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Effect of waveguide uniformity on phase matching for frequency conversion in channel waveguides

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We have studied the effect of nonuniformity in graded index, channel waveguide dimensions on the phase-matching condition for guided-wave nonlinear frequency conversion. Both theoretical and experimental results using normalized waveguide parameters and quasi-phase matching for second- harmonic generation in annealed proton-exchanged $LiNbO_3$ waveguides show the existence of an optimum waveguide design which is insensitive to inhomogeneities in the waveguide dimensions. Application of such a waveguide design using normalized approach can significantly relax the fabrication tolerance, leading to nonlinear guided-wave devices with long interaction lengths and useful conversion efficiencies.

Phase matching between the nonlinear polarization wave and the generated electromagnetic wave is crucial for efficient conversion in any nonlinear frequency mixing experiment. Several phase-matching techniques including birefringent, quasi-, and balance phase matching have been used for guided-wave frequency conversion.[1–3] However, since the propagation constant of the guided mode depends not only on the material dispersion, but also on the waveguide dispersion, inhomogeneities in the waveguide index profile can seriously limit the phase-matchable interaction length and consequently, the conversion efficiency.

It has been pointed out that by choosing the appropriate waveguide dimensions, the phase-matching condition can be made insensitive to small variations in the dimensions of the waveguides.[3,4] A correlation between the experimental results and the theory has been reported for step index planar waveguides.[4] In this letter, we address the problem of optimum graded-index channel waveguide design for efficient frequency doubling using two-dimensional (2D) normalized waveguide parameters. The mismatch between the propagation constants of the fundamental and the second-harmonic waves was studied as a function of the waveguide dimensions. The normalized approach for the graded-index 2D profile makes the analytical results useful in general, regardless of the waveguide parameters in question. In addition, we experimentally demonstrate that longer phase-matched interaction lengths for frequency doubling can indeed be achieved in the optimum waveguide geometry.

In a nonuniform waveguide, phase-matching condition cannot be maintained over long interaction lengths. We consider the case of frequency doubling and assume that due to the waveguide nonuniformity, the fluctuation of the phase-mismatch quantity, $\delta k = (2\pi/\lambda^{\omega})\delta(N^{2\omega} - N^{\omega})$, is distributed randomly over the interaction length L, with a Gaussian probability distribution

$$P(\delta k=s)=\frac{1}{\sqrt{\pi}\sigma}e^{-s^2/\sigma^2}, \tag{1}$$

where σ is the square-root mean value of the phase-mismatch variation δk, N^{ω} and $N^{2\omega}$ are the two mode indices to be phase matched, and λ^{ω} is the fundamental wavelength. Then the consequent reduction in the conversion efficiency is given by[5]

$$P_{\text{mismatch}}/P_{\text{phasematch}} = \exp(-\sigma^2L^2/2), \tag{2}$$

where L is the interaction length. For at least 80% of the second-harmonic power to be maintained over the phase-matching length L_{pm}, the maximum value of σ should satisfy $\sigma L_{pm} \leqslant 1$. It is seen from Eq. (2) that the fluctuations in the mode index mismatch $\delta(N^{2\omega} - N^{\omega})$ must be $\leqslant 10^{-5}$ for $L_{\text{pm}} = 1$ cm. This turns out to be the most stringent requirement on waveguides for second-harmonic generation and has been confirmed experimentally;[6] it translates to a 0.1% uniformity in the waveguide cross-sectional dimensions over 1 cm interaction length. As will be seen in the following discussion, these constraints can be relaxed by careful choice of the waveguide dimensions.

To study the effect of the waveguide dimensions on the phase-matching condition, we must first establish the relation between propagation constant of the guided mode and the waveguide dimensional parameters. As such, we consider the annealed proton-exchanged (APE) $LiNbO_3$ channel waveguides and use a simple quasi-analytical technique[7] based on the effective index method which is well suited for an optimization purpose. APE channel waveguides, which have received considerable attention in nonlinear frequency conversion using quasi-phase-matching schemes,[2,8] are particularly appealing since annealing has been shown to provide larger guide with smaller Δn,[2,8] and recovered optical nonlinearity.[9]

We consider an APE channel waveguide on a Z^+-cut (Y propagating) $LiNbO_3$ crystal. Similar to the quasi-analytical procedure outlined elsewhere,[7,10] the mode index of these channel waveguides can be expressed analytically as a function of the normalized waveguide depth V_d and width V_w (Ref. 11)

$$V_d=(2\pi d_z/\lambda^{\omega})(2n_b^{\omega}\Delta n_e^{\omega})^{1/2},$$

and (3)

