Characterization of focusing grating couplers for telecom wavelengths in the first and second diffraction order

A Elmanova¹, I Elmanov¹, P An¹,², V Kovalyuk¹,², A Kuzin¹,⁴, A Golikov³ and G Goltsman¹,²,³

¹ Department of Physics, Moscow Pedagogical State University, 119992, Russia
² FRC Institute of Applied Physics RAS, 603950 Nizhny Novgorod, Russia
³ National Research University Higher School of Economics, Moscow 101000, Russia
⁴ Skolkovo Institute of Science and Technology, 121205, Russia

Abstract. In this work we studied how focusing grating couplers, developed for telecommunication C-band wavelength range, can be applied in the near infrared range. In the paper we presented prospects of usage of both first and second diffraction maxima of theoretically computed diffraction grating couplers for photonic aims. The dependence of the central wavelength of the grating on the etching depth of the photonic layer, on the period and filling factor of the grating was studied. We have compared our experimental results with numerical study, performed using finite elements method of solving differential equations. The work is important for different photonic applications and introduces new prospects in application of the already fabricated devices, developed for telecommunication wavelengths.

1. Introduction

Focusing grating couplers (FGCs) have found their wide application for input/output of radiation due to the well-developed CMOS processing together with waveguides, as well as flexible footprint in any place of the nanophotonic chip [1]. Such couplers have efficient filtering of light in the selected spectral range, usually corresponding to the first order of interference [2]. FGCs are considered one of the most compact systems for light coupling from an optical fiber to a photonic integrated circuit (PIC) [3]. However, for a number of quantum applications, for example, quantum key distribution or linear optical quantum computing, in order to reduce parasitic illumination, the coupler efficiency in higher diffraction orders should be known [4].

In this work, the spectra of FGCs, developed for operation at a telecom wavelength of 1550 nm, in the first and second diffraction order was studied. The approximate positions of the first and second diffraction maxima were verified by numerical simulation and experimentally. We used silicon nitride as one of the most popular platforms for developing PICs [1]. However, thanks to the wide bandgap, silicon nitride can be successfully used in both C-band and near IR wavelengths [5]. At the same time, lower optical contrast makes such devices less sensitive to fabrication inaccuracies, and also reduces the scattering loss due to the sidewall roughness [6]. Several works on the development and use of grating couplers have already been presented on this platform, with the coupling efficiency reaching -4.2 dB [7] for a wavelength of 1550 nm. For the FGCs fabrication, one of the most common methods is electron beam (e-beam) lithography [8]. It allows to precisely vary such device parameters as the period p, width w of the grating, hence and the filling factor (ff):
The dependence of the characteristics of focusing devices on them has been actively studied, both theoretically and experimentally [9]. After the e-beam lithography process, the next important step is reactive ion etching structures. Here semi-etched design is used, because it provides a better coupling through evanescent field between different devices on photonic scheme and waveguides than full etching (like optical ring resonators, directional couplers, etc) [10]. In our work, we investigated the performance of the FGCs at different etching depths and wavelength region.

2. Simulation

Before experimental study, it was necessary to determine what diffraction orders we are working with and in what approximately wavelength range one should expect the maximum transmission on diffractive couplers. When positioning an optical fiber with a coupler grating, we consider the fiber inclined at 8 degrees. This angle is shown in Figure 1a. In this case, it is possible to approximately calculate the position of the diffraction maxima of the order of \( m \) using the well-known formula [11]:

\[
ff = \frac{w}{p}
\]

The dependence of the characteristics of focusing devices on them has been actively studied, both theoretically and experimentally [9]. After the e-beam lithography process, the next important step is reactive ion etching structures. Here semi-etched design is used, because it provides a better coupling through evanescent field between different devices on photonic scheme and waveguides than full etching (like optical ring resonators, directional couplers, etc) [10]. In our work, we investigated the performance of the FGCs at different etching depths and wavelength region.

2. Simulation

Before experimental study, it was necessary to determine what diffraction orders we are working with and in what approximately wavelength range one should expect the maximum transmission on diffractive couplers. When positioning an optical fiber with a coupler grating, we consider the fiber inclined at 8 degrees. This angle is shown in Figure 1a. In this case, it is possible to approximately calculate the position of the diffraction maxima of the order of \( m \) using the well-known formula [11]:

\[
n_{eff} = n_{cover} \cos \varphi_c + m \frac{\lambda}{p}
\]

here \( n_{eff} \) — effective refractive index, \( n_{cover} \) — refractive index for the waveguide layer (considering the structure as fully etched), \( \varphi_c \) — coupling angle (in our case it is equal to \( 90^\circ - 8^\circ = 82^\circ \)), \( m \) — diffraction order, \( \lambda \) — central wavelength in vacuum and \( p \) — period of the diffraction grating (for non-apodized case). Thus, when calculating a structure with a central wavelength of 1550 nm, a grating period of approximately 1.086 µm and a refractive index of the waveguide layer of 1.9963 (for a given wavelength), we obtain an effective refractive index of near 1.839. For wavelengths around 850 nm, the effective refractive index will not be 1.839, but rather (according to the proportional ratio) 1.6663. Then the wavelength of the second maximum falls on even longer wavelengths. Thus, for a device designed for wavelength of 1550 nm, a second maximum is expected in the region of 850–900 nm.

