Design of a deep etched focusing subwavelength grating with a metallic reflector for membrane based photonic integration platforms

A. J. Millan-Mejia, Y. Jiao, J. J. G. M. van der Tol and M. Smit

Photonic Integration, Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.

In membrane photonic integration technologies, grating couplers are widely used to couple light between the photonic circuits and optical fibres. Here we present the design of a novel deep etched focusing subwavelength grating with a metallic reflector. This device is optimized for the InP membrane on silicon (IMOS) platform. The simulated coupling to a fibre efficiency is as high as 76 %, with the fibre tilted 10° from the grating normal. The use of a metal reflector make the performance of the device independent of the underlying layer stack, providing flexibility to the platform.

Introduction

In recent years, among the photonic integrated circuit (PIC) community, membrane based platforms have gained much attention. The high refractive index contrast makes this platform suitable to boost further integration by reducing the footprint of devices and possibly having a better energy efficiency. However, the size reduction of the devices have made the coupling between on-chip devices and optical fibres a complex task to solve. Grating couplers have been widely used to solve this task because these devices allow to couple light in and out of a PIC with relatively low losses.

The different grating designs have performance restrictions, mainly due to the known interference effect between the direct up-ward wave toward the fibre and the reflection from the interface between the bonding layer and the substrate [1]. This situation necessitates a strict control of the bonding layer thickness to obtain the correct interference. Additionally, cross talk originating from the power leaking down-ward could decrease performance in highly dense photonic circuits. Among some of the solutions to these problems, one proposing a metal grating of $600nm$ thick with $305nm$ wide gold embedded in SiO_x has been predicted to have 90% up-ward diffracted light [2] . This device is promising, but such geometries are challenging to fabricate with standard techniques. Another approach uses a metallic grating formed by buried stripes patterned in SiO_x and a metal mirror layer. This solution is predicted to have up to 73% of light coupled to a fibre at 10° from the grating normal [3]. Realization of such gratings have resulted in coupling efficiency of 54% [4]. This solution is attractive, but it requires its own electro beam lithographies (EBL) and etching steps, which increases the complexity to fabricate optical circuits in the same chip.

In this proceeding, we propose a deep etched focusing subwavelength grating with a metallic reflector for TE polarization. This solution is compatible with both silicon on insulator (SOI) and InP membranes. We design and optimize this for the IMOS platform.

The study uses two-dimensional Finite-Difference Time-Domain simulations (FDTD) for a grating period of 20 elements.

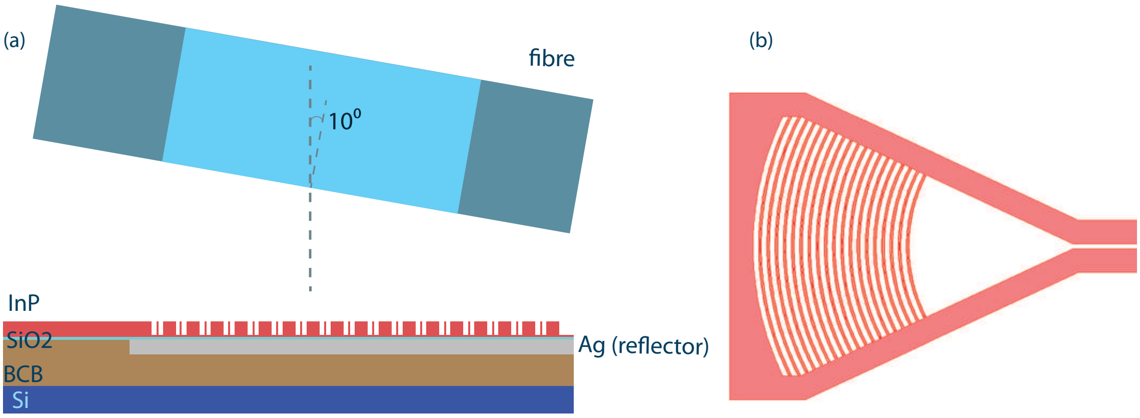

Figure 1: (a) Schematic of the grating with the metal reflector. (b) Focusing grating geometry

Design and optimization

The InP membrane consist of standard IMOS passive 300nm thick layer bonded to a Silicon wafer with a buffer layer consisting of 50nm of SiO_x and a thick benzocyclobutene (BCB). A Ag layer (300nm) is present in the section where the grating is placed. The use of Ag is preferred for its low absorption compared to other metals. The grating consists of a deep etch in the dielectric material (270nm) leaving a thin footing layer which is useful for protection in the fabrication process. This geometry will reduce the fabrication complexity, since if is done by fabricating the grating together with the other passive waveguides and devices. This results in a cheaper, shorter and more reliable fabrication process. Figure 1 (a) shows a schematic of the metal grating design.