$$V_w=(\pi w/\lambda^{\omega}n_b^{\omega}\Delta n_e^{\omega})^{1/2},$$

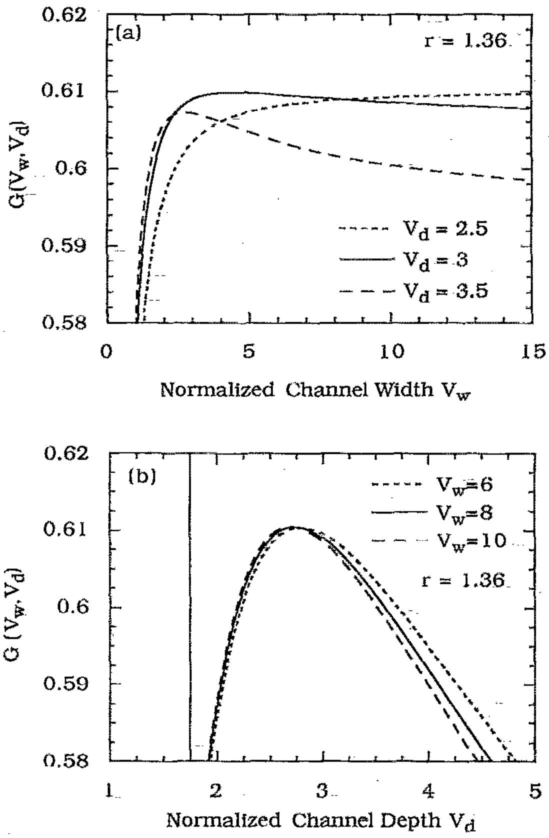

FIG. 1. $G(V_w, V_d)$ as a function of (a) the normalized channel width V_w for three different normalized channel depths, and (b) the normalized channel depth V_d for three different normalized channel widths. The vertical dotted line in (b) indicates the cutoff depth for the fundamental wavelength ($\lambda^\omega = 916$ nm). The dispersion factor $r = 1.36$ corresponds to the realistic case of blue light generation in APE guides.

where d_z and w are the waveguide depth ($1/e$ point) and width, respectively, n_b^ω is substrate index and Δn_e^ω is the surface extraordinary index change at the pump wavelength λ^ω. The mode index mismatch $N^{2\omega} - N^\omega$ can be separated into the bulk index mismatch term $n_b^{2\omega} - n_b^\omega$ and a waveguide dimensional dependence term by defining a normalized parameter $G(V_d, V_w)$:

$$N^{2\omega} - N^\omega = n_b^{2\omega} - n_b^\omega + \Delta n_e^\omega G(V_d, V_w), \tag{4}$$

where $G(V_d, V_w) = rb^{2\omega} - b^\omega$. $b^{\omega,2\omega}$ is the normalized mode index[11] for the fundamental or harmonic frequency, and the dispersion parameter $r = \Delta n_e^{2\omega}/\Delta n_e^\omega$. Notice $G(V_d, V_w)$ depends only on the normalized waveguide geometrical parameters incorporated in V_d and V_w and on weakly wavelength dependent r. We will omit the detailed calculations here and only show the results. In Figs. 1(a) and 1(b), $G(V_d, V_w)$ is shown as a function of the normalized channel waveguide width V_w and depth V_d, respectively. The cutoff point for the lowest-order mode at the fundamental wavelength is also indicated by the vertical line in Fig. 1(b). A general feature of these curves is the existence of a turning point. As the normalized depth or width increases, G increases rapidly to its maximum, then slowly decreases, and in Fig. 1(a), it reaches nearly a constant value for the appropriate depth (where $\partial G/\partial V_d \approx 0$). From Fig. 1(b), it is clear that, independent of the channel width, the largest fabrication tolerance can be obtained, where $\partial G/\partial V_d = 0$, thus G is not sensitive to the first-order variation in V_d. Notice that the width dependence is much weaker than the depth dependence beyond the tuning points. This effect is related to the asymmetry of the index profile along the depth direction and indicates that symmetric waveguides will provide much better dimensional tolerance for phase matching.

To verify the validity of the theoretical modeling, we performed guided-wave quasi-phase-matched frequency doubling experiments[2,8] in a series of APE $LINbO_3$ channel waveguides with varying widths and depths. Two domain inverted gratings with periods $\Lambda = 6.6$ and 6.8 μm were first created on the same $LiNbO_3$ substrate by titanium diffusion.[2] Then a set of channel waveguides (mask opening width between 1.0 and 10.0 μm, with 0.5 μm increment) was fabricated by proton exchange in pure benzoic acid at 180 °C for 1 h. The exchanged waveguides were then annealed at 350 °C for periods in the range of 4– 13 h to obtain different channel depths. A cw argon-pumped Ti-sapphire tunable laser was used as the fundamental pump source; its output ($\lambda^\omega = 780$–920 nm) was endfire coupled into the channel waveguides with a 40× microscope objective (N.A. = 0.65). Part of the infrared beam was sent to a wavemeter to monitor the wavelength and the bandwidth with an accuracy of 0.01 nm. A TV camera was used to display the mode profiles of both the fundamental and second-harmonic output. Typical conversion efficiency in these channel guides ranges from 23% to 50%/W cm^2.