For numerical simulation we used the finite element method (FEM) in the COMSOL Multiphysics. A 2D model of a grating coupler was developed. We optimized our parameters for C-band of IR radiation and used parameters possible for fabrication (etching depth \( h_{etch} = 450 \) nm, filling factor \( ff = 0.86 \), period of the grating \( p = 1.086 \) µm, silicon substrates with SiO2=2.6 µm and Si3N4=450 nm layers atop). First the distribution of normalized electric field and the modulation of optical field for coupling (Figure 1b) was calculated. Then the dependence of the coupling efficiency on the thickness of SiO2 was calculated (Figure 1d). After it was determined, the highest efficiency was found to be for silicon oxide layer thickness 2.6 µm, therefore the fabricated structures had this parameter. Simulation of the propagation of an electric field (TE mode) was carried out for a given wavelength with the parameters of a fully-etched device, and in the wavelength range of about 800 nm. The dependence of the transmission on the Gaussian beam position was also found (Figure 1e). Transmission peaks were found and their effectiveness was evaluated. The maximum efficiencies for the 1520–1570 nm range is 17.8% at a central wavelength of 1558.86 nm, as well as for the 800–810 nm range is 0.87% at a central wavelength of 807 nm were found.

3. Device design and fabrication

For the device fabrication we used commercially available silicon substrates with SiO2=2.6 µm and Si3N4=450 nm layers atop. The fabrication process consisted of one e-beam lithography step. First, ZEP 520A resist was deposited by spin coating procedure. Then, the electron beam lithography was done by Crestec CABL-9050C and resist was developed in O-Xylene, protecting covered silicon nitride under reactive ion etching (RIE) in Ar and CHF3 gas mixture. Finally, using oxygen plasma the resist was removed. Overall view of the fabricated device is shown in Figure 2a. The device consists of two FGCs, connected via silicon nitride waveguide at a distance of 250 µm. Thus, one device acts as an input port,
the other as an output port. More photographs are given on Figure 2d,e. For the primary study, we used a sample with array of structures with period 1.086 µm, filling factor 0.7 and etching depth 225 nm. Then we used five samples with equal arrays of structures, but with a different etch depth (Figure 2f). All devices have a taper angle of 45°, the number of gratings is 20. A 2D array of structures with devices with different filling factors in a range of 0.84 to 0.88 with step 0.01, with different periods, varied from 1.058 to 1.088 with step 0.004 µm was studied. Each was etched to different depths (447, 435, 345, 281, and 170 nm).

Figure 1. (a) Schematic view of the FGC and optical fiber above at an angle of 8° to the normal. The width of the filled part \( w \), period \( p \) and etching depth \( h_{etch} \) are marked. (b) Distribution of normalized electric field for Gaussian beam at \( \lambda = 1550 \text{ nm} \) with an angle of 8° to the grating, \( D_{1/e} \) – mode field diameter. The perfect match layer (PML) on boundaries. (c) Normalized E field for Gaussian beam shown in (b). The period is \( p = 1078 \text{ nm} \); the filling factor \( ff = 0.86. \) (d) Dependence of the coupling efficiency on the silicon oxide thickness for the two diffraction orders. (e) Dependence of the normalized electric field on the inside Gaussian beam. The mode field diameter is equal to 10.4 µm at a wavelength of 1550 nm. (f) Dependence of intensity transmission on the Gaussian beam position.

4. Device design and fabrication

In this work, we used two experimental setups for measuring the transmission spectra of nanophotonic devices. The first setup for measurements at telecom wavelengths consists of a tunable laser (NewFocus TLB-6600 with tune range 1510-1620 nm), a polarization controller, 3D stage with piezo motors, a fast photodetector, as well as a fast analog-to-digital converter (Figure 2b). The fiber array was optimized to work in the wavelength range of the C-band. The second setup (Figure 2c) consisted of the broadband fiber-coupled supercontinuum source (Leucos Rock 400 4) and the spectrum analyzer (Maya 2000 Pro). Light from source pass to the fiber array for near infrared spectra, which is fixed with angle 8º. The results obtained by set up for telecom wavelength (1.55 µm) and is shown in Figure 2g. The results were approximated using Lorentz Fit. Therefore, for infrared range we got FWHM = 35.428 nm and for visible FWHM = 20.193 nm (Figure 2g, h). For the input (\( P_{in} \)) and output power (\( P_{out} \)), the coupler efficiency (under the condition of low losses in the next waveguide and the same input and output) can be found as:

\[
\mathcal{C} = \sqrt{\frac{P_{out}}{P_{in}}}. \tag{3}
\]
For all of the devices, spectra were obtained, the dependences of the efficiency and position of the central wavelength on the period, filling factor, and etching depth were investigated. Based on the data, color contour maps were compiled (Figure 3) for both ranges (near 1550 nm and 850 nm). The dependences of the central wavelengths of the devices on the etching depth were obtained at a constant filling factor and period.

