EUROPEAN CONFERENCE ON INTEGRATED OPTICS

Design of a Broadband Polarization Controller Based on Silicon Nitride-Loaded Thin-Film Lithium Niobate

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Polarization controller is designed on Si_3N_4-loaded thin film $LiNbO_3$. Broadband operation in the wavelength band from 1.45 to 1.65 µm is achieved by using a mode evolution TM/TE splitter/converter, two mode evolution 3-dB couplers and two electro-optic phase shifters. A single TE-mode output can be can be achieved by applying control voltages lower than 5 V for any input polarization state.

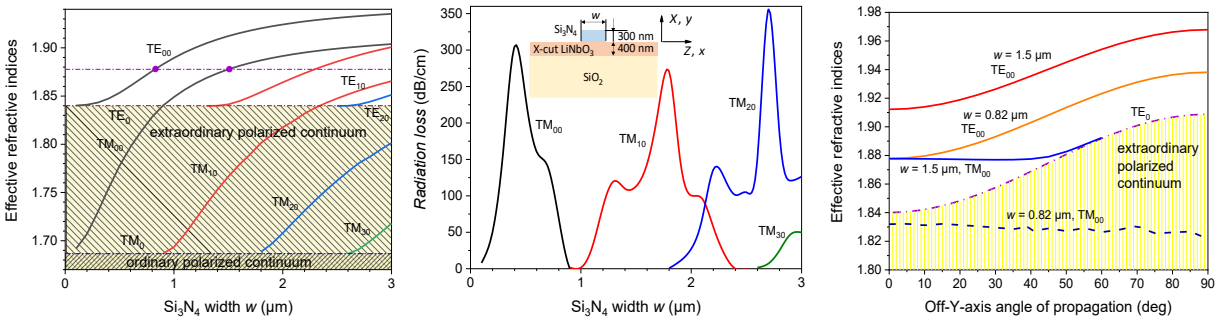
Keywords: *Polarization control, mode evolution splitter, broadband 3-dB couplers*

INTRODUCTION

Polarization controllers are important components of optical communication systems. Integrated-optic polarization controllers in Ti:$LiNbO_3$ waveguides have been described already several decades ago [1]. Recent development of the lithium niobate on insulator (LNOI) technology [2] allows to design more compact electro-optic devices with lower control voltage [3]. Our design, although similar to that described in [3], was proposed independently and differs in several features. Firstly, we choose the silicon nitride-loaded LNOI waveguides [4, 5] as an alternative to $LiNbO_3$ rib waveguides in order to avoid uneasy etching of the $LiNbO_3$ crystal. Secondly, to ensure broadband operation, we implemented an adiabatic mode evolution TM/TE coupler [6] as a polarization splitter/converter, and thirdly, mode evolution 3-dB couplers, somewhat similar to those described in [7] and [8], are designed. An X-cut $LiNbO_3$ slab is chosen for efficient electro-optic phase shifting. Numerical simulations by COMSOL Multiphysics and the proprietary Fourier modal method [9] predicted the total loss in the polarization controller of about 0.5 dB in the range from 1.45 to 1.65 µm. The operation voltage of phase shifters, required to direct the full input power to the single TE_{00} mode of the output port, was found to be lower than 5 V.

PROPERTIES OF Si_3N_4-LOADED LNOI WAVEGUIDES

The thickness of the $LiNbO_3$ slab was chosen as 400 nm, the Si_3N_4 layer is 300 nm thick. Air is used as an upper cladding, since any higher-index overlayer reduces the strength of the required TM/TE coupling. The dispersion and radiation loss curves of the waveguides oriented along the Y-axis of the $LiNbO_3$ crystal are shown in Figs. 1(a) and 1(b), respectively. The waveguide cross-section is shown in the inset of Fig. 1(b). Fig. 1(c) shows the angular dependences of the effective refractive indices for propagation declined from the crystal Y-axis by an angle. Results were calculated for the wavelength of 1550 nm using COMSOL mode solver.



(a) (b) (c)

Fig. 1. Dispersion properties of the Si_3N_4-loaded LNOI waveguides. X, Z are crystal axes of the $LiNbO_3$ slab, x, y are coordinates.

The TE modes propagate without radiation into the $LiNbO_3$ slab since their effective indices are larger than the effective index of the planar TE_0 mode of the $LiNbO_3$ crystal slab. The TM modes–although predominantly ordinary polarized–are free of radiation losses only for wide enough waveguides.

