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Mode transformation in hybrid waveguides based on lithium niobate for efficient coupling to a standard single mode fiber

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Topology of a hybrid waveguide device, which performs an effective transformation of a standard gradient titanium in-diffused waveguide mode to a hybrid waveguide mode, is considered. With its help a rather large optical mode with size optimal for coupling with standard single-mode fibers can be converted to a mode with a smaller size. Two the most perspective materials for hybrid waveguide fabrication were considered: silicon and titanium dioxide. The theoretical analysis has shown that transformation efficiency of more than 99% is achievable for waveguide devices based on titanium dioxide with contact lithography resolution.

Keywords: integrated optics, waveguide, lithium niobate, optical mode, taper, silicon, titanium dioxide

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Introduction

Lithium niobate ($LiNbO_3$) is one of the essential materials used at present to construct ultrabroadband optical modulators [1]. The thin-film hybrid waveguide technology [2] is of special interest, since such waveguides with their high numerical aperture and small size of the mode spot provide an opportunity to construct integrated-optics modulators with a half-wave voltage below 1 V and a bandwidth upward of 10 GHz [3]. The input and output of optical radiation and the matching of integrated-optics circuits with a standard single-mode optical fiber are among the crucial technical challenges arising in the application of modulators based on thin-film hybrid waveguides. The following two approaches to these problems are currently in wide use: the application of surface gratings [4] and the use of a specialized lensed optical fiber with a waveguide converter based on a taper (waveguide element with a tapering cross section) [5–7]. Both approaches require high alignment accuracy. An air gap present between the fiber end and the input element may induce interference effects because of rereflections and makes the design of coupling modules susceptible to external influences (such as temperature variations).

The technology of coupling between a single-mode optical fiber and standard gradient waveguides on lithium niobate substrates fabricated by diffusion methods (thermal diffusion or proton exchange) is well-proven and involves the use of polished coupling modules with a glued-in standard single-mode fiber [8] that are glued to the end of an integrated-optics circuit. Fine coupling between the fiber and waveguide modes guarantees low optical coupling losses (less than 0.5 dB), and a monolithic design provides high mechanical integrity and resistance to variations of the environmental conditions.

We propose to use standard diffusion waveguides with a hybrid waveguide structure on their surface for coupling with an optical fiber. This hybrid structure converts the diffusion waveguide mode with a low numerical aperture, which is matched with a standard single-mode telecommunication fiber, to a mode with a high numerical aperture and a small mode spot that is characteristic of thin-film hybrid waveguides based on lithium niobate. The idea of application of hybrid waveguide structures in mode conversion has been proposed in our earlier study [9] on enhancing the efficiency of a waveguide single-photon detector, but it has not been analyzed quantitatively in detail. The aim of the present study is to perform a theoretical analysis of mode conversion and determine the optimum design and materials for the fabrication of a hybrid waveguide mode converter.

1. Converter model

The design of the proposed mode converter is presented in Fig. 1. A channel titanium in-diffused waveguide is formed along crystallographic axis y on an x-cut lithium niobate substrate. This orientation is the most widely used one in electrooptic modulators [1] operating with a quasi TE mode polarized linearly along axis z. Since the two widely used diffusion technologies (thermal titanium diffusion and proton exchange) allow one to fabricate waveguides with similar characteristics (size, refraction index profile, mode shape), but a proton-exchange waveguide does not support TM modes [10], a titanium in-diffused waveguide was chosen for the mode converter model so as to examine it in utmost detail.

Section A of the converter (Fig. 1) is the section with a straight titanium in-diffused waveguide, and section C is the section with a hybrid waveguide based on a strip of material with a high refraction index (higher than that of lithium niobate) located above the titanium in-diffused waveguide. The waveguide element located in between (section *B*) implements adiabatic mode conversion.

A dielectric strip with a high refraction index, which crosses the path of an optical wave in section *B*, alters the spatial distribution of intensity of modes. As the lateral dimensions of the strip increase, the titanium in-diffused waveguide mode is converted into a mode localized in the strip with a high refraction index and a mode of the hybrid waveguide structure with a high numerical aperture.

