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Grating coupler on single-crystal lithium niobate thin film

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ABSTRACT

The grating coupler on single-crystal lithium niobate thin film (lithium niobate on insulator, LNOI) was designed. A bottom reflector was added in the LNOI material to improve the coupling efficiency. The grating structure was optimized by FDTD method. The material parameters such as layer thickness of lithium niobate thin film, SiO_2 thickness were discussed with respect to the coupling efficiency, and the tolerances of grating period, etch depth, groove width and fiber position were also studied systematically. The simulated maximum coupling efficiency from a grating coupler with (without) bottom reflector to a single-mode fiber is about 78% (40%) in *z*-cut LNOI for TE polarization.

1. Introduction

Lithium niobate on insulator (LNOI) is an interesting platform for integrated photonics due to its high refractive-index contrast, excellent nonlinear-optic and electro-optic properties [1–3]. In recent years, many devices have been developed based on LNOI, such as low-loss waveguides [4,5], micro-disk and micro-ring resonators [6–8], efficient electro-optical modulators [9], and Y-branch splitters [10,11]. However, there exist difficulties in coupling light from a single mode fiber to LNOI devices due to the large mode mismatch between the single-mode fiber and the submicron-LNOI-waveguide. Grating couplers have been successfully demonstrated on SOI [12–16], and it can be placed anywhere on a chip to couple light in and out. Such a surface coupler which requires no facets polishing and allows wafer-scale testing is attracting growing attention and research enthusiasm. On LNOI material, by adding a refractive index matching layer on top of lithium niobate thin film, a peak transmission of −4 dB in simulation and −12 dB in experiment per coupler was demonstrated [17]. By using inductively coupled plasma (ICP) method following electron beam lithography (EBL), a peak transmission of −4.58 dB in simulation and −9.45 dB in experiment per coupler was demonstrated [18]. Grating couplers on LNOI still attract further systematic research.

In this paper, a grating coupler is designed with two dimensional simulation and the parameters of the grating are systematic studied. Other than adding a refractive index matching layer on the LNOI top, a bottom reflector is added between the SiO_2 layer and the LN substrate to improve the coupling efficiency of the grating coupler. The maximum coupling efficiency for grating coupler with a bottom reflector is 78% (−1.08 dB) for TE polarization, and the 3-dB-bandwidth is 98 nm.

2. Design of grating coupler

When a beam of light transmitted through a grating, light would be diffracted and radiated, the first order diffraction could be described by Bragg condition [19]:

$$N_{eff} - n_{top} \sin\theta = \frac{\lambda}{\Lambda} \quad (1)$$

where N_{eff} denoted the effective index of LNOI waveguide mode, n_{top} was the refractive of air layer ($n_{top} = 1$), Λ was the period of the grating, λ meant the free-space wavelength ($\lambda = 1550$ nm), θ was the fiber angle with respect to the normal direction of surface. The above equation was used to obtain the range of grating period (Λ), which was used in FDTD for the later calculation and optimization.

To avoid a high second order reflection at the waveguide-grating interface, θ was chosen to be $8^\circ - 10^\circ$ [20]. The effective refractive index should fulfill the inequality: $n_{sio_2} \le N_{eff} \le n_{LN}$, where n_{sio_2}/n_{LN} was the refractive index of silicon dioxide (1.46)/lithium

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niobate thin film (2.138). By substituting the inequality into Eq. (1), an estimated range of Λ with respect to the fiber angle would be obtained: $\lambda/(2.138-\sin\theta) \le \Lambda \le \lambda/(1.46-\sin\theta)$. When the fiber angle tilted from 0° to 10°, the Λ could be in the estimated range of 725 nm $\le \Lambda \le$ 1204 nm.

The above Λ could only be used as reference value and a further numerical optimization should be taken into practice. Finite-Difference Time Domain (FDTD) method with perfectly matched layers boundary conditions (PML) was used in the simulation. The FDTD method was a direct time and space solution for solving Maxwell's equations in complex geometries. By performing Fourier transforms, the electromagnetic fields as a function of frequency or wavelength could be calculated, thus the complex quantities, such as the Poynting vector, normalized transmission, and far field projections could be obtained. PML boundaries could absorb electromagnetic energy incident upon them, allowing radiation to propagate out of the computational area without interfering with the field inside. The structure considered and simulated was shown in Fig. 1. From bottom to top were $LiNbO_3$ substrate, Au layer, buried oxide layer and $LiNbO_3$ thin film. The ordinary and extraordinary refractive indices of the LN thin film at wavelength 1550 nm were set to be 2.2112 and 2.138 in simulation, respectively. The values were calculated by Sellmeier equation and they showed excellent agreement with experiment [21]. Grating was etched into the $LiNbO_3$ thin film. It contained a group of continuous grooves with 12 μm width, which could match the fiber mode size in x direction. The length of grating zone was approximately 15 μm in y direction. The optical fiber was tilted at an angle θ to the normal direction of surface to avoid a high second order reflection.

The complex three-dimensional problem could be reduced to two-dimensional because the width of the LNOI waveguide was much larger than the height [22]. The optical fiber mode field was approximated by a Gaussian beam with a beam diameter of 10.4 μm in calculation, which was a typical value for single mode fiber. Coupling efficiency was calculated from the LNOI waveguide to the single mode fiber. The period was allowed to change in steps of 10 nm in the interval from 725 nm to 1204 nm.

