Bound States in the Continuum in $LiNbO_3$ Waveguides: An Assessment

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Several types of integrated photonic waveguides based on $LiNbO_3$ crystal support propagation of modes which can be classified as bound states in the continuum. Their properties are discussed from the point of view of their suitability for implementation in photonic devices.
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INTRODUCTION

The concept of the bound state in the continuum (BIC) was introduced nearly 90 years ago in quantum physics by von Neumann and Wigner [1] as a theoretical construction. Recently it was shown that it has interesting applications also in photonics [2]. Different kinds of BICs have been found in various photonic structures – gratings, photonic crystals, etc. Such BICs are represented by standing waves characterized by the quality factors approaching infinity. On the other hand, propagating BICs are confined guided modes with suppressed coupling to the continuum of radiation modes into which they are embedded. The coupling can be suppressed, e.g., by destructive interference of two or more radiation channels due to particular device symmetry, or by polarization properties. In the case that the coupling is not completely suppressed, the modes propagate with nonzero radiation loss and can then be considered as quasi-BICs (q-BICs). In the traditional guided-wave terminology, they are known as leaky modes [3].

BICs or q-BICs can be identified in several kinds of waveguide structures containing $LiNbO_3$ crystal. At first we show that the traditional and most widely used titanium in-diffused (Ti:$LiNbO_3$) waveguides [4] and annealed proton exchanged (APE) $LiNbO_3$ waveguides [5] fall into this category. Then we turn our attention to dielectric-loaded waveguides [6] based on lithium niobate on insulator (LNOI) platform [7], and finally, to the proton-exchanged LNOI waveguides [8]. The properties of BIC or q-BIC modes in these structures will be shown, and the suitability of their implementation in integrated photonic devices for real-world applications will be briefly discussed.

Ti:$LiNbO_3$ AND APE $LiNbO_3$ WAVEGUIDES

Lithium niobate is an optically negative anisotropic crystal with the birefringence $n_o - n_e \approx 0.08$. The titanium in-diffusion results in (slightly different) increases of both ordinary and extraordinary refractive indices by the amount typically smaller than the $LiNbO_3$ crystal birefringence. In the APE process, only the extraordinary refractive index is increased by a similar amount, while the ordinary refractive index remains nearly unchanged or even slightly decreased. An example of the refractive index profiles of a Z-cut Ti:$LiNbO_3$ planar waveguide and effective indices of the TE and TM modes are shown in Fig. 1a).

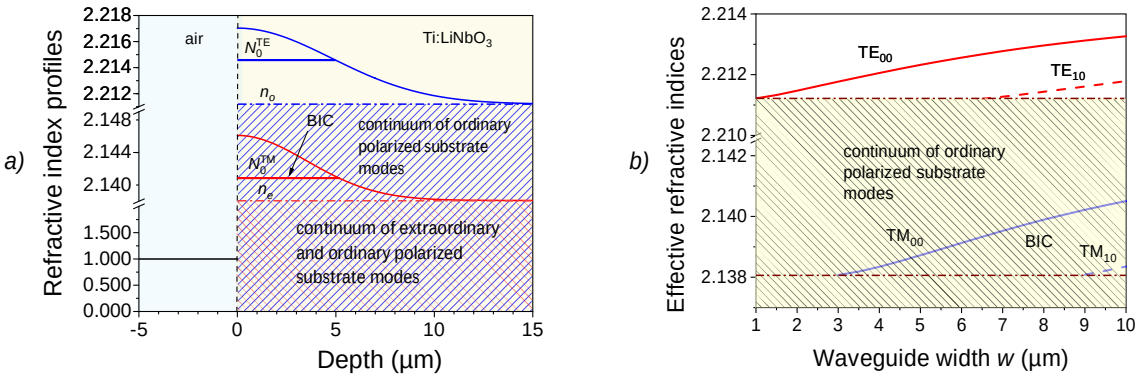

Fig. 1. a) Refractive index profiles of planar Z-cut Ti:$LiNbO_3$ waveguide; b) Dispersion curves of a channel waveguide. Refractive index changes due to Ti diffusion are $\Delta n_e = 0.005\left[\mathrm{erf}\left(\frac{w/2+x}{D_x}\right)+\mathrm{erf}\left(\frac{w/2-x}{D_x}\right)\right]e^{-(y/D_y)^2}$, $\Delta n_o = (0.010834\cdot\Delta n_e)^{0.55}$, $D_x = 4$ μm, $D_y = 5$ μm *[9].*