Titanium ($n_{TiO_2} = 2.31$ [11]) and silicon ($n_{Si} = 3.48$ [12]) were tested as materials for thin-film hybrid waveguide structures. The efficiency of application of these materials in the design of hybrid waveguides on lithium niobate substrates was proven [2].

2. Numerical analysis

Mode analysis of hybrid waveguides at the output of the mode converter (in section *C* in Fig. 1) was performed first. The finite element method implemented in COMSOL at a telecommunication wavelength $\lambda = 1550$ nm was used in this analysis.

The converter model was simplified for calculation convenience and for clarity: the gradient profile of the refraction index distribution of the titanium in-diffused waveguide was substituted with a step-index profile with an equivalent size of the mode spot [13], the refraction index of the substrate for quasi TE polarization was taken equal to $n_s^e = 2.140$, the refraction index of the waveguide channel was $n_w^e = 2.145$, and the effective height and width of the waveguide channel were $H_{LiNbO_3}^{TE} = 4.5\,\mu$m and $W_{LiNbO_3}^{TE} = 8.0\,\mu$m, respectively. The parameters for orthogonal (quasi TM) polarization differed due to the anisotropy of the crystalline substrate [13]: $n_s^o = 2.210$, $n_w^o = 2.212$, $H_{LiNbO_3}^{TE} = 7.5\,\mu$m, and $W_{LiNbO_3}^{TE} = 10.5\,\mu$m.

It was found that mode TE_{loc} localized in the strip with a high refraction index has the capacity to propagate along the hybrid waveguide at different ratios between H_d and W_d (Fig. 2). In the case of silicon, which has a higher refraction index than titanium, the localized mode emerges at a smaller strip size and, consequently, has smaller lateral dimensions and a higher numerical aperture. However, titanium is preferable from the technology standpoint, since large dimensions of a titanium strip ease the demands for accuracy of the fabrication equipment, thus providing an opportunity to fabricate mode converters using the methods of contact photolithography. Note that even titanium allows one to reduce the effective mode diameter by a factor of more than 3 and raise the local intensity of optical radiation and the efficiency of electrooptic control by more than an order of magnitude.

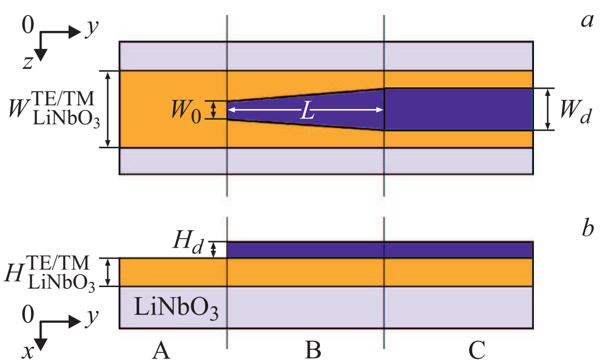

Figure 1. Topology of the hybrid waveguide mode converter: *a* — top view, *b* — side view.

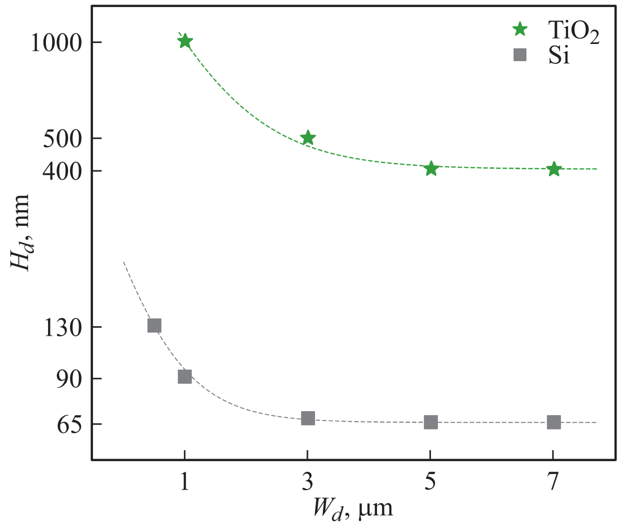

Figure 2. Conditions of existence of a TE_{loc} mode localized in the strip with a high refraction index.

