High-efficiency apodized bidirectional grating coupler for perfectly vertical coupling

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We propose and experimentally demonstrate an apodized bidirectional grating coupler for high-efficiency perfectly vertical coupling. Through grating apodization, the coupling efficiency (CE) can be notably improved and the parasitic reflections can be minimized. For ease of fabrication, subwavelength gratings are introduced, which are also beneficial for the coupling performance. Simulation shows a record CE of 72%. We found the coupler is quite robust to the variation of incidence mode field diameter and fiber misalignment. A CE of -1.8dB is experimentally measured with a 1-dB bandwidth of 37nm.

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Grating couplers (GCs) are widely used in silicon photonic chips [1-3], offering the advantages of large misalignment tolerance, wafer-scale testability, and flexibility in placement. Typically, GCs are designed for interfacing with single mode fibres (SMFs) slightly tilted off vertical to suppress the second-order back-reflection. To improve the CE, high grating directionality and perfect mode matching are pursued with techniques such as using a multiple-etch process [4, 5], backside mirror [6], silicon overlay [7] and apodized gratings [4]. However, less attention has been paid to develop perfectly vertical GCs that make the alignment and packaging process much easier than for the tilted designs. Using perfectly vertical GCs can avoid costly fiber angle polishing required in optical packaging. Such merit makes them very attractive in coupling with multi-core fibers (MCFs) [8, 9] or vertical cavity surface-emitting lasers (VCSELs) [10, 11] where the coupling loss is very sensitive to incident angle and spatial channel positions.

Normally, perfectly vertical GCs have relatively poor CE due to considerable parasitic reflections, namely the waveguide internal back-reflection and the upward reflection. To overcome this drawback, various approaches have been proposed, including the use of additional slits [12], chirped gratings [13], dual layer gratings [14], utilizing a tilted silicon membrane structure [15, 16], blazed anti-back-reflection structures [9], L-shaped grating structures [17] and focused overlay gratings optimized by a genetic algorithm [8]. However, most of the above devices require either additional fabrication steps (etching or deposition) or a feature size below 100nm which is incompatible with 193nm deep UV lithography. Furthermore, very few of the above approaches discuss the alignment tolerance which is also important in real applications.

In this letter, we report for the first time the experimental demonstration of a high-efficiency apodized bidirectional perfectly vertical GC using subwavelength gratings. A calculated CE of -1.43dB (72%) and a measured result of -1.8dB (66%) are achieved. To the best of our knowledge, this device is the most efficient perfectly vertical GC reported to date, realized in a single-etch process without using a silicon overlay or backside mirror. The device is highly efficient and robust to the mode field diameter variation and incidence misalignment, showing a great potential for packaging with a VCSEL light source, as shown in Fig .1(a).

The proposed GC is based on an apodized bidirectional grating structure with subwavelength gratings, as shown in Fig. 1(b). It is designed for a silicon-on-insulator (SOI) wafer with a 340nm-thick top silicon layer and a 2µm-thick buried oxide layer. The gratings are designed to be central symmetric as shown in Fig .1(b), containing 20 grating cells in which 10 cells with SWGs are located at both ends. The SWGs and the grating slits are designed to share the same etching depth. With constant grating period (ΛSWG) and filling factor (FFSWG), subwavelength gratings are utilized to further enhance the CE, reduce the waveguide back-reflection and ensure a minimum feature size beyond 100nm. Because of the symmetry, only 10 grating cells need to be designed. From the view of chip-to-fibre coupling, fibre-chip CE can be expressed as

*η.* (1)

The factor (1 - ρ) represents the retained optical power injected into the grating region after the reflection at the wavelength/grating interface (ρ). Γ is the grating directionality defined as the upward diffraction power divided by the total grating radiation power. *η* corresponds to the mode matching efficiency between the grating diffraction mode and fibre mode. For fibre-to-chip coupling, the CE for perfectly vertical GCs can be simplified as

. (2)

*R* stands for theupward reflection power with vertical incidence. *T* represents theoptical power transmitted towards the silicon substrate, referred as substrate leakage. γ(TE0) is defined as the ratio of the optical power coupled to the fundamental TE mode over the total coupled power into the waveguide. Given the input-output reciprocity, both the upward reflection and the substrate leakage are functions of *Γ* and *η*. The two optical losses can be substantially reduced by improving the directionality and mode matching.



Fig. 1. (a) Schematic diagram of the integration of the proposed GC and a VCSEL light source. (b) The structural view of the proposed apodized bidirectional GC (ABGC) with subwavelength grating sections.

To choose the optimal etch depth, the grating directionality *Γ* and the grating coupling strength *α* are calculated as a function of grating filling factor (defined as *W*/*Λ*, where W is the grating teeth width) and etch depth. The simulation results are shown in Fig. 2(a) and Fig. 2(b). As observed, *Γ* and *α* are both higher with a larger grating etch depth. Normally, a higher value of *Γ* and maximum coupling strength *α* are preferred. However, other design trade-offs need to be considered. When the grating etch depth is 190nm, grating cells with smaller filling factor would be chosen for a fixed coupling strength distribution from each grating pitch and thus this decreases the grating directionality and minimum feature size. According to our simulations, an etch depth of 170nm is chosen to balance both the device performance and fabrication tolerance.

