High Coupling Efficiency Waveguide Grating Couplers for Bound-states-in-the-Continuum waveguide on Lithium Niobate

(Student paper)

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We propose a new approach to increase the coupling efficiency of grating couplers in the low-index-contrast bound-states-in-the-continuum (BIC) waveguides. The design is based on patterning a high refractive index material (polysilicon) on the low-index BIC circuits formed on lithium niobate. Coupling loss for TM as low as 1.33 dB is predicted.

Keywords: *Integrated optics, waveguide gratings, lithium niobate, bound states in the continuum.*

INTRODUCTION

Waveguide grating couplers (GCs) are an attractive approach to couple light between optical fibers and integrated waveguides, offering the advantages of large fabrication tolerance, wafer-scale testing, and arbitrary positioning on the chip, without needing the facet polish or high alignment tolerance associated with edge couplers. GCs can also be integrated with waveguide photodetectors and lasers [1, 2]. Using the optimized shift-pattern overlay method [3, 4], coupling efficiency of silicon grating couplers as high as -0.89 dB was experimentally realized using only photolithography with a standard silicon photonics foundry process [5]. Lithium niobate on insulator (LNOI) has attracted much attention, offering the advantages of high modulation bandwidth and low modulation voltages [6]. One important block of development in LiNbO3 photonics is the high-efficiency grating coupler. However, in the lithium niobate platform, realizing high coupling efficiency grating coupler remains a challenge. This is not only due to the mode mismatch between the fiber and waveguide, but also due to the smaller refractive index contrast. To improve the coupling efficiency of gratings on LNOI platform, the use of a bottom metal reflector to improve the directionality was needed. Using this approach, the best results experimentally obtained for TM coupling was 2.1 dB [7] with very fine structure due to the grating apodization, and 0.89 dB was reported for TE coupling [8], but the fabrication of metal mirrors adds additional fabrication processes of substrate thinning and backside metal deposition. Another challenge is that the etching lithium niobate typically produces some off-vertical etch angle as it is very difficult to consistently achieve vertical etching. To avoid the difficult etching of lithium niobate, silicon on lithium niobate based grating couplers have been proposed. However, the coupling efficiency reported for silicon directly on lithium niobate gratings was only about -18 dB [9]. Silicon nitride gratings on lithium niobate have much better results, with silicon nitride gratings on LNOI attaining 4.02 dB [10] and 5.82 dB [11] coupling losses.

In this paper, we propose a novel approach that can significantly improve the coupling efficiency beyond that attained for the silicon nitride gratings on LNOI. The basic idea is based on taking advantage of the guiding of light using BIC on the LNOI platform [12], and using the high refractive index of a polysilicon overlay layer. The high refractive index overlay has been previously used in silicon waveguide gratings [13]. On the BIC based LNOI platform, the main difference is that the high refractive index overlay forms a slot waveguide in the vertical direction, and the structure moves more of the mode into the etched polysilicon grating region, thus increasing the grating strength. Besides, the vertical slot structure can also be regarded as a cavity in the vertical direction. By carefully designing the thickness of the low index silica and the upper polysilicon layer, we can use the cavity to improve the coupling efficiency of the grating. The 3D FDTD simulation of the proposed structure predicted the coupling losses to be as low as 1.33 dB. The proposed structure in Fig. 1 does not need the etching of the LiNbO3, and the minimum feature size required for the grating is 387 nm. The grating design is therefore compatible with patterning by the deep ultraviolet photolithography tools commonly available in foundries, and the grating is therefore suitable for large-volume production using photolithography, unlike finer nanostructured gratings that require electron beam lithography. The silica deposition on the LNOI and the deposition of the polysilicon layer are standard processes commonly available in silicon processing facilities. Also, this design method does not require substrate thinning for adding bottom metal reflectors (as done in references [7, 8]) to improve the coupling efficiency.

Device Structure and simulation

The 2D and 3D schematic diagram of the proposed waveguide grating coupler on LNOI (X-cut) is shown in Fig. 1. The structure is formed by the deposition of silica on the LNOI wafer, and channel waveguides are formed by etching the silica at an appropriate width (2.3 μm) to create the low-loss BIC channel waveguide. In the BIC waveguide most of the mode is confined in the high index lithium niobate [12]. The waveguide grating is formed by depositing, patterning and etching a polysilicon overlay on the top silica. As the deposited silica has a smaller refractive index than the polysilicon or the lithium niobate, the polysilicon-silica-lithium niobate structure will form a slot waveguide in the vertical direction. The slot waveguide pulls more of the mode into the silica region [14], and there is thus better optical overlap with the polysilicon grating, improving the grating strength. Besides, the high(poly-Si)-low(silica)-high(LiNbO3) refractive index structure can form a cavity in the vertical direction. With careful design of the thickness of the silica layer and polysilicon layer, we can improve the directionality and have most of the light emitted upwards to further improve the coupling efficiency of the grating. In our proposed design, the simulations were for an X-cut LNOI wafer, but the same approach can be applied to Z-cut LNOI wafers. In this paper, the BIC mode is used simply to avoid the practical difficulty of etching the LiNbO3 layer. For the BIC mode, most of the light in the waveguide region is still in lithium niobate, and it is possible to use the LNOI BIC waveguide for acousto-optic modulation [15] and electro-optic modulation [16]. Thus, the method we proposed here works effectively as a grating coupler and can also utilize the excellent electro-optic properties of the LNOI platform. The working principle described in this paper can also be used with designs where the LiNbO3 layer is etched to form conventional channel waveguides. We designed the polysilicon grating to couple the quasi TM mode into the BIC channel waveguide.