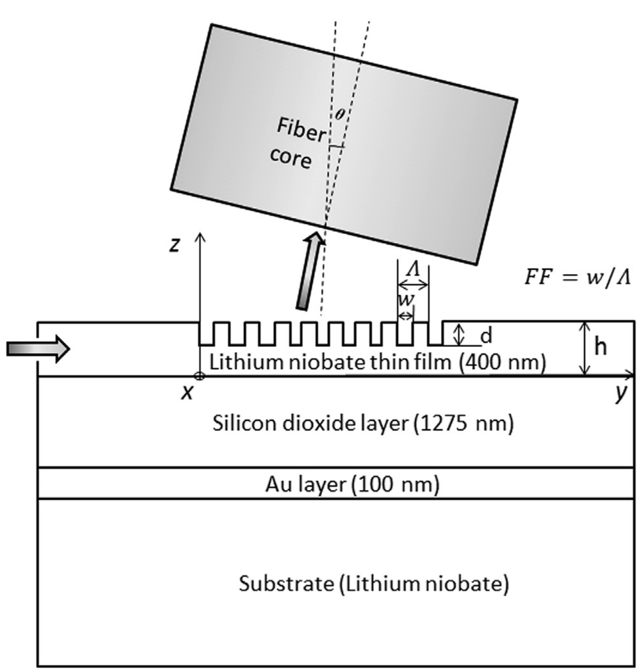

Fig. 1. Schematic structure of the proposed grating coupler in LNOI.

3. Results and discussion

The coupling efficiency result was shown in Fig. 2. Without Au reflector, the maximum coupling efficiency was approximately 40% (cyan line), with about 40% light lost to the lithium niobate substrate and 20% diffracted to the surrounding. When a thin layer of Au was added between the SiO_2 layer and the lithium niobate substrate, it would work as a mirror. It reflected the power coupled towards the substrate, so the coupling efficiency would be improved by the reflected light. For coupler with a bottom reflector, the maximum coupling efficiency would reach to 78% with a reflection less than 3% at the waveguide-grating interface near 1550 nm, and the 3-dB-bandwidth was 98 nm. But there was still about 20% scattered to the surrounding (compared the green-line and black-line). This might due to the identical grating teeth, etch depths (d) and periods, an uniform grating coupler would yield an exponentially decaying power along the y direction, so there would be a mismatch between the out-coupled field and the fiber mode (Gaussian beam), led to the result discussed above.

To achieve the best coupling efficiency, the grating coupler parameters should be designed and controlled carefully. But in practice, these parameters might have fabrication or setup errors (such as fiber angle) more or less. It was necessary to study the effects of the fabrication or setup tolerances on the coupling efficiency. The parameters considered were as follows: fiber angle, fiber position, layer thickness of $LiNbO_3$ thin film (h), d, Λ and filling factor (FF, defined as the fraction of the period occupied by the groove width).

The coupling efficiency with respect to SiO_2 thickness was shown in Fig. 3. The curve oscillated between the minimum and the maximum with the SiO_2 thickness. A similar phenomenon was observed in SOI gratings [23]. The reason might be that when a beam of light was diffracted by the grating region, parts of light would radiate upward, and parts of light would scatter to the substrate and be reflected by the Au/SiO_2 interface. When the reflected light and the incident light met the phase matching condition, the field intensity and coupling efficiency would be enhanced, otherwise would be weakened. The best thickness of SiO_2 was determined by the parameters, such as λ and θ. Therefore, thickness of buried oxide layer should be chosen properly in the fabrication of LNOI, and for the grating structure in this paper, the optimal thickness was set to be 1275 nm.

The alignment tolerances for both positional and angular errors

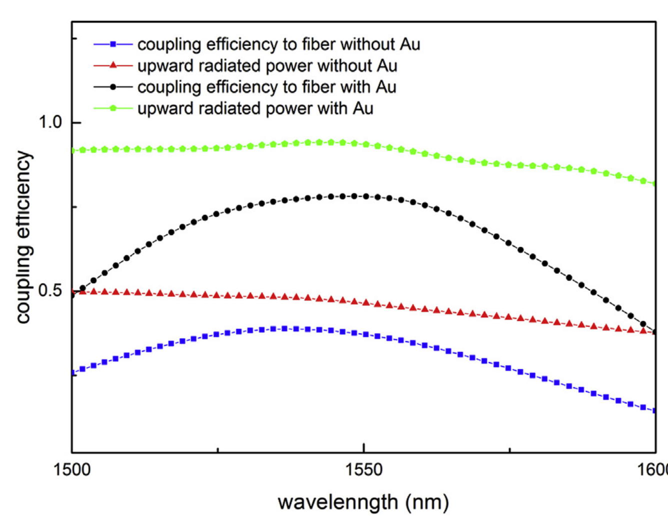

Fig. 2. Calculated result for grating coupler in z-cut LNOI for TE polarization (Λ = 928 nm, FF = 0.5, h = 400 nm, d = 160 nm, θ = 8°).