# Inverse design of perfectly vertical apodized grating couplers with a gold reflector

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*Grating couplers (GCs) have been widely used for optical coupling between photonic chips and optical fibers. But they can also be used as transmitters and receivers for free-space optical (FSO) processing. In order to design high-performance perfectly vertical GCs, we combined the apodization of the grating, to enhance the directivity using inverse electromagnetic design techniques, with a gold reflector to reduce the downward transmission. For a Gaussian beam, vertically incident from free-space, the simulation results show that a coupling efficiency of about 80% is possible for C-band with these novel GCs.*

## Introduction

Silicon photonics is a promising scalable platform that integrates a massive number of devices on the same chip by heterogeneous integration or monolithic integration. It has been efficiently used for optical switching and networking for data centers [1]. Besides, another important application is free-space optical (FSO) processing, which has received more attention in recent years. The mixture of silicon photonics and FSO processing contributes to the miniaturization of FSO systems to the chip scale, which will reduce the size, weight, and power consumption (SWaP) of the optical systems [2]. The optical coupling to the chip is of critical importance, which commonly includes edge coupling and grating coupling. The edge coupler has excellent coupling efficiency due to the better optical mode match between the input optical beam and the edge coupler [3]. Unfortunately, the edge coupler lies on the edge of the chip that should be diced and is limited to linear dimensions. Conversely, due to the three-dimensional (3D) character of FSO, the grating couplers (GCs) that are much more flexible in terms of arbitrary coupling position on the chip are probably the most suitable method for the optical coupling of FSO-to-chip.

In 3D optical information processing, the direction of FSO is usually uncertain, but the most broadly used and typical direction is perfectly vertical to the surface. Even if it's not vertical, it can also be processed by using lens transformation. Therefore a high-efficiency GC designed for perfectly vertical coupling is particularly critical. Actually, the optical mode is generally Gaussian in most FSO systems. In order to design high coupling efficiency GCs, the optical mode of the grating must match the Gaussian [5]. In the case of typical partially-etched GCs, the available degrees of freedom are the period, duty cycle, etch depth, and grating film thickness, which limit the number of optimizable degrees of freedom to only a handful of parameters.

In this paper, we present the results using the inverse design from finite difference time domain (FDTD) numerical simulations and demonstrate an apodized GC with a gold reflector, which shows a high optical coupling efficiency from free space to silicon photonics chips. The apodized grating breaks the symmetry of the uniform grating [5], which leads to single-direction propagation of coupled light and the gold mirror reflects almost all optical power upward to decrease the substrate loss. The rest of the paper is organized as follows. We first introduce basic working principles and theories for the GC. Next, we discuss numerical simulation results for the uniform GCs, GCs with a gold reflector, and apodized GCs with a gold reflector. We then compare and analyze the simulation results of the three types of GCs, leading to the optimal coupling efficiency of more than 80%. Finally, we present the conclusions.

## Device principle and methods

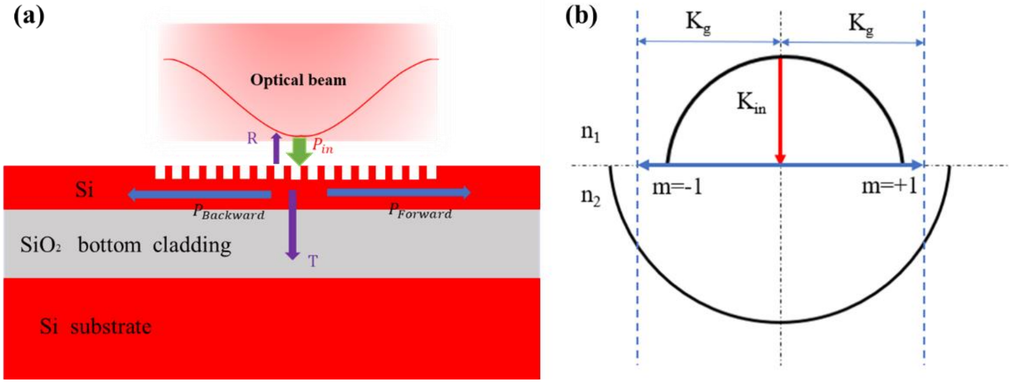

Figure 1. (a) Cross section of the uniform GC; (b) Wave-vector for a perfectly vertical receiving GC.

Considering a receptive GC, the optical beam above the chip along the grating waveguide will be diffracted forward and backward because of the effective index modulation by the etched grooves. Figure 1a shows the schematic cross-section of the standard uniform GC on SOI. The Bragg diffraction condition is the basic principle of GCs. The Bragg diffraction condition reveals the relationship between the input wavevector $K_{in}$ of an FSO beam above the GC surface, the grating vector, and the waveguide vector $K_{wg}$ of the waveguide mode. The Bragg diffraction condition is [6]:

$$K_{in} \sin\theta + mK_g = K_{wg} \tag{1}$$

where $m$ is the grating diffraction order. For the perfectly vertical coupling, $\theta = 0$, the equation can be simplified, and is given by:

$$mK_g = K_{wg} \tag{2}$$

The Bragg diffraction can be better described by a wave-vector diagram. It is very obvious to predict the diffraction order from the wave-vector diagram. As shown in Figure 1b for a perfectly vertical coupling, the angle of the incident optical beam is 0 and then the forward and the backward propagating guided modes will meet the Bragg condition at the same wavelength due to the symmetry, for diffraction order $m = -1$ and $m = +1$. It should be noticed that the wave-vector diagram can only be used to judge the actual diffraction light and the diffraction direction, but can not give the diffraction efficiency of the grating.

