Reducing Radiative Loss in Intersecting Waveguides by Fractionally Doping the Intersection Region

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Abstract—**A multiple scattering analysis of single mode intersecting optical waveguides predicts that coupling from guided to radiation fields (i.e., an insertion loss) can be reduced by modifying the refractive index in the volume common to both guides. We observe a significant reduction in radiative loss for both polarizations with this modification.**

INTERSECTING waveguides have been incorporated into integrated optics as crossovers for switch arrays [1], [2], as passive polarization splitters [3], [4], and as the waveguide element in electrooptic switches [5]. The insertion loss in and the power coupled between intersecting waveguides are both functions of the intersection angle (θ) and the optical confinement (characterized by the normalized waveguide width, the V-parameter) [6]–[10]. Design requirements on coupling can therefore preclude minimizing losses. This is particularly important for small-angle intersections ($\theta \leq 4°$) where losses are larger [6]. Calculations predict that coupling to radiative fields (i.e., radiative loss) can be significantly reduced by a third parameter, modification of the refractive index in the intersection region (i.e., fractional doping) [11]. Modification of the refractive index in the intersection region therefore introduces a new parameter (albeit one which also affects guided-guided field coupling) [12] which allows us to minimize the radiative losses in this structure.

Ti-diffused channel waveguides in $\hat{c}$-cut y-propagating $LiNbO_3$ are considered in all calculations and measurements that follow. Fractionally-doped intersecting waveguides were fabricated in a two step process: the intersecting waveguide geometry was photolithographically patterned in Ti, $\tau_0 \sim 67.5$ nm thick by $w = 6.5$ μm wide, over a fractional doping rectangle of Ti of width $w = 6.5$ μm and thickness $0 \leq \Delta\tau \leq 67.5$ nm (see Fig. 1). Here τ_0 is the initial thickness of the Ti film of the intersecting waveguide structure and $\Delta\tau$ is the excess dopant film thickness which produces the additional index change in the intersection region. Thermal diffusion of the Ti into the $LiNbO_3$ substrate under wet oxygen at 1050°C for 6 h produces low loss (≤ 0.2 dB/cm) strongly confining channel waveguides for both polarizations. Insertion losses of intersecting waveguides (the sum of the two guided light fields referenced to an isolated waveguide) were measured as a function of the fractional doping parameter in the intersection region ($1 + \Delta\tau/\tau_0$). Each structure was fabricated with six-fold redundancy; the structures with the highest power outputs were used as data. Different substrates were used for each degree of excess doping. Measurements were made by lens-coupling light of $\lambda = 1.3$ μm wavelength (polarized normal to the $LiNbO_3$ surface for the TM polarization and parallel to the substrate surface for the TE polarization). The fractional doping $\Delta\tau/\tau_0$ was varied from $\Delta\tau/\tau_0 = 0$ (the so-called single-Δn geometry) to twice the index enhancement in the intersection region over that in the intersecting waveguide arms, $\Delta\tau/\tau_0 = 1$ (the 2-Δn geometry).

Radiation losses were calculated for the TM polarization using the multiple scattering analysis [7]–[9] carried out to first order. This method treats recursively one waveguide of an intersecting pair as an extended scattering element of the other guide. Unlike the mode interference analysis, this treatment of the optical field is valid for waveguide geometries whose cross section changes along the direction of light propagation, viz., intersecting guides. The multiple scattering analysis predicts that for small intersection angles, the light scattered into radiation fields from the intersecting waveguide arms and from the fractional doping can be made to interfere destructively in the far field [11]. The relative magnitudes of the far field patterns from the two scattering sources can be matched by varying the amount of excess doping, optimizing the loss reduction. For the doping concentrations considered here the refractive index for the extraordinary (TM) polarization varies linearly with Ti concentration [13]. The index change in the intersection region is therefore assumed to be proportional to the Ti thickness before diffusion $\Delta\tau$. The normalized waveguide width V was determined from a previous comparison of calculations and measurements of the coupling between intersecting waveguides [12]. A value of $V/\pi = 0.82 \pm 0.02$ is consistent with well-confined single-mode waveguides ($V/\pi \leq 1$) and was used for the radiative loss calculations.

Figs. 2(a)–(c) and 3(a)–(c) show the experimental radiative loss results in waveguides intersecting at 0.5°, 1.0°, and 1.5° for the TM and TE polarizations, respectively. Also shown in Fig. 2 are the multiple scattering calculations for the TM polarization. The calculations predict that fractional doping reduces insertion loss below that found for the stan-

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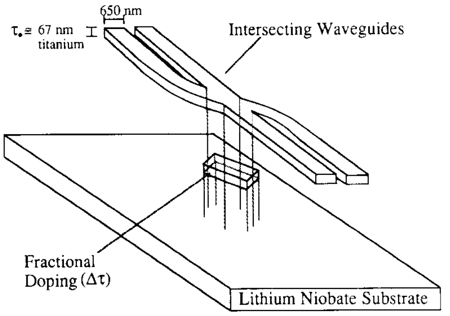

Fig. 1. Schematic diagram of fractionally doped intersecting waveguide fabrication. The thickness of the fractional doping (before diffusion) was varied from $\Delta\tau/\tau_0 = 0$ to $\Delta\tau/\tau_0 = 1$.

