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A Compact Apodized Grating Coupler for Perfectly Vertical Coupling

(Student paper)

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We present a compact perfectly vertical apodized grating coupler in the C-band on the silicon-on-insulator platform. The optimized and measured coupling losses of apodized GCs are 3.0dB and 5.86dB respectively for the TE mode in the C-band. The apodized grating couplers were fabricated by e-beam with a simple 70 nm shallow etch and a minimum feature of 100 nm, compatible with CMOS technology.

Keywords: *Apodized grating couplers (GCs), coupling loss, compact perfectly vertical GCs, inverse design.*

INTRODUCTION

Grating couplers (GCs) are crucial components in integrated photonics circuits based on the silicon-on-insulator (SOI) platform, which has been widely used for coupling light to and from optical fibers, photodetectors, lasers, and so on. In recent years, the application of GCs for free-space optical (FSO) communication has received more attention, because GCs can also be used to convert an optical waveguide mode to a free-space radiation mode establishing the connection between chips and free-space [1]. Due to the three-dimensional (3D) character of FSO, the free-space optical beams are typically collimated and the optical mode field is Gaussian distributed. Especially in the focal plane array (FPA) systems, the direction of the free-space beams is perfectly vertical to the surface of the silicon chip [2]. Therefore, high-performance GCs as the reception elements are extremely important to realize perfectly vertical coupling. An emission GC for perfectly vertical coupling inevitably induces second-order diffraction resulting in low coupling efficiency (CE). For receiving GC, due to the symmetry of the grating geometry for uniform GC, the leftward and the rightward propagating guided modes of the uniform grating will meet the Bragg condition at the same wavelength also leading to low CE. So far, a lot of effort has already been devoted to the design and optimization of GCs. In order to increase the coupling efficiency, the slanted grating [3], polymer wedge [4], multi-layer gratings [5], and front mirror [6] have been constructed to break the symmetry of geometry and reduce second-order diffraction. However, those complex structures require a complex fabrication technique that is not compatible with CMOS processes. Fortunately, the emerging inverse design approach provides a novel method for the design of GCs, allowing more degrees of freedom to design apodized GCs to match the Gaussian beam for better coupling efficiency. HP LABS had reported experimental coupling losses of 2 dB for inverse-designed grating couplers with a partial etch depth of 159 nm and a Si height of 304 nm [7]. Those dimensions are however not compatible with the current mainstream silicon photonics process with a 220 nm thick silicon device layer.

In this work, through using the gradient-based inverse design methods, we optimize apodized GCs resulting in a Gaussian-like distribution that better matches the input Gaussian beam. The apodized GCs are designed and fabricated on 220 nm silicon-on-insulator with a 70 nm shallow etch, which is provided in most silicon platform foundries. We experimentally demonstrate a high-performance perfectly vertical apodized GC working in the C-band with a compact footprint of 27×40 μm^2. The designed and measured coupling losses of apodized GCs are 3 dB and 5.86 dB for TE mode, respectively. This is the best performance of compact perfectly vertical GCs in the C-band with a minimum feature size of 100 nm, compatible with CMOS technology.

DESIGN

The apodized GCs are designed using the gradient-based inverse design methods [8] that are included in the Python suite called LumOpt. Compared to the previous particle swarm optimization (PSO), relying on random perturbations, the gradient-based optimization algorithm enables obtaining the best solution in fewer iterations. Moreover, gradient-based inverse design methods can realize super multi-parameter optimization through the adjoint method in electromagnetic design problems. For the design of GCs, the number of degrees of freedom for optimization depends on the number of periods of the grating. Because of this, we can design the apodized grating with different leakage factors for every period to achieve the Gaussian distribution of the power field of the grating.

The typical silicon-on-insulator (SOI) structure with a 220 nm silicon device layer and a 2 µm buried oxide layer on a silicon substrate is used to design apodized GCs with 70 nm shallow etching. A Gaussian optical beam at 1550 nm wavelength with an effective mode diameter of 10.4 µm (waist diameter) at an angle of 90° is used as the input beam during the design. The optimization purpose is to improve the mode overlap between the fields scattered from the grating and the predefined field profile. In order to overlap a Gaussian input beam, the intensity of the light diffraction from the grating should increase and decrease gradually along the direction of the grating. This means the leakage factor of the grating should also gradually grow and then fall in the direction of the grating. The apodized grating structure can satisfy this non-linear variation. The gradient-based optimization using the adjoint method is employed to rapidly generate electromagnetic structures with many degrees of freedom using 2D-FDTD simulation. Minimum feature size is enforced at the same time to ensure manufacturability.

Table 1. Width of the ribs and grooves of the apodized grating coupler

P	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R (nm)		454	489	564	881	476	361	468	551	401	397	361	374	396	405
G (nm)	100	100	100	100	109	145	117	124	157	173	190	186	187	155	168
P	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
R (nm)	262	233	102	439	395	424	189	417	125	427	378	410	385	138	351
G (nm)	286	100	173	131	159	136	150	104	140	184	144	192	116	220	171

The schematic diagram of the geometry of the optimized apodized GCs is depicted in Fig. 1(a) and includes 30 periods (P) with the rib (R) and groove (G) dimensions as listed in Table I, where R1 and G1 are the width of the nearest rib and groove to the output waveguide respectively. The minimum width and spacing during optimization are limited by the feature size of 100 nm to simplify fabrication. The different widths of rib and groove for every period break the symmetry of the grating geometry. The simulated electric field of the optimized apodized GCs is shown in Fig. 1(b). And visually it is obvious from Fig. 1(b) that the field profile of the apodized grating is strong in the middle. Most of the optical power is vertically coupled to the left output waveguide and the electric fields on the right side are weak, as shown in Fig. 1(d), proving that the apodized GC obtained by inverse design exhibits a high directivity and exceeds 50% (3.0 dB) coupling efficiency. As Fig. 1(e) shows, the normalized intensity of optical diffraction from the apodized grating results in a Gaussian-like distribution, which better matches the input Gaussian beam to achieve higher coupling efficiency.