Figure 2. (a) SEM photographs of the fabricated devices. (b) Schematically depicted experimental setup for wavelengths range 200-1100 nm. (c) Schematically depicted experimental setup for wavelengths range 1520-1610 nm. (d) SEM photograph of one of the FGCs. (e) SEM photograph with the grating with period and the grating teeth marked. (f) Atomic force microscope image of one of the fabricated couplers. (g) Experimental transmission spectrum and Lorentz fit for the fabricated device in telecomm wavelength range. Full width at half maximum and notch wavelength are noted. (h) Same as (g) in near IR wavelength range.

5. Discussion

The obtained contour maps for two wavelength ranges can be compared (Figure 3 a,c). The position of the central wavelength changes similarly, and the efficiency also. Therefore, the notch wavelength of the GC be shifted by changing period or filling factor, as this is a predictable mechanism. The efficiency peaks for both ranges are in the area of low periods (less than 1.07 µm) and filling factors in between 0.85 and 0.87 (Figure 3b,d). It is important to study of the dependence of the wavelength of devices on the etching depth (Figure 4a,c). So, for the least fabricated period of 1.058 µm for various filling factors, the average value of the ratio of increments of the wavelength to the etching depth was -0.1789 and for near IR it was 0.1749. By taking derivatives over the etching depth from both sides of the formula (2), one can obtain the relation for $m = 1$:

$$\frac{d \eta_{eff}}{dh_{etch}} = \frac{d \lambda}{dh_{etch}} \cdot \frac{1}{P}$$  \hspace{1cm} (4)

From where one can get the ratio of the increment of the effective refractive index to the change in the etching depth. On average, this increment for the fabricated structures $1.672 \cdot 10^{-4}$ nm$^{-1}$. The transmission patterns of fabricated and simulated structures were also compared (Figure 4 b, d).
6. Conclusions
We have studied the performance of FGCs designed for telecommunications wavelengths in the visible range. We have found the same correspondence in the efficiency and notch wavelength depending on period and filling factor of the grating for the two wavelengths ranges. We also determined the dependence of the central wavelength on the etching depth for both diffraction orders, and, therefore, the dependence of the effective refractive index on the etching depth. We have compared the experimental transmission pictures with the simulated curves. We found that the central wavelength is shifted for several nm and the efficiency is of the same order for the simulated and experimental data.
This work is of significant importance for research and work with quantum emitters, for using pumping at a wavelength of shorter than radiation, thus filtering pumping from radiation, and studying the emission spectra of nanophotonic devices in two different wavelength ranges.

Figure 4. (a) Dependence of the central wavelength on the etching depth in the telecom range for the devices. (b) Comparison of the experimental and simulated curves for the device with period 1078 nm, \(ff = 0.86\) and etching depth 280 nm in the telecom range. (c) Dependence of the central wavelength on the etching depth in the near IR range. (d) Comparison of the experimental and simulated transmission for the FGC with period 1078 nm, \(ff = 0.86\) and etching depth 280 nm in the near IR range.

Acknowledgements

The research was performed by support of the Russian Science Foundation grant No. 19-72-10156.

References

[1] Quaranta G, Basset G, Martin O J F and Gallinet B 2018 Laser Photonics Rev. 12 1800017
[2] Song S H and Lee E H 1995 Appl. Opt. 34 5913-5919
[3] Wood M, Sun P and Reano R M 2012 Opt. Express 20 164-172
[4] Ding Y, Bacco D, Cai X, Zhou X, Rottwitt K and Oxenløwe L F 2017 Quantum Inf. 3 25
[5] Zou J, Yu Y, Ye M, Liu L, Deng S and Zhang X 2015 Opt. Express 23(20) 26305-26312
[6] Zhang H, Li C, Tu X, Song J, Zhou H, Luo X, Huang Y, Yu M and Lo G Q 2014 Opt. Express 22(18) 21800-21805
[7] Doerr C R 2010 IEEE Photonics Technology Letters 22 19 461-1463
[8] Song J H, Kongyuyuy T D, Troia B, Saseendran S S, Soussan P, Jansen R and Rottenberg X 2019 OSA Continuum 2 1155-1165
[9] Laere F, Bogaerts W, Taillaert D, Dumon P, Van Thourhout D and Baets R 2007 Conf. on Optical Fiber Communication and the National Fiber Optic Engineers Conf. Proc. 1-3
[10] Rath P, Kahl O, Ferrari S, Sproll F, Lewes-Malandrakis G, Brink D, Ilin K, Siegel M, Nebel C and Pernice W 2015 Light: Science & Applications 4 338
[11] Waldhäusl R, Schnabel B, Dannberg P, Klez E B, Bräuer A and Karthe W et al 1997 Appl. Opt. 36 9383-9390