengths. **(c)** Intensity profile of the focused beams at target location with Gaussian fit (lines).

for vertical emission and backward reflection. To avoid such strong reflections, we design our coupler to emit a beam at a slight angle of 5° (Fig. 2(a)). So, for each location x on the grating coupler, we want to focus the light to a narrow spot 5 mm above the chip shifted 592 µm of the coupler's centre. Thus, at each x we need a different θ. Since n_{eff} varies with ff, a range of (ff, Λ) points will give desired θ (Eq. (5)). We then select the optimal $(ff_{single}, \Lambda_{single})$ for which the α matches the closest to $\alpha_{desired}$ (Eq. (6)).
To design the multiwavelength coupler, we take for each x the average of ff_{single} over the different wavelengths. When we heuristically consider Λ_{single} at each λ, we notice already that $\alpha(635\,nm)$ increases, $\alpha(850\,nm)$ decreases whilst $\alpha(780\,nm)$ remains constant (Fig. 2(b)). Next, we optimize the local grating period $\Lambda(x)$ using a semi-analytical algorithm as described in [2], [5]. This algorithm optimizes $\Lambda(x)$ to focus the light at the three wavelengths all to the same target. As a result, the optimized Λ strongly fluctuates. Because α depends on Λ, it moves further away from $\alpha_{required}$ and also fluctuates (Fig. 2(b)). Figure 2(c) show the intensity profile at the target location. They are near-Gaussian with beam diameters 8% within the design target of 30 µm (Table 1).

Figure 3 compares the targeted $B(x)$ with our calculated (Eq. (3)) and simulated result of our optimized multiwavelength grating coupler. As expected, the data points in our result largely fluctuate, but we do still observe a Gaussian distribution. First, we see that the peak of the semi-analytically and FDTD Gaussian distribution is within 24 µm and 41 µm of the target location, respectively. The deviations between the peaks of the FDTD results are up to 4 µm identical to those of the profiles at the target location (Fig. 2(c)). Thus, the coupler emits the beams in the same direction. Secondly, we observe that the beam diameter w of the beam emitted by our model is up to 1.8x lower than our target value. This indicates how largely α deteriorates after independently optimizing Λ. However, we notice that our model underestimates the emission of the scatterers in the first 70 µm as compared to rigorous FDTD simulations. One reason is that our model assumes a uniform array of scatterers vs a strong fluctuating Λ. As a result, w of the simulated intensity profile is 1.2-1.8x wider than our model predicts (Table 1). Only w at $\lambda = 850\,nm$ is below the target with 12% compared to 56% as our model predicted.

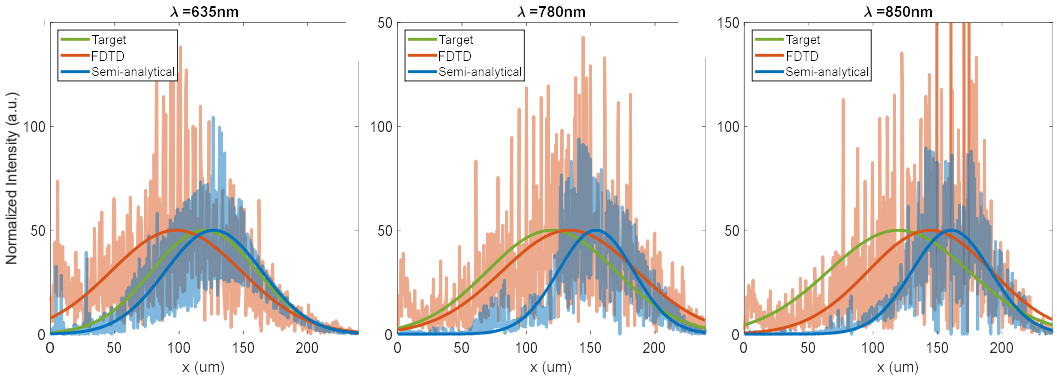

Figure 3 Validating our semi-analytical model. Comparing upward emitted intensity profile at wavelengths of **(a)** 635, **(b)** 780 and **(c)** 850 nm as targeted (green) and calculated by FDTD (red) or our semi-analytical model (blue). The solid lines represent Gaussian fits through the data points.

Table 1 Comparison of the beam diameters of the intensity profile at the near-field and focus location.

Location	Method	$635\ nm$	$780\ nm$	$850\ nm$
Near-chip plane	Design target	164 µm	200 µm	218 µm
	FDTD Simulation	202 µm	210 µm	192 µm
	Semi-analytical Calculation	150 µm	117 µm	122 µm
At focus location	FDTD Simulation	27.6 µm	30.0 µm	32.4 µm

Conclusion

We designed a grating coupler that emit a near-Gaussian beam that is focused 5 mm above the chip at a wavelength of 635 nm, 780 nm and 850 nm. The beams are emitted in the same direction with an angle of 5 ° to avoid strong Bragg reflections. They have a diameter of 28-33 µm, within 8% of the design target. At the start of the grating coupler, our semi-analytical model underestimates the strength of the scatterers. We think this is caused because our model assumes a uniform grating profile. In the future, we will investigate how sensitive our model is to variations in the grating period.

Acknowledgements

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