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Electro-optical modulator based on photonic crystals on innovative thin films $LiNbO_3$

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Abstract. We report on the design and the realization of an electro-optic modulator based on photonic crystals in a thin film lithium niobate ($LiNbO_3$). The device has been numerically optimized using an adjoint method to allow the modulation of either a TE or a TM mode. The fabrication relies on an alternative fabrication platform compared to commercial thin film layers.

Introduction

Artificial intelligence is a new global challenge for the 21st century. While electronics begins to reach its physical limitations [1] restraining the potential development of computing material, optics appears as the solution to support the development of artificial intelligence. Optics allows not only a natural speed-up since the propagation speed of photons is much higher than that of electrons, but also a reduction of the ecological footprint by a lower power dissipation [2]. The electro-optical modulator is the key component in the process of manipulating the electromagnetic field (phase and amplitude). In addition, the modulator footprint needs to be minimal to allow the large density integration required by computational photonic architectures.

We propose here an ultra-compact electro-optical modulator, with a total active length of 6.5 µm and fully integrated on a suspended $LiNbO_3$ waveguide of effective width of 10 µm embedded in a $LiNbO_3$ membrane. In addition to its high contrast index, the suspended $LiNbO_3$ waveguide presents electro-optical properties allowing the use of Pockels effect to modulate a signal.

The modulator design relies on novel optimization algorithms. The device addresses modulation of either a TE or a TM guided mode in the telecommunications C-band spectral range. Compared to previously reported $LiNbO_3$ photonic crystal modulators with high insertion losses of 12 dB or more [3, 4], our device promises lower insertion losses through better light confinement inside a membrane surrounded by adiabatic transitions. The proposed fabrication method is an alternative to the ion slicing technique used for lithium niobate-on-insulator (LNOI) wafers. Our approach is based on plasma etching followed by precise dicing [5], which leads to a considerable reduction in power consumption in the fabrication of the thin-film-based component.

1 Theoritical results

The principle of the proposed modulator lies in the excitation of a photonic crystal cavity mode at the telecom wavelength. The photonic crystal is etched in the waveguide inscribed in a thinned lithium niobate membrane after titanium diffusion. The electro-optical modulation is achieved by electrodes placed on both sides of the photonic crystal as depicted in Fig. 1. The high r_{33} electro-optical coefficient is exploited by choosing an X-cut wafer with light propagation along the Y-axis. By applying an external electric field, the index of the niobate will change via the electro-optical effect (Pockels effect) leading to a spectral shift of the cavity mode and thus to a change in the transmission through the component.

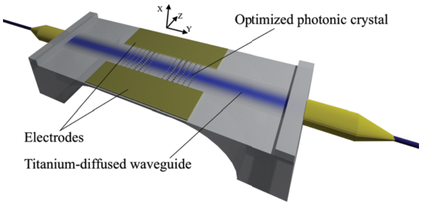

Figure 1. Illustration of the proposed modulator. Dimensions are exaggerated. The blue area represents the index gradient of the titanium diffused-waveguide. The guide is thinned to a membrane in its center by a precision saw where the photonic crystal is inscribed.

The photonic crystal we propose has a geometry based on cylindrical air holes of 150 nm radius within a square lattice of 430 nm period providing a photonic bandgap centered on the telecom wavelength. The cavity is then obtained by inserting a line defect in the crystal center, perpendicularly to the waveguide axis. The wavelength of the cavity mode will be controlled via the size of the defect so that it matches that of the optical telecoms. Numerically, we have determined the whole geometry (radii of air holes at the periphery of the cavity and the defect size) by using an adjoint-based optimization [6] on plane-wave equation results taking into account the crystalline axes.

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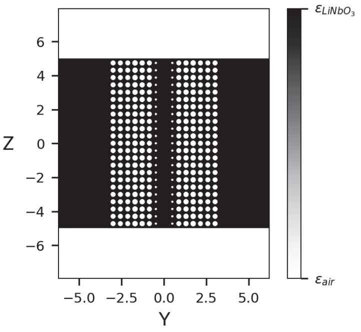

Figure 2. Profile index of the optimized photonic crystal

The optimization process leads to a structure with a cavity mode wavelength for each polarization, TE and TM, spaced by 95 nm from both sides of the 1550 nm working wavelength. The Fig. 2 shows the cavity which is made of 5 lines of holes placed on each side of the device with various diameters.