The deep etched grating has the problem of high Fresnel reflection due to the high effective refractive index difference between etched and non etched areas. In order to reduce this reflection, a subwavelength section is added [5], which reduces the effective refractive index difference. A focusing geometry is used to reduce the size of the grating and avoid the presence of adiabatic tapers from the standard waveguide width (400nm) to a desired width [6]. Figure 1 (b) illustrate the focusing grating design.

After defining the geometry of the grating, an optimization procedure was performed. Having the emission normal to the surface is not possible because that period corresponds to the Bragg grating condition. An angle $\theta = 10^o$ is selected, which is far enough from the Bragg grating condition to reduce reflections.A thin layer of SiO_x (50nm) is placed under the InP membrane. The period is determined from the formula $q\lambda_0 = n_{eff}\sqrt{y^2+z^2} - zn_t cos\theta_c$, where q is an integer number of each grating line, n_t is the surrounding refractive index, λ_0 the wavelength in the vacuum and n_{eff} the effective refractive index that the light experience in the grating. We execute a 2D-FDTD particle swarm optimization of 15 generation with 12 elements each, having the effective refractive index, the filling factor and the subwavelength section width as parameters. We obtain

an effective refractive index $n_{eff} = 2.169$ which result in a period of $776nm$ with a subwavelength section of $100nm$ and a filling factor of 56%. A grating with these parameters shows the best performance with an emitted upward power of 76% at $1.55\mu m$ wavelength. The absorption due to the metal is calculated to be around 2.4%. The reflection into the fundamental mode of the waveguide is 3.5%. Figure 2 (a) shows the coupling efficiency. The bandwidth is $72nm$ which covers the entire C-band. The highest coupling efficiency to a fibre is 76% while the up-ward efficiency is 90%. This indicates that an apodization scheme could remarkably increase the efficiency of the grating.
Because of the small dimensions of the elements in our design and the difficulty to accurately fabricate them, a fabrication tolerances study was carried on. The most critical dimension in our design corresponds to the subwavelength section. We sweeps its dimension and measuring the coupling efficiency and reflections into the waveguide. Figure 2 (b) shows the results. It is important to realise than small changes have an significant impact in the efficiency of our grating. $10nm$ deviation would decrease the efficiency more than $1.5dB$ and the reflection can go up rapidly. Thight control during the fabrication must be applied. Apodization schemes could also be use to improve the tolerances.

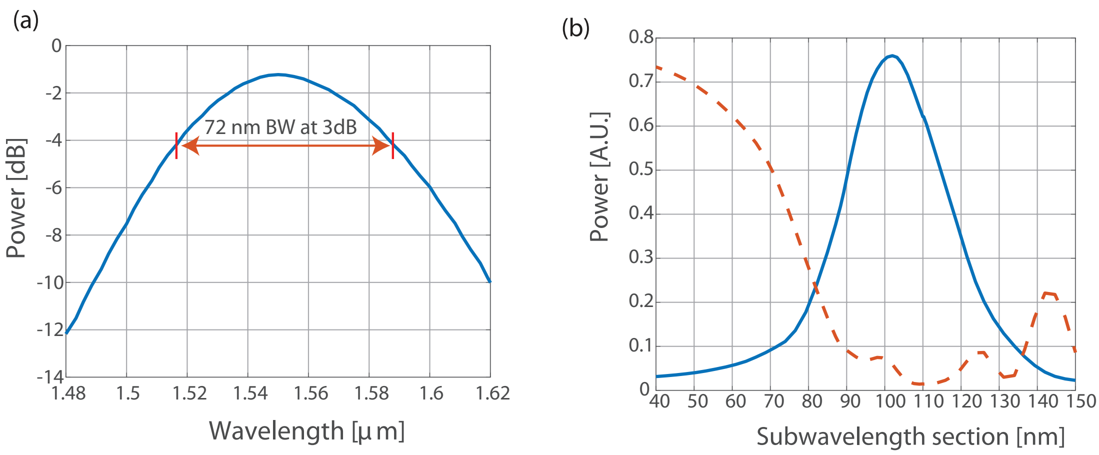

Figure 2: (a) Coupled efficiency to a single mode fibre tilted at 10° from the grating normal. (b) Coupling efficiency vs. width of the subwavelength section