In order to improve the mode matching efficiency, a Gaussian output field profile with 10.4µm beam diameter needs to be obtained by grating apodization. Meanwhile, it is optimal to obtain a diffracted Gaussian beam with radiation center positioned at the center of the gratings. The distribution of the coupling strength *α(x)* should satisfy

(3)

The calculated results are plotted in Fig. 3(a). It should be noted that the lower bound of the integral ‘0’ represents the starting point of the grating radiation and is not coincide with the zero point defined at the grating center. For simplification, the grating length ranges from -6 µm to 6 µm in our calculations. It is observed that *α(x)* is far off symmetry with the grating center. This means a symmetric grating structure () can never produce a perfect Gaussian radiation mode with a unidirectional coupling scheme, especially with the radiation center right in the grating center. Fig. 3(b) shows the calculated *α(x)* corresponding to different grating radiation centers. Clearly, *α(x)* can be tuned to approach symmetry when the radiation center is moved towards the starting point. This

means a Gaussian-like optical beam can be obtained with a symmetric grating structure.



Fig. 2. (a) The calculated grating directionality as a function of grating filling factor and etch depth. (b) The calculated grating coupling strength as a function of grating filling factor and etch depth.



Fig. 3. (a) Calculated grating apodization curve for a diffracted field with a radiation center (RC) overlaping with the grating center. (b) Calculated grating apodization variations with different RCs of diffracted fields. (c) The diffracted fields of unidirectional (Uni-Ediff) and bidirectional coupling (Bi-Ediff) of two different apodization designs.

For the bidirectional coupling scheme [18, 19], two grating radiation fields excited by two incident waveguide modes will produce a quasi-Gaussian mode after constructive interference. As shown in Fig. 3(c), two apodization designs are utilized for comparison of the diffraction field for both unidirectional and bidirectional coupling schemes. Design A corresponds to the filling factor of the 10 grating cells varying from 0.5 to 0.15, and Design B corresponds to a filling factor variation range from 0.33 to 0.09. The bidirectional coupling for Design A has a relatively low mode matching efficiency with the Gaussian field, but a higher CE. This can be attributed to a higher directionality compared to Design B. This indicates a design trade-off between the optimization of mode matching efficiency and directionality.

Based on the above calculations, the grating period and filling factor of each grating cell are carefully designed for an optimal CE. Unfortunately, the optimized GC design has a minimum feature size of only 55nm. For ease of fabrication, we set the minimum feature size to 100nm for our GC design. Subwavelength gratings are therefore employed, which can engineer the effective index of the grating segments due to its non- diffractive behavior [20]. As the subwavelength gratings are designed with period of 400nm in the y-direction, FFSWG is set as a constant of 75% for ease of design and fabrication. A second-order approximation of the EMT [5] is employed to obtain the effective refractive index of the subwavelength gratings, which was verified by 3D FDTD simulations. Thus, the GC design with subwavelength gratings can be optimized using 2-D FDTD simulations with an effective material replacing the subwavelength structure, according to the EMT. As depicted in Fig. 2(a), the grating directionality can be improved by introducing the subwavelength structure. The design parameters for both the original apodized GC (Design I) and subwavelength apodized GC (Design II) are presented in Fig. 4(a).



Fig. 4. (a) The optimized grating cells parameters of Design I and Design II. (b) Calculated electric field profile of the apodized GC.

Fig. 4(b) shows the cross-sectional view of the calculated electric field intensity profile of Design II with subwavelength structures, using a Gaussian mode incidence with 10.4µm mode diameter. The zig-zag field pattern in the waveguide indicate that multiple modes are excited. To investigate this phenomenon, we utilize a mode expansion monitor to calculate the CEs of different modes. It is found that both the fundamental mode and the first-order mode are excited, although the majority of the power is in the fundamental mode. Such a problem can be eliminated by using a SOI platform with a thinner top-silicon layer (e.g. 220nm). The calculated CE (to the fundamental mode) and up-reflection of the uniform GC, Design I and Design II with 2D FDTD method are shown in Fig. 5(a). The peak CE of Design II is 72% (-1.43dB), which is also verified by 3D FDTD simulations with a result of 71.3%. Clearly, the CE of the apodized GC designs are significantly higher than that of the uniform GC. The upward reflection at 1573nm is reduced from 17% of the uniform GC to only 5% (-13dB). According to our simulation, the reflection can be further reduced to -20dB, however, with an expense of 4% decrease in CE. Although the CE is high, there is still room for improvement. Simulations indicated the CE can reach 80% with a backside mirror.