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Figure 3 presents the theoretical dependences of effective refraction indices of waveguide modes of the hybrid structure (normalized by the refraction index of the substrate) on the strip height at fixed width $W_d = 3\,\mu$m for titanium and $W_d = 1\,\mu$m for silicon. Owing to the large difference in effective refraction indices and the difference between the fields of modes, the localized mode interacts weakly with the principal mode of the titanium in-diffused waveguide. This is the reason why a specialized device based on a taper (a waveguide layer with a smoothly varying width) is needed for efficient radiation transfer (Fig. 1).

The propagation of light in the mode converter based on a taper was examined in detail. This mode converter should transform the waveguide mode adiabatically. As was already noted, a titanium-based hybrid waveguide structure may be fabricated using contact photolithography with less strict requirements as to the accuracy in size of waveguide elements. Therefore, a titanium taper was analyzed. Height $H_d = 500$ nm of the titanium strip and output width $W_d = 3\,\mu$m of the taper were chosen based on the results of analysis of the existence conditions of the localized mode (Fig. 2). Starting width $W_0 = 1\,\mu$m

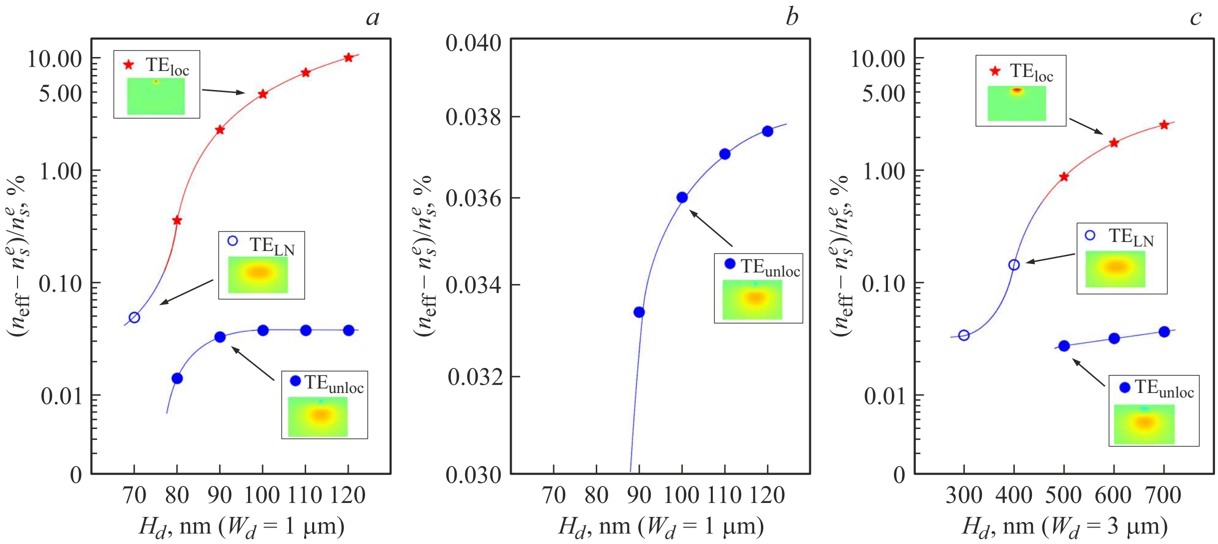

Figure 3. Dependences of effective refraction indices of hybrid quasi TE modes on strip height H_d: a, b — for silicon at strip width $W_d = 1\,\mu$m, c — for titanium at fixed width $W_d = 3\,\mu$m. Graphical insets illustrate the distribution profiles of the electric field of modes.

