Efficiency of focusing grating couplers versus taper length and angle

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Abstract. Here we experimentally studied dependence of a focusing grating coupler efficiency versus taper length and angle on silicon nitride platform. As a result, we obtained a dependence for the efficiency of a focusing grating coupler on the parameters of the taper length and angle.

1. Introduction
Today one of the most pressing problems of integrated optics is the search of ways for improving the coupling between optical fibers and waveguide structures [1]. In modern photonics, the most widely adopted methods for input and output optical radiation from a chip are based on end-face (or butt-coupling), focusing grating couplers (FGCs) [2] as well as near-adiabatic-mode-converters [3] approaches. Due to capabilities to study of hundreds of on-chip devices, ease of alignment and fabrication, as well as flip-chip technology [4] the last approach is the most popular and a large amount of research has been done to improve the efficiency of FGC, including geometry analysis [5], apodization [6], directionality [2] and so on. Additional solutions for efficiency improvement are the use of different materials [7] and individual layers [8, 9]. In addition, there are several works in literature report on studies of the FGC coupling efficiency with different geometrical solutions [10, 11, 12].

In this work, we focus on the study FGC coupling efficiency dependence on two geometrical parameters: the taper length ($L$) and taper angle ($\alpha$).

2. Device designing and fabrication
We designed a 2D array of devices with two sweep parameters: $L = 10\div30 \, \mu m$ and $\alpha = 30 \div 60$ degrees (Figure 1(a)). The total number of devices in the array was 225. The typical element of the array consisted of two FGCs for input and output light, connected by rib waveguide bus with 1$\mu$m width for all the devices (Figure 1(b)). The FGC filling factor [13, 14] was fixed and equal to 0.33$\pm$. The Commercially available Si wafers with 450 nm Si$_3$N$_4$ surface as an optical layer and SiO$_2$ as an optical buffer between Si and Si$_3$N$_4$ were used. The fabrication process consisted of one e-beam lithography step. First, ZEP 520A resist was deposited by spin coating procedure. Then, the image of the structure was drawn in the resist using an electron beam lithography by CABL-9000C and resist was developed in O-Xylene, protecting covered silicon nitride under reactive ion etching (RIE) in Ar and CHF$_3$ gas mixture. Finally, using oxygen plasma the residual resist was removed.
3. Experimental setup and results

For testing of nanophotonic devices in a spectral range of 1510 ÷ 1620 nm we used a tunable laser source (New Focus TLB-6600) and a fast photodetector (Hamamatsu G9801), controlled by a NI DAQ system. We used a precision (X, Y, Z, angle) stage with piezoelectric picomotors (NewFocus 8303) and an optical microscope to align the nanophotonic structures with the two-channels optical fiber array.

Typical transmission spectra of two nanophotonic devices with different taper angles ($\alpha = 32^\circ$ for black solid line, and $\alpha = 60^\circ$ for red solid line) at a fixed taper length of $L = 22.86 \, \mu m$ are shown in Figure 2a. We used a Gaussian fit (blue and green lines) to extract the output power at the central wavelength. We measured all 225 devices on the chip and found that the maximum of the spectra was distributed at the central wavelength $\lambda_c = 1543 \pm 1.55 \, \text{nm}$, demonstrating a good reproducibility of the period and the fill factor of FGCs. Optical output power ($P_{\text{out}}$) for fabricated nanophotonic devices can be found as:

$$P_{\text{out}} = P_{\text{in}} \times C^2 \times T_{\text{wg}},$$

(1)

where $P_{\text{in}}$ is input power, $C$ is coupling efficiency and $T_{\text{wg}}$ is the waveguide optical transmission. Considering the optical losses, previously found for the same nanophotonic architecture from the data obtained by O-ring resonators ($< 1 \, \text{dB/cm}$) [14], losses can be neglected ($T_{\text{wg}} \approx 1$) and coupling efficiency can be found as:

$$C = \frac{P_{\text{out}}}{P_{\text{in}}}.$$

(2)

In Figure 3(b) we plot the experimentally obtained color contour map of the maximum FGC efficiency at a central wavelength $\lambda_c$ at different $L$ and $\alpha$. The highest FGC efficiency corresponds to areas with a taper length from 21 to 23 $\mu m$ and a taper angle from 33 to 36 degrees with the highest efficiency value equals to $C = 0.18$.