In this (essentially 2D) case, there is no coupling between the extraordinary polarized TM mode with the ordinary polarized TE radiation modes, the effective indices of which span the whole interval between zero and n_0. The electric field intensity vectors of guided TM and radiation TE modes are namely mutually orthogonal. Thus, such a mode can be classified as a *pure BIC propagating state*. Since the modes of *channel* waveguides are, as a rule, hybrid, having all electric field components nonzero, one might expect some coupling of (quasi-)TM modes with the ordinary polarized continuum, which would result in radiation loss. However, no such losses have been reported in literature, despite the fact that such waveguides are already for decades indispensable components of integrated photonic devices of key importance. Our numerical simulations of Ti:$LiNbO_3$ channel waveguides using COMSOL Multiphysics found extremely low radiation losses, lower than 10^{-4} dB/cm. This is by several orders of magnitude lower value than experimentally measured losses on real waveguides, which are typically close to 0.1 dB/cm. Thus, the TM modes of channel waveguides are BICs, too. The dispersion curves of simulated channel waveguides are shown in Fig. 1b). The refractive index profiles used for simulations are given in the figure caption. The TM modes of APE waveguides behave similarly, they are thus also BICs, while the TE modes are not supported.

LOW-INDEX DIELECTRIC-LOADED LNOI WAVEGUIDES

Recent availability of a novel high refractive index contrast platform, LNOI, has stimulated a new wave of interest in $LiNbO_3$ integrated photonic devices. Lateral confinement is typically ensured by etching a ridge in the $LiNbO_3$ layer. A Z-cut LNOI structure behaves as a planar waveguide in which the waveguide birefringence is enhanced by the natural birefringence of the $LiNbO_3$ crystal. The TE modes of this planar waveguide, propagating in any direction in the plane, represent the continuum of radiation modes, into which the lower-index TM modes of shallow ridge waveguides can couple [10]. To suppress radiation, an optimum ridge width is to be chosen [11]. Such waveguides thus support propagation of TM q-BICs. In deep enough ridge or even rib waveguides, both TE and TM modes are fully guided. An interesting approach to avoid uneasy etching of the $LiNbO_3$ layer has been recently described in [6]. A low-index electron beam resist (n_{poly} = 1.5429) was used as a dielectric load for lateral confinement of modes on Z-cut LNOI. The low-loss TM modes of properly chosen widths of the polymer loading stripe are q-BICs or BICs while the TE modes propagate without radiation as ordinary guided modes.

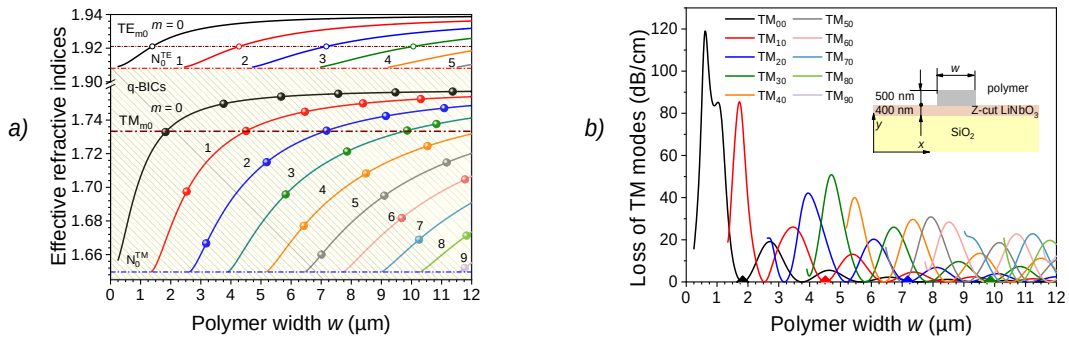

Fig. 2. a) Effective refractive indices of TE and TM modes and b) radiation loss of TM modes of the polymer loaded LNOI waveguides as a function of the polymer stripe width w. Waveguide cross-section is shown in the inset of Fig. 2b). Full dots in Fig. 2a) indicate minimum radiation loss.