First, we measured ($N^{2\omega} - N^\omega$), the difference between the mode indices of the fundamental guided mode at the phase-matched pump and harmonic wavelengths for each channel waveguide. For a given period of the domain inverted grating, ($N^{2\omega} - N^\omega$) was calculated from the phase-matching wavelength,[2,8] and the dimensional dependence of the mode index mismatch factor G was extracted using Eq. (4). Second, the effect of waveguide dimensions on phase-matching tolerance for waveguide uniformity in the waveguide was determined from the phase-matching bandwidth $\Delta\lambda$; for the given waveguide uniformity, the phase-matching tolerance is proportional to the effective length L_{pm} of the waveguide over which phase matching occurs. The phase-matching length L_{pm} is deduced from the relation $1/L_{pm} = 4\Delta\lambda\ \partial[(n^{2\omega} - n^\omega)/\partial\lambda]$; here we neglect the waveguide dispersion and approximate the phase mismatch by the bulk value. The propagation losses in these waveguides are estimated to be less than 2 dB/cm, therefore the broadening of the bandwidth due to losses is negligible.

In Figs. 2(a) and 2(b), we plot the extracted waveguide mismatch factor G and the phase-matching length as a function of the normalized waveguide width and depth, respectively. The data of Fig. 2 demonstrate the correlation between the phase-matching length and the gradient of the waveguide mismatch factor G, especially in the depth dimension, where a large phase-matching length can be obtained when $\partial G/\partial V_d = 0$. This indicates the existence of an optimum waveguide dimension in which phase-matching

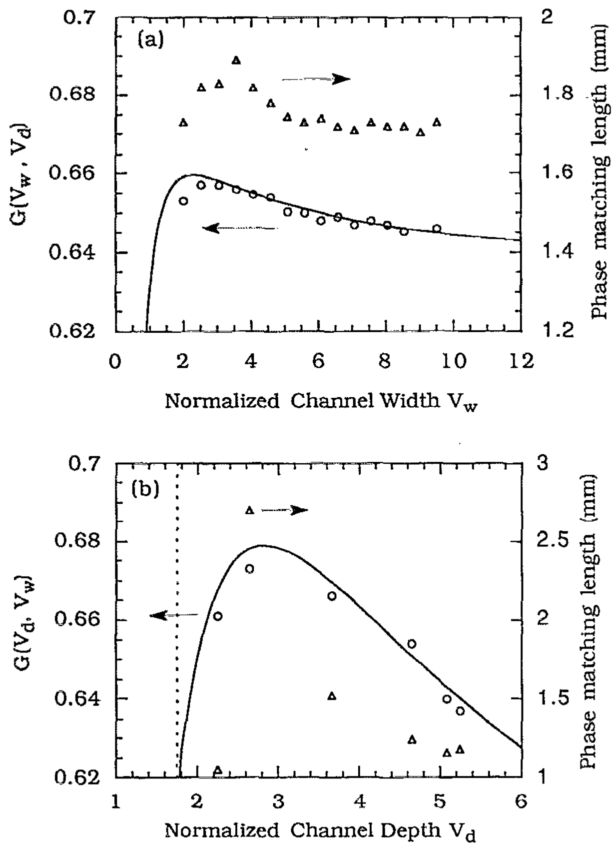

FIG. 2. Calculated and measured values for $G(V_w, V_d)$ and the measured phase-matching length as a function of (a) the normalized channel width V_w for $V_d = 5.0$, and (b) the normalized channel depth V_d for $V_w = 7.8$. The center fundamental wavelength of $\lambda^{\omega} = 876$ nm was used in the calculations. The vertical dotted line indicates the cutoff depth for the fundamental wavelength.

condition is not sensitive to waveguide inhomogeneities.

To compare the experimental results with the predictions of our model, theoretical curves are also shown in Fig. 2 along with the experimental points. In these curves, we use the extraordinary index dispersion data of $LiNbO_3$ from Edwards and Lawrence.[12] The dispersion of Index change Δn_e was determined by the IWKB method.[13] A detailed description of the complete characterization of these APE guides will be reported elsewhere.[10] In the range of the phase-matching wavelength (866–881 nm), an average dispersion factor $r = 1.45$ was used in the calculation.[10] As seen in Fig. 2, a reasonable agreement between the experimental data and our theoretical curves is obtained. The tuning points of the experimental data are slightly displaced from the theoretical ones. We attribute this to the error in calculating the mode index at the pump wavelength since the mode is near cutoff and the effective index method is likely to give large error. Another possible error arises from the small dependence of the waveguide depth on the mask opening. Nevertheless, it is clear that this simple model provides general guidelines for designing optimum waveguides for frequency conversion in graded-index channel waveguides. These experimental results agree and further confirm the previous prediction on the phase matching tolerance condition.[3]

In conclusion, we have modeled the effect of waveguide dimensions on the phase-matching condition for guided-wave frequency conversion using the normalized waveguide parameters. We show the existence of optimum channel waveguide dimensions where phase matching is relatively insensitive to the waveguide inhomogeneity. The model has been verified with excellent agreement with the experimental results. Application of the normalized approach outlined here results in channel waveguides with broader fabrication tolerances, leading to efficient guided-wave frequency conversion.

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