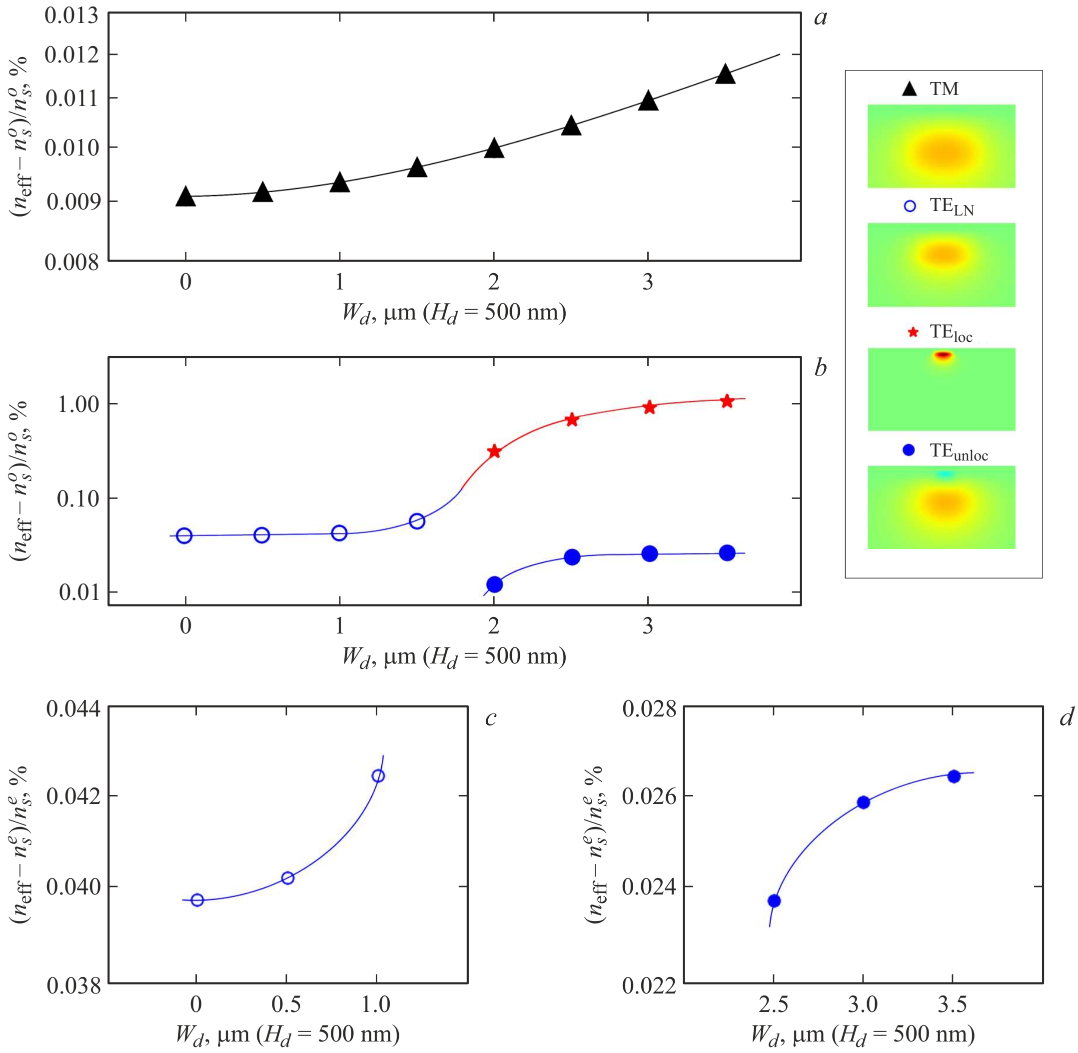

Figure 4. Dependences of the effective refraction index of waveguide modes on width W of the titanium taper at fixed height $H_d = 500$ nm for the TM mode (a) and TE modes (b–d). Graphical insets illustrate the distribution profiles of the electric field of modes for different cross sections of the taper.