4. Discussion

In general, the coupling efficiency depends on phase and amplitude matching. The phase matching can be maximized due to the period of the diffraction grating as well as amplitude matching is determined by the compliance of the optical spot from the fiber ($D$) and the working area of the FGC (Figure 3(a)). This can be achieved with different configurations of taper length $L$ and taper angle $\alpha$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a, b). (a) Optical micrograph of one of the fabricated focusing grating couplers (FGCs), where the taper length ($L$) and the taper angle ($\alpha$) are highlighted by color; (b) Scanning electron microscope image of a nanophotonic device with two FGCs and the waveguide.}
\end{figure}
\[ S = \frac{D}{2} \cdot \cot \frac{\alpha}{2}, \]  

(3)

Figure 2 (a, b). (a) Measured transmission spectra of two focusing grating couplers (FGCs) with different geometrical parameters: \( L = 22.86 \, \mu m \) and \( \alpha = 32^\circ \) (black solid line), \( L = 22.86 \, \mu m \) and \( \alpha = 60^\circ \) (red solid line). Blue and green lines correspond to Gaussian fit. (b) Dependence of the coupling efficiency on the taper length at different taper angle (\( \alpha = 36.42^\circ \), \( 53.57^\circ \)). Dots and squares are experimental data as well as solid lines correspond to Lorentz fit. The arrows show the maximum efficiency (\( C_{\text{max}} \)) for each curve.

where \( S = L + \Delta \) is the distance from the end of taper to the point where the output power has the maximum value and where optical fiber should be placed.

To analyze the experimental results, we plotted the dependence of the coupling efficiency on the taper length and fitted it by a Lorentz function (Figure 2 (b)). If the angle is fixed, then the efficiency reaches its maximum value (\( C_{\text{max}} \)) at a certain taper length. When the angle increases, the efficiency maximum shifts towards shorter taper lengths.

Figure 3 (a, b). (a) Focusing grating coupler design: \( D \) is mode field diameter of an optical fiber SMF-28, \( \alpha \) is the taper angle and \( S \) is the distance from the end of taper to the point where the output power has the maximum value. (b) Color contour map of the efficiency on taper length and taper angle with fitted dependences of \( C_{\text{max}} (L) \) (purple dash-dot line).
Since the phase matching is the same for all the devices in the array (the period and the filling factor do not change), this behavior can be explained by the fact that for a given angle and length of the taper, amplitude matching is performed in the best way. In this case, the waveguide mode should fit completely into the FGC geometric region, and the maximum of the light scattering by the grating should coincide with the center of the optical fiber mode.

To test our guess, we extracted the dependences of $C_{\text{max}}(L)$ and fitted it using equation 3. The result of the fit (purple dash-dot line) is shown together with the experimental data (Fig. 3b). The extracted optical spot dimension ($D$) data from the experimentally obtained data correspond to 13 μm, which is close to the modal diameter of the telecommunication fiber SMF-28 ($D = 10.4\pm0.5$ μm). We associate the increase in diameter due to the final height of the fiber above the FGC. Considering the numerical aperture NA = 0.14, the height of the optical fiber above the coupling can be reasonably estimated as 10 μm.

5. Conclusions
In conclusion, we studied dependence of grating couplers efficiency vs the taper length ($L$) and taper angle ($\alpha$) for central wavelength $\lambda_c = 1543 \pm 1.55$ nm. It was found that the maximum efficiency of FGCs for fixed $\lambda_c$ efficiency is achieved at low taper angles and long lengths. Further work related to 3D modeling of FGCs in COMSOL Multiphysics, apodization in the FGC structure [15, 16] integrating the FGCs into resonator and antireflection layers can allow to significantly improve the coupling efficiency.

Acknowledgments
G. Goltsman and V. Kovalyuk acknowledge support by Ministry of Education and Science of the Russian Federation №14.583.21.0065 (RFMEFI58317X0065).

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