The transmission of the structure is calculated using the Finite Difference Time Domain (FDTD) method and a broadband source. The anisotropy of the crystal is taken into account by considering either the ordinary or extraordinary refractive index of $LiNbO_3$ in accordance with the considered polarization propagated within the waveguide. Fig. 3 presents the obtained normalized transmission for the TE and TM polarization states.

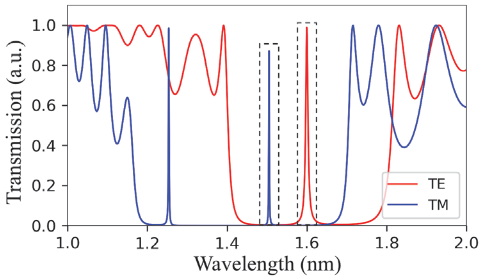

Figure 3. Transmission spectrum of the optimized photonic cavity (after displacement and modification of hole radii)

2 Fabrication

$LiNbO_3$ is known to be a difficult material to nanostructure. The most common method is dry etching by reactive-ion etching (RIE) assisted using fluorinated compounds.The reaction between lithium atoms and the fluorinated gases however leads to the creation of lithium fluoride (LiF) molecules which degrade the fabricated structure quality by redeposition on the already-etched surface. To avoid this issue, $LiNbO_3$ etching is only carried out using an inert gas: pure argon.

Literacy reports the use of a high-power (several hundreds of Watts) ion-etching machine (ICP-RIE - Inductively Coupled Plasma Reactive Ion Etching) where the etching is enhanced using plasma to increase the ion energy [7]. Even with this solution, obtaining the submicrometric resolution for photonic crystals remains a challenging task for collective fabrication. Indeed, the necessary etching power induces heating of the thin film.

Another difficulty arises from the substrate itself. To obtain an LNOI wafer, multiples critical fabrication steps are involved including molecular bonding, ion slicing, and mechanical polishing [8]. As a result, the supply of LNOI wafers is less accessible than bulk wafers.

To solve these two problems, the etching and the substrate availability, a technology based on dicing-polishing is used to make the etching step prior to the membrane. By structuring the bulk material, the thermal conduction is improved and the heating effect is limited. Thus, the etching of the crystals can be carried out on the bulk substrate by a simple plasma etching through a resist mask. The membrane is produced afterward by dicing polishing.

The Fig. 4 shows one of our preliminary results of $LiNbO_3$ crystals etched with the process. A 1 µm-thick electronic positive resist mask made of AR-P 6200.18 is deposited. The etching is then realized under pure Argon etching at a low pressure of 2.5mTorr with an applied power of 150W and a temperature of 5°C in a Corial 200R RIE system.

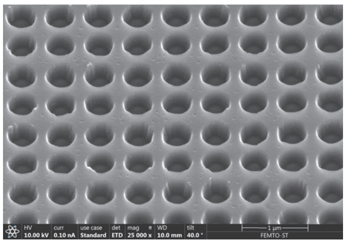

Figure 4. $LiNbO_3$ photonic crystals made by collective etching

The membrane being suspended in air, presents an enhanced light confinement. Another advantage of our fabrication method relies on a reduced ecological footprint. Indeed, our method requires only 1.26 kWh per membrane, so that even for a six-inch wafer with 400 membranes, the energy consumption is still more than 200 kWh lower than for LNOI manufacturing [8].

Conclusion

We have proposed a structure made by optimized photonic crystals embedded in $LiNbO_3$ waveguide. To obtain a better light confinement, a suspended membrane guide has been chosen to host the photonic crystals. We also show how high-resolution nanostructures can be made by collective etching. This method opens the way to $LiNbO_3$ photonic platforms with increased integration capacity.

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