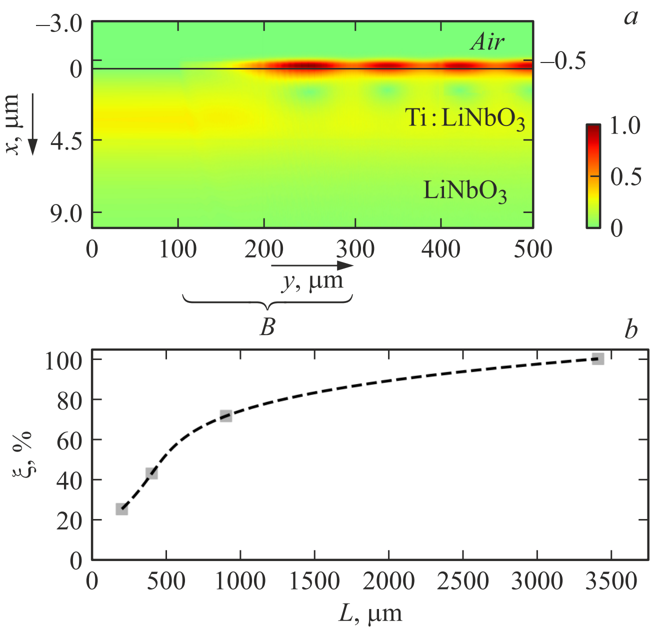

Figure 5. Results of analysis of light propagation through the titanium taper ($H_d = 500$ nm, $W_0 = 1\,\mu$m, $W_d = 3\,\mu$m): *a* — spatial distribution of intensity for the taper with length $L = 200\,\mu$m, *b* — dependence of the efficiency of mode conversion in the taper on its length L.

and length $L = 3400\,\mu$m of the taper were chosen so as to ensure adiabatic mode conversion. The results of analysis of hybrid taper modes presented in Fig. 4 revealed that the TM mode of the titanium in-diffused waveguide is unaffected by the presence of the hybrid waveguide layer: its effective refraction index remains unchanged, and the quasi TM mode is not converted at the taper. As for the TE mode, the conversion of the titanium in-diffused waveguide mode into a localized mode of the hybrid structure occurs as the taper width increases smoothly from 1.5 to $2\,\mu$m. The dispersion curves for orthogonally polarized TE and TM modes are located far from each other, since the values of n_s^e, n_s^o differ greatly and the effective refraction indices of modes deviate only slightly from these values. This ensures the lack of polarization transformations.

The numerical beam-propagation method (BPM) [14] was used to analyze the process of light propagation along the taper, verify the adiabaticity of operation of the mode converter, and estimate quantitatively the efficiency of conversion into a localized mode of the hybrid waveguide. The principal TE mode of the titanium in-diffused waveguide served as the input signal. Since the mode conversion has a finite efficiency depending on the taper length, a fraction of optical power continues to propagate in the titanium in-diffused waveguide. This is manifested in the form of an interference pattern of propagating modes that is seen in the results of BPM modeling (Fig. 5, *a*). Using the interference contrast, we calculated the efficiency of mode conversion at the taper as the ratio of power of localized mode TEloc to the overall power of modes at the taper output: $\xi = \frac{P_{\mathrm{Te_{loc}}}}{P_{\mathrm{Te_{loc}}} + P_{\mathrm{Te_{unloc}}}}$ (Fig. 5, *b*). The conversion efficiency was more than 99% at taper length $L = 3400\,\mu$m, and the operating mode of the taper was nearly adiabatic.

Conclusion

The results of the above theoretical analysis demonstrate that hybrid waveguide structures may be used efficiently in conversion of modes of standard gradient waveguides on lithium niobate substrates into localized modes of hybrid ridge waveguides. Titanium and silicon were considered as promising materials for mode converters. It was demonstrated that a mode converter in the form of a titanium taper provides a conversion efficiency in excess of 99% without polarization transformations, which is especially important for efficient electrooptic modulation. The obtained results may be used to develop a technology for coupling between hybrid thin-film integrated circuits and a standard single-mode telecommunication fiber.

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Conflict of interest

The authors declare that they have no conflict of interest.

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