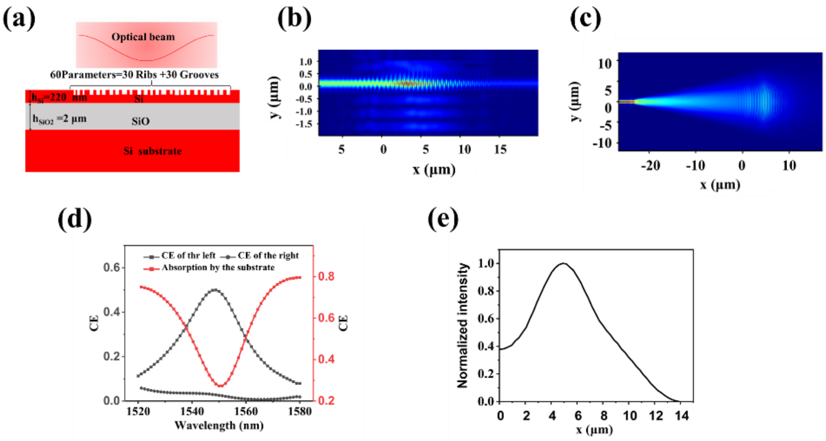

Fig. 1. (a) Schematic diagram of the geometry of the apodized GCs. (b) simulated electric field of the apodized GCs. (c) Electric field amplitude distributions of apodized grating coupling form 3D-FDTD simulation. (d) Coupling efficiency of the apodized GCs. (e) The intensity of the light distribution along the direction of the grating.

To further validate the accuracy of the geometric structure, the apodized grating coupler is then simulated in the 3D-FDTD simulation environment. Moreover, the focusing grating with circular lines is used to decrease the footprint, making the GC more suitable for high-density photonics integrated circuits. The electric field amplitude distributions of the optical field at 1550nm are illustrated in Fig. 1(c). And the light is coupled into the left waveguide by the compact taper.

FABRICATION AND EXPERIMENT

We fabricated apodized GCs on a standard SOI wafer with a silicon layer thickness of 220 nm and BOX layer thickness of 2 µm. The grating couplers and the connecting waveguide are defined with 70 nm shallow etch using electron beam lithography (EBL) and inductively coupled plasma (ICP) etching. The minimum feature size of 100 nm can be fabricated using these processes to attain the minimum feature of the designed apodized GCs. To enable measurement, two GCs with the same structure are connected to a 500 µm-long straight waveguide. Fig. 2(a) shows an optical microscope image, a zoom-in on one GC, and a scanning electron microscope (SEM) image for apodized GC. The fabricated focusing apodized GCs have a compact footprint of 27×40 µm^2.

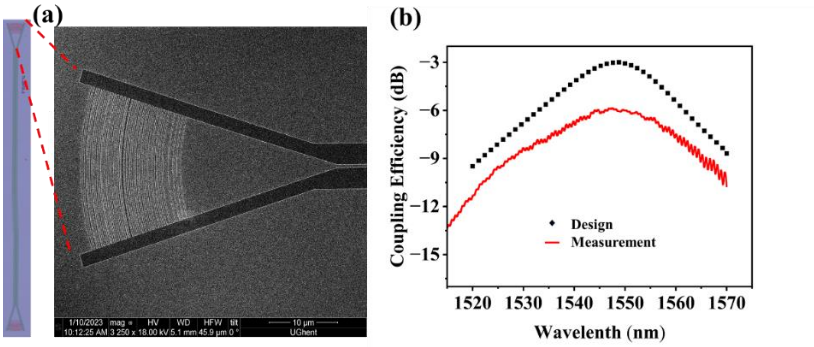

Fig. 2. (a) Microscope image of the fabricated device and the zoom-in SEM image of the apodized GC. (b) Designed and measured coupling loss of the apodized grating coupler.

For the optical characterization, we used the optical measurement setup, including a tunable laser a polarization controller, and an optical power meter. The fundamental mode of standard SMF-28 fibers, which are used as input and output couplers for 0°, can be regarded as a free-space Gaussian optical beam with 10.4 µm diameter (waist diameter). The measured coupling efficiency of the apodized grating coupler over a wavelength range (1520 nm ~ 1570 nm) is shown in Fig.2 (b). The peak of the coupling loss is 5.86 dB/facet for the TE mode at the wavelength of 1547 nm. It can also be seen from Fig.2 (b) that the transmission spectrum of the apodized GC is smooth, which proves that the back reflection of the apodized GC is effectively suppressed. The measurement results are worse than the design results. We suppose that this is due to the fabrication process. As measured by SEM, each period of the fabricated grating is 5-15nm narrower than that of the design. Therefore, we plan to optimize the fabrication process to improve the performance of GCs.

DISCUSSION

In conclusion, we proposed compact apodized GCs using the inverse design on the SOI platform for perfectly vertical coupling. The optical scattering of the optimized apodized GCs exhibits a Gaussian-like distribution that better matches the input Gaussian beam, resulting in higher coupling efficiency. The simulated and measured coupling losses of optimized apodized GCs are -3.0 dB and -5.86 dB for TE mode, respectively. The footprint of the compact focusing apodized GCs is 27×40 µm^2, making it suitable for lager-array integration. To the best of our knowledge, the experimental coupling efficiency is the best realized so far on 220 nm thick Si with just a single 70 nm etch depth and no bottom mirror. In addition, the proposed compact apodized GCs are compatible with CMOS technology.

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