The alignment tolerance of GCs is very important in real applications, especially for the integration with VCSEL lasers. The excess loss resulted from a photonic packaging mainly comes from the mode expansion in the vertical cavity formed by the solder bump and the horizontal misalignment [10]. Thus, it is important to investigate the tolerance to mode field diameter variations and optical alignment. Fig. 5(b) shows that Design II is quite robust to variations of MFD and incidence misalignment. The excess coupling loss is smaller than 0.3 dB within a MFD range from 7 to 13.6 µm. The excess loss caused by ±2 µm waveguide-direction misalignment is only 0.6dB. Such a superior coupling tolerance would be very attractive for flexible applications and low-cost photonic packaging.



Fig. 5. (a) Calculated CE and upwards-reflection (UR) of the uniform bidirectional grating coupler (UBGC), Design I and Design II. (b) Coupling tolerance of Design II on the MFD variations and waveguide direction misalignment.

We fabricated the devices on a 200mm silicon-on-insulator wafer with electron-beam lithography and Inductively Coupled Plasma (ICP) etching. An oxide overlayer of 750 nm is deposited. A test device with a MMI combiner is fabricated as shown in Fig. 6(a). 400µm-long tapers and waveguide bends with 100 µm radius are used. The optical loss of the MMI coupler and output GC can be normalized using a neighboring MZI test device. The SEM images are captured after the oxide cladding was removed in a HF:H2O (1:7) solution for 4 minutes, shown in the inset of Fig. 6(a). Fig. 6(b) shows the measured CE of the fabricated Design II and uniform GC. Clearly, Design II exhibits improved CE and reduced Fabry-Perot (FP) ripples. The CE spectrum is blue-shifted for about 25nm with a central wavelength around 1550nm, which is possibly caused by a 15nm over-etch. The same issue will also lead to increased back reflections. Simulation shows the minimum upward reflection to fibre and waveguide back reflection is increased from 5% (-13dB) and 2% (-17dB) to 9.7% (-10.1dB) and 6.6% (-11.8dB), respectively, assuming the etching depth is 15nm deeper than expected. The CE simulation of Design II is then calibrated. The simulation and measurment results match well. A peak CE of -1.8dB (66%) is obtained experimentally with an excess loss of < 1.35dB within ±3µm fibre displacement. The measured 1-dB bandwidth is about 37nm, which agrees well with the simulation value of 42nm. As shown in table 1, our device exhibits advantages of high efficiency, large bandwidth and ease of fabrication compared with other reported perfectly vertical GCs.

To conclude, we propose and demonstrate a single-etch apodized bidirectional GC for highly efficient perfectly vertical coupling. The optimized design exhibits a peak CE of 72% and a minimum upward reflection of 5% in simulation. This coupler is robust to MFD variations and alignment error. The excess coupling loss for an incident MFD ranging from 7 to 13.6 µm is smaller than 0.3 dB. The excess loss caused by ±2µm waveguide-direction misalignment is 0.6dB. Measurement shows the peak CE reaches -1.8 dB and the 1-dB optical bandwidth is 37 nm. The measured excess loss within a fibre misalignment range of ±3 µm is only 1.35 dB.

**Table 1. Comparison of figures of merits of the perfectly vertical GCs**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Coupling**  **Efficiency (%)** | | **Back**  **Reflection (dB)** | | **1-dB Optical**  **Bandwidth (nm)** | | **Fabrication Steps** | | **Grating Height (nm)** | **Feature Size (nm)** | **Footprint (µm2)** |
| **References** | **Sim** | **Exp** | **Sim** | **Exp** | **Sim** | **Exp** | **Etching** | **Deposition** |
| **[12]** | **50** | **-** | **-** | **-** | **-** | **-** | **1** | **1** | **370** | **160** | **-** |
| **[16]** | **66.2** | **57** | **<-20** | **-** | **33** | **28-39** | **3** | **1** | **340** | **145** | **~60×10** |
| **[14]** | **70** | **-** | **<-20** | **-** | **<35** | **-** | **2** | **1** | **300** | **130** | **-** |
| **[9]** | **78** | **60** | **<-20** | **<-11** | **-** | **-** | **2** | **-** | **220** | **81** | **~200×14** |
| **[9]** | **87** | **71** | **<-11** | **<-6** | **-** | **-** | **2** | **-** | **220** | **<40** | **~200×14** |
| **[8]** | **62** | **54** | **<-20** | **<-16** | **43** | **33** | **1** | **1** | **380** | **206** | **30×24** |
| **This work** | **72** | **66** | **<-17** | **-** | **42** | **37** | **1** | **-** | **340** | **100** | **~800×12** |

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Fig. 6. (a) The microscope photo of the test device with the SEM images of Design II shown in the inset. (b) The measured CE of Design II and uniform bidirectional coupler (UBGC), and the calibrated simulation result of Design II. The inset shows the measured fiber misalignment tolerance of Design II.

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