Fabrication process proposal

In this section we describe the proposed fabrication process for the subwavelength grating with a metallic reflector in the IMOS platform.
Firstly, after a standard InP surface cleaning, a SiO_2 layer of $50nm$ is deposited with Plasma Enhanced Vapor Deposition (PECVD). The next step is to deposit $2nm$ of germanium and $300nm$ of silver with e-beam evaporation. The presence of the thin layer of germanium enhances the adhesion of silver on SiO_2. A lift off process is used to define the metal only in the grating areas, and there where EBL marks are needed. It is noted that the metal will also work as e-beam mark for the subsequent e-beam lithography.
The next step consists on performing a flip-chip adhesive bonding on a silicon substrate with BCB. The $III-V$ substrate will be removed with selective wet etching, using the waveguide layer as an etch stop layer. For the selective wet etching process, $HCL : H_3PO_4$ and $H_2O : H_2SO_4 : H_2O_2$ are used to etch respectively InP and InGaAs/InGaAsP cap

layers. The grating, waveguides and other passive devices are made with a combination of 50*nm* of SiN_x as a hard mask and ZEP/C_{60} as e-beam resist, respectly. ZEP/C_{60} resist is preferred to standard $ZEP520A$ because of its enhanced thermal resistance and reduction on proximity effects during the exposure. After exposing the devices with e-beam lithography and developing the resist, the pattern is transferred to the SiN_x with a CHF_3 RIE process. The etching of the semiconductor is performed with inductively coupled plasma (ICP) dry etching, using a methane-hydrogen chemistry.
Finally we clean our chip with a combination of stripping with plasma and dipping in a H_3PO_4 solution. This fabrication process is similar to that of IMOS passive devices, making the design of this grating promising.

Conclusions

A deep etched focusing subwavelength grating with a metallic reflector has been presented. This design makes the grating independent of the buffer layers giving flexibility and robustness to the membrane platforms. A coupling efficiency to a fibre up to 76% has been predicted for the IMOS platform. This design reduces the fabrication complexity by realizing it together with other passive devices. The design has low fabrication tolerances, so careful lithography is needed in order to fabricate successful gratings. Apodization can improve both the coupling efficiency and the tolerances.

ACKNOWLEDGMENT

We would like to thank the ERC NOLIMITS project.

References

[1] D. Taillaert, W. Bogaerts, P. Bienstman, T. F. Krauss, P. Van Daele, I. Moerman, S. Verstuyft, K. De Mesel and R. Baets, ”An out-of-plane grating coupler for efficient butt-coupling between compact planar waveguides and single-mode fibers”, in *IEEE Journal of Quantum Electronics*, vol. 38, issue: 7, pp. 949 - 955, 2002.

[2] P. T. Lin, C. Y. Wu, and P. T. Lee, ”Buried metal grating for vertical fiber-waveguide coupling with high directionality”, in *Advanced Photonics Congress*, paper IM4B.6, 2007.

[3] V. Dolores-Calzadilla, D. Heiss, and M. Smit, ”Highly efficient metal grating coupler for membrane-based integrated photonics”, in *Opt. Lett*, vol. 39, issue: 9, pp. 2786-2789, 2014.

[4] Aura Higuera-Rodriguez, Victor Dolores-Calzadilla, Yuqing Jiao, Erik J. Geluk, Dominik Heiss, and Meint K. Smit, ”Realization of efficient metal grating couplers for membrane-based integrated photonics”, in *Opt. Lett.*,vol. 40, issue: 12, pp. 2755-2757, 2015.

[5] Y. Wang, X. Wang, J. Flueckiger, H. Yun, W. Shi, R. Bojko, N. A. F. Jaeger, and L. Chrostowski, ”Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits”, in *Optics Express*, vol. 22, issue: 17, pp. 20652 - 20662, 2014.

[6] F. Van Laere,T. Claes, J. Schrauwen, S. Scheerlinck, W. Bogaerts, D. Taillaert, L. O’Faolain, D. Van Thourhout and R. Baets, ”Compact Focusing Grating Couplers for Silicon-on-Insulator Integrated Circuits”, in *IEEE Photonics Technology Letters*, vol. 19, issue: 23, pp. 1919 - 1921, 2007.