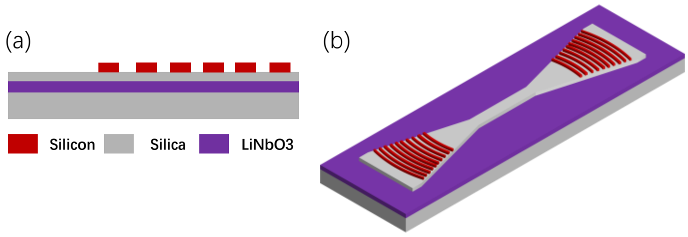

Fig.1 Schematic of the high coupling efficiency grating for lithium niobate on insulator. (a) 2D cross-section view. (b) 3D view.

We carried out design optimization, using the genetic algorithm to optimize the thickness of the silica layer and the polysilicon grating, with each period optimized using a different duty cycle. The optimization algorithm was used for an LNOI wafer with 400 nm thick lithium niobate and silica substrate of 2 μm thickness on a silicon handle wafer. The optimization algorithm is similar to the one we used previously for silicon grating couplers [17], and the final optimized parameters of the proposed grating are shown in Fig.2. There are some discontinuities in the parameters in Fig.2, as is needed to engineer the grating strength for improved matching of the diffracted mode with the optical mode and in reducing the back reflection, and which was also evident in the vertical silicon grating coupler design [17].

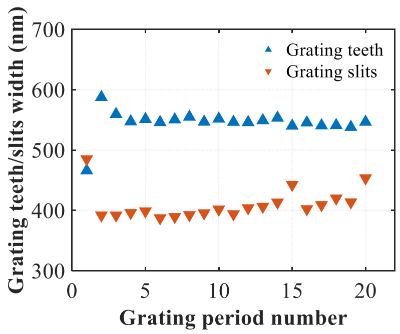

Fig.2. Final structural parameters after optimization for the grating coupler.

The optimized grating has a minimum feature size of 387 nm. The final optimized thickness of the deposited silica layer and polysilicon layer are 300 nm and 300 nm, respectively. The top polysilicon overlay is fully etched, which simplifies the fabrication process. As the BIC waveguide is quite wide (2 μm), the alignment of the polysilicon mask with the waveguide falls well within the overlay accuracy of photolithography, and the design is compatible for fabrication by photolithography. The proposed grating coupler has high coupling efficiency for coupling to standard single-mode fiber with a core diameter of 9 μm and mode field diameter of 10.4 μm at 1550 nm. The optimized grating efficiently couples the TM polarization into the BIC waveguide. The simulated transmission spectra of the optimized waveguide coupler, obtained from the final 3D FDTD simulation, is presented in Fig.3. The final optimized grating coupler has a predicted coupling efficiency of -1.33 dB at 1548.4 nm and 3 dB bandwidth of 46 nm from 1517 nm to 1563 nm.

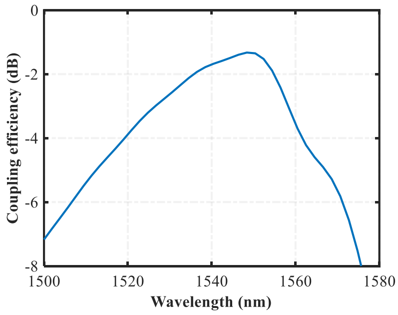

Fig.3. Coupling efficiency spectra of the final optimized grating coupler.

DISCUSSIONS

We proposed a new high coupling efficiency grating coupler in the LiNbO3 platform using a high index polysilicon grating on silica. The vertical slot waveguide and cavity structure enable the grating to provide high coupling efficiency. The proposed grating coupler has a minimum feature size of 387 nm and is compatible for fabrication using photolithography. 3D simulation results predict a coupling efficiency of -1.33 dB at 1548.4 nm with a 3 dB bandwidth of 46 nm from 1517 nm to 1563 nm. The fabrication of the grating coupler is still underway at the time of writing this summary, but we expect to present experimental results at the conference to validate the simulations.

Acknowledgements

This work was funded by Hong Kong Research Grants Council General Research Fund 14207021.

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