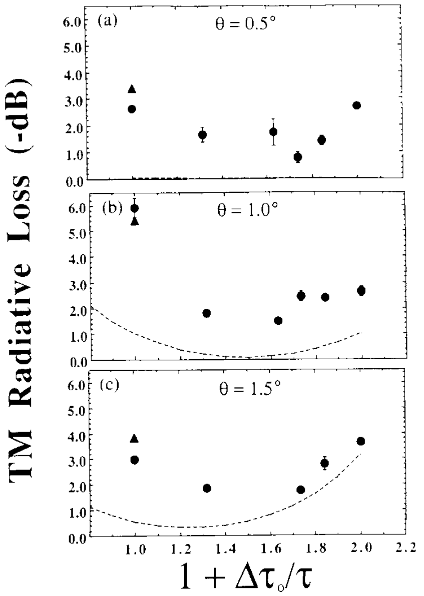

Fig. 2. Radiative loss measured as a function of the fractional doping for the TM polarization. Error bars assume Gaussian distribution of five measurements on the same structure. (In some cases, error bars are smaller than data points.) Multiple scattering calculation results are shown as a dashed line (for $\theta = 0.5°$, theoretical results are approximately coincident with abscissa). Intersection angles: (a) 0.5°, (b) 1.0°, and (c) 1.5°. Data from [14] (▲) are also shown.

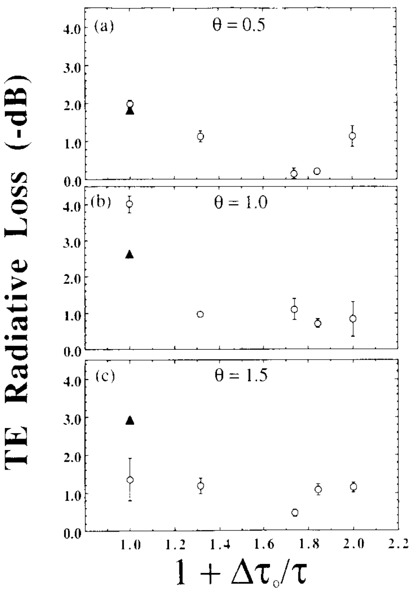

Fig. 3. Radiative loss measured as a function of the fractional doping for the TE polarization. Error bars assume Gaussian distribution of three measurements on the same structure. Intersection angles: (a) 0.5°, (b) 1.0°, and (c) 1.5°. Data from [14] (▲) are also shown.

dard single-Δn ($\Delta\tau/\tau_0 = 0$) and $2\Delta n$ ($\Delta\tau/\tau_0 = 1$) geometries. For the two larger intersection angles ($\theta = 1.0°$ and 1.5°), the loss reductions obtained by fractional doping are qualitatively consistent with the multiple scattering predictions: fractional doping reduces radiative losses below that of these two standard geometries. Measured losses were reduced ~ 1 to ~ 4 dB below those for the single-Δn geometries for both polarizations. For all three angles, loss minima are calculated to be substantially less than one dB, while the experimental data exhibits a uniformly larger loss than the theory predicts. While measured loss reductions were very similar for both polarizations, our experimental results show an overall shift toward lower loss for the TE polarization. In the best case, a loss minimum of ~ −0.15 dB was obtained with an excess doping of $\Delta\tau/\tau_0 \sim 0.8$ for the TE polarization in guides intersecting at 0.5°. By comparison for the TM polarization, a loss minimum of ~ −1.0 dB was measured for $\theta = 0.5°$ with an excess doping of $\Delta\tau/\tau_0 \sim 0.6$.

The discrepancy between theory and measurement may be due to the fact that these radiative loss calculations neglect higher order interactions (e.g., that fraction of light which is first coupled to the guided field of the adjacent waveguide and then radiated by way of being recoupled to the radiation field of the first guide). This explanation is consistent with the fact that the experimental results and calculations show better agreement as the intersection angle becomes larger (i.e., as the contribution to guided-guided field coupling becomes smaller).

In conclusion, a first order multiple scattering calculation predicts that for the TM polarization the radiative losses of small angle intersecting channel waveguides can be significantly reduced, as compared to those of the standard single-Δn or 2-Δn intersecting waveguide geometries, by fractionally doping the intersection region. A qualitative agreement between theory for the TM polarization and measurements is observed. Measurements reported here show that this loss reduction mechanism is also effective for the TE polarization. Insertion losses (relative to straight waveguides) as low as ~ −1.0 dB for the TM polarization and ~ −0.15 dB for the TE polarization were observed in fractionally doped guides intersecting at 0.5°. We note that refinements of the fractional doping geometry may result in further loss reductions.

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