POLARIZATION CONTROLLER

The configuration of the polarization controller is schematically shown in Fig. 2. The TE-polarized input mode propagates through the TM/TE splitter/converter essentially unaffected, while the TM-polarized mode is converted into the TE mode of the bottom waveguide. Two cascaded combinations of the phase shifter and the 3-dB coupler are used to coherently combine the TE-polarized fields from both output ports of the TM/TE splitter/converter into a single output port. It can be easily shown that by proper adjustment of the relative phase of inputs of any (lossless) 3-dB coupler, the amplitudes in both output ports can be equalized. The second phase shifter is used to adjust the relative phase so that both input waves are coherently superposed in one of the output ports of the second 3-dB coupler. The control voltages U_{eq} and U_c of the phase shifters can thus be optimally adjusted by minimizing the output from the other port.

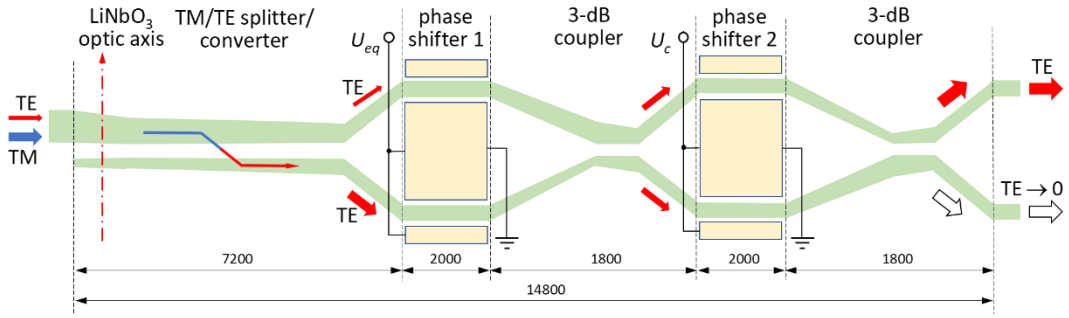


Fig. 2. Configuration of the polarization controller.

ADIABATIC MODE EVOLUTION TM/TE COUPLER

The design of an adiabatic mode evolution TM/TE coupler started with the observation that the effective indices of the TE_{00} mode of the waveguide of the width of 0.8 µm and of the TM_{00} of the waveguide of the width of 1.5 µm are nearly identical (see the violet dots in Fig. 1(a)). If these waveguides come close to each other, the modes get hybridized due to the 3D vector character of their electric fields. This is reflected by the appearance of the avoided crossing of their dispersion curves [6] which corresponds to the polarization conversion during the mode evolution. The spectral position of the avoided crossing depends on the waveguide widths and on their separation. Proper adiabatic shaping of the coupler is required to ensure efficient polarization conversion in the required wavelength band.

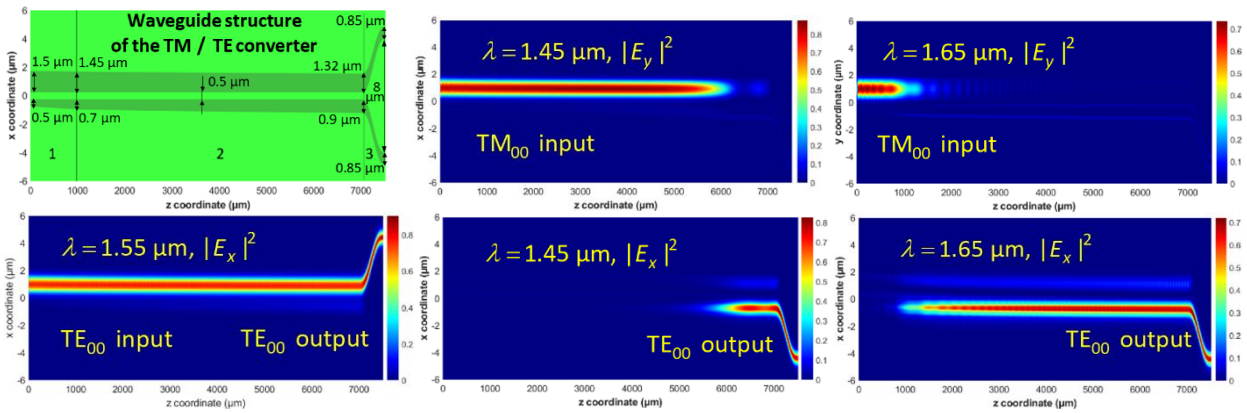


Fig. 3. Broadband adiabatic TM/TE splitter/converter. Waveguide structure and field distributions of the TM mode for the wavelengths 1.45 µm and 1.65 µm and of the TE mode for the wavelength 1.55 µm.