## Device design and simulation

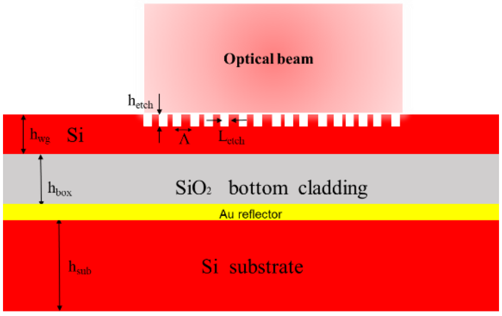

Figure 2. Sectional structure of apodized GC with a gold reflector.

The whole simulation was done using two-dimensional (2D) finite-difference time-domain (FDTD) simulations with the commercial software package Lumerical FDTD Solutions. We simulated the GCs performance for the SOI waveguide structure shown in Figure 2. In order to obtain high coupling efficiency, an apodized grating and bottom reflector were combined into the GCs. Specifically, the apodized grating disturbed the symmetry of a uniform grating to enhance the direction of coupling light to one side. Inserting a bottom reflector, such as a gold reflector with close to 100% reflectivity, redirected the optical power diffracted to the substrate to the grating layer, resulting in high coupling efficiency.

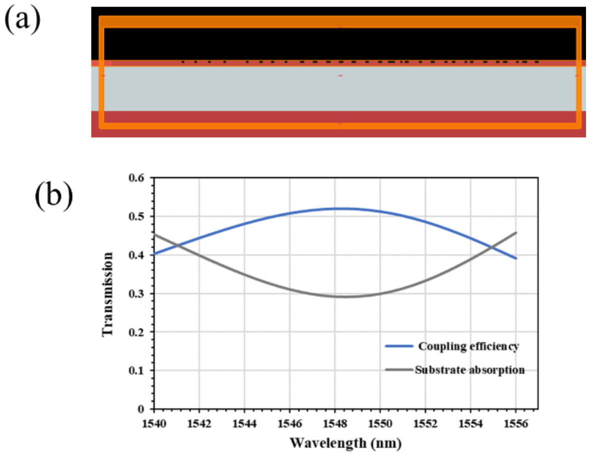

Figure 3. (a) Geometric structure simulated using 2D FDTD; (b) Calculated transmission spectra of perfectly vertical apodized GC

The apodized grating was designed using the gradient-based inverse design which breaks fundamental limits of previous intuition-based device methodology. The inverse design provided a far larger number of degrees of freedom for the grating. For every pitch, two geometric parameters, period and duty cycle, could be varied, with the result that the degrees of freedom depends on the number of pitches shown in Figure 3a. The apodized grating diffracted field was able to match the Gaussian field distribution, leading to a 52% coupling efficiency, as shown in Figure 3b. This is better than the uniform GCs. However, substrate absorption seriously affected the coupling efficiency. To the best of our knowledge, inserting a metallic bottom reflector was the best solution for substrate absorption.

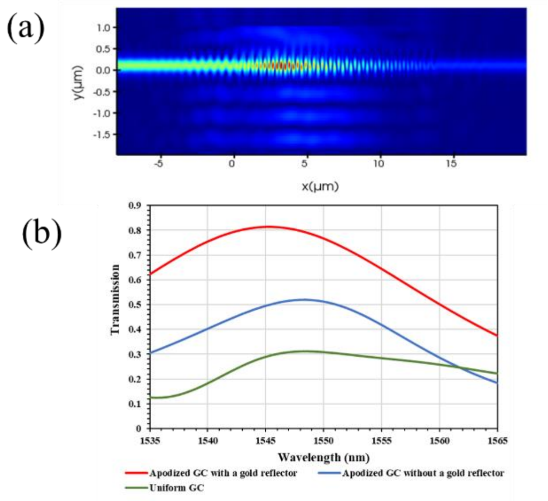

Figure 4. (a) Field intensity profiles radiated from the apodized GC with a gold reflector; (b) Coupling efficiency of the three types of GCs.

To further increase the efficiency of GCs, an 80nm thick gold layer was added under the buried layer to act as a backside metal reflector redirecting the optical power diffracted to the substrate in our design, as illustrated in Figure 2. And the thickness of the device layer and the buffer layer were 220nm and 4μm respectively. The 10μm diameter Gaussian beam was perfectly vertically incident on the GC. The frequency-domain electric field amplitude profile of the GC is given in Figure 4a. Obviously, the optical power was coupled onto the left waveguide directionally. As depicted in Figure 4b, the peak coupling efficiency of the apodized GC with a gold reflector of 81.3% was achieved at 1545nm. The GC had 25 periods and the minimum feature was 100nm, which could be achieved by electron beam lithography or deep ultra-violet photolithography.

## Conclusions

In conclusion, we presented efficient perfectly vertical apodized GCs with a gold reflector using inverse design. We designed and optimized a GC with a high coupling efficiency of 81.3% for C-band, taking advantage of the apodized grating and the gold reflector by improving the diffraction directionality of the grating. The perfectly vertical GCs were believed to be suitable for FSO processing.

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