As it is indicated in Fig. 2a) by the dash-dot line, the effective refractive indices of the four lowest-order TM modes are nearly identical, $N_{eff} \approx 1.733$, just for stripe widths corresponding to minimum radiation loss. This interesting feature was utilized in [12] for design of four-channel mode de/multiplexor based on directional couplers. Note, however, that the same principle can be applied to the design using ordinary TE modes, too, as it is indicated by open circles on the dispersion curves of TE modes in Fig. 2a). In this case, radiation losses are absent, so that they do not play any restrictive role. Moreover, for TE modes, the electrooptic modulation using laterally placed electrodes as in [6] is much more efficient.

PROTON EXCHANGED LNOI WAVEGUIDES

Lateral confinement can be created in LNOI waveguides also by proton exchange (PE) [8]. The cross-section of the waveguide is shown in Fig. 3a). We numerically simulated the structure with the thickness of the $LiNbO_3$ layer of 500 nm. The depth refractive index profile was approximated by the Gaussian function with the diffusion coefficient $D_y = 2$ μm, lateral diffusion was neglected. The extraordinary refractive index variation due to PE at the surface

was $\Delta n_e = 0.08$. Calculated effective indices of TM modes versus the width of the PE section are plotted in Fig. 3b). The radiation losses were found negligible for any width of the PE section. (The measured losses reported in [8] were by orders of magnitude higher, but they could be assigned to waveguide imperfections, not to radiation.)

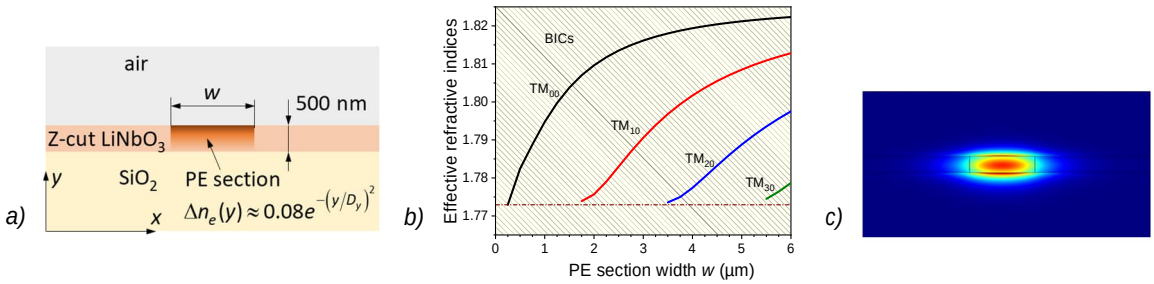

Fig. 3. a) Cross-section of the proton exhanged channel waveguide in Z-cut LNOI, b) dispersion curves of TM modes, c) electrical mode field distribution of the TM_{00} mode for w = 2 μm.

The propagation constants of the TM modes belonging to the channel PE waveguide are embedded in the continuum of the omnidirectionally propagating planar TE_0 modes supported by the lithium niobate slab. However, because of negligible radiation, the TM modes can be also considered as BIC states. Since their electric field is well localized in the lithium niobate slab, see Fig. 3c), they can be also utilized for efficient electro-optic modulation.

CONCLUSIONS

All three kinds of $LiNbO_3$ waveguide structures considered are capable of supporting BICs, or low-loss q-BICs. While the Ti:$LiNbO_3$ and APE $LiNbO_3$ waveguides have already proved their nearly unrivalled usefulness in a number of commercial applications (decades before the concept of BICs was introduced into photonics!), the polymer-loaded LNOI structure seems to be an interesting example of implementation of q-BIC rather than a competitive candidate for realistic applications; employing the q-BIC here is neither necessary nor advantageous. The real applicability of PE LNOI structure would require considerable improvement in the fabrication technology in order to reduce the waveguide loss while keeping the refractive index change high enough for sufficient lateral mode localization.

More types of waveguide structures, including those based on X-cut $LiNbO_3$, will be discussed during the presentation at the conference, too.

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