The designed waveguide structure shown in Fig. 3 consists of a 1000 µm linear taper section 1 ensuring sufficient decoupling of the input waveguides, the 6000 µm long adiabatic mode evolution section 2, and the 500 µm long output bends 3 separating the waveguides from the 0.5 µm gap to edge-to-edge distance of 8 µm and simultaneous tapering both waveguides to the output width of 0.85 µm. In section 2, both waveguides are logarithmically tapered; the upper one from 1.45 µm at the input to 1.32 µm at the output while the bottom one from 0.7 µm to 0.9 µm. Fig. 3 also shows the conversion from the input TM_{00} mode of the upper waveguide to the input TE_{00} mode of the bottom one for wavelengths 1.45 µm and 1.65 µm. The TE_{00} input mode propagates essentially unaffected to the upper output branch for any wavelength in this band. The TM/TE coupler loss not exceeding 0.2 dB in the spectral range from 1.45 µm to 1.65 µm was calculated using the full-vector 3D Fourier modal method [9].

BROADBAND 3-dB COUPLERS

To ensure the broadband operation, we implemented adiabatic mode evolution 3-dB couplers consisting of input adiabatic asymmetric waveguide bends followed by a mode evolution pair of waveguides linearly tapered to identical widths, which are then separated by symmetric bends. The design is shown in Fig. 4, together with the demonstration of its broadband operation. Numerical simulation using the Fourier modal method predicted the total loss lower than 0.05 dB and the splitting asymmetry lower than 0.2 dB in the whole spectral range.

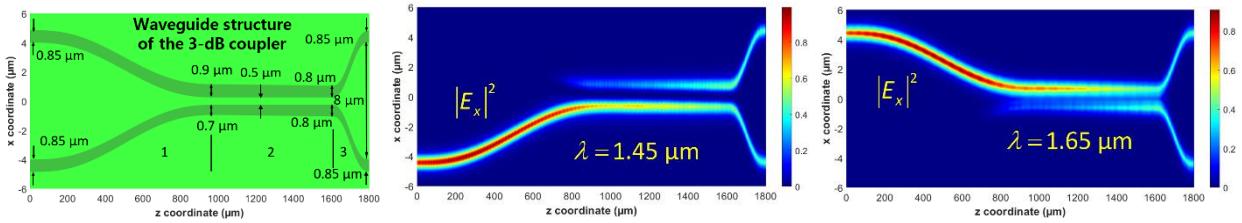


Fig.4. Broadband 3-dB coupler. Waveguide structure and field distributions at the wavelengths of 1.45 µm and 1.65 µm.

ELECTRO-OPTIC PHASE SHIFTERS

Standard push-pull configuration of the electro-optic phase shifters is implemented. The designed electrodes are 6 µm wide, separated by 1 µm from the Si_3N_4 stripe, and are composed of 150 nm SiO_2 buffer covered with 200 nm of gold. Numerical simulations by COMSOL showed that the voltage of 1 V applied to the electrodes excites nearly uniform horizontal electric field intensity of 2×10^5 V/m in the $LiNbO_3$ slab. The distribution of the electric field is shown in Fig. 5. Optical absorption loss due to the presence of electrodes lower than 0.25 dB/cm and the half-wave voltage of the phase shifters lower than 5 V were predicted.

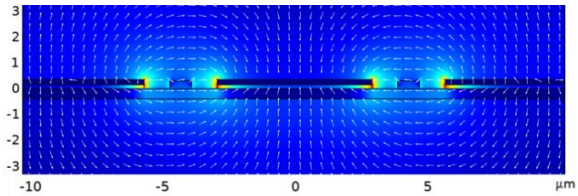


Fig. 5. Distribution of the DC electric field in the phase shifters.

CONCLUSION

A successful proof-of-concept design of the broadband polarization controller based on the "etch-less" Si_3N_4-loaded thin film $LiNbO_3$ was presented. An efficient polarization control was numerically demonstrated in the wavelength band from 1.45 to 1.65 µm with low insertion loss and low operation voltage.

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