

Radiation to Guided Modes Power Transfer for the Characterization of Reverse-Proton-Exchanged Waveguides

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The characterization of buried waveguides realized through reverse-proton-exchange in lithium niobate is achieved in a non-conventional way by measuring the coupling angles of radiation modes giving phase matching with second harmonic guided modes

Keywords: reverse-proton-exchanged waveguides, second harmonic generation.

Introduction

Buried waveguides are attracting an increasing interest in many fields of integrated optics since they allow a reduction of scattering losses with respect to conventional waveguides lying on the surface of the substrate, and, moreover, they present a nearly symmetrical refractive index-profile in the depth direction, which results in an improved matching between fibre and waveguide fields [1,2]. In the case of guiding structures realized for second order nonlinear interactions, they present a further advantage as to a better fields overlap between modes at different frequencies. By exploiting this feature in a second-harmonic generation process from a fundamental field at $1.55\mu\text{m}$, a normalized conversion efficiency of $150\% \text{ W}^{-1}\text{cm}^{-2}$ has been recently achieved in reverse-proton-exchanged (RPE) waveguides [3] realized in periodically-poled lithium niobate .

For RPE waveguides in lithium niobate and in lithium tantalate, no exhaustive modelling of the fabrication process has been reported so far in the literature. One of the main reasons is that, due to the buried refractive index profile, it is not possible to fully exploit standard characterization techniques based on prism coupling, such as m-lines spectroscopy for planar waveguides [4]. The field profile of the low order modes is in fact so confined below the substrate surface that the overlap with the field generated below the prism by total reflection is not sufficient for coupling. Only the effective indices of high order modes can thus be measured, and this fact limits the accuracy in the determination of the refractive index profile and hence in the modelling of the waveguides fabrication process.

This paper is addressed to the characterization of planar RPE waveguides and describes a new method which allows the determination of the effective refractive indices (n_{eff}) of the guided modes, even of the lower order ones. The method exploits a second harmonic generation process between fundamental (ω) ordinary radiation modes, coupled into the structure through a conventional prism, and second harmonic (2ω) extraordinary guided modes, which are the only guided modes supported by RPE waveguides [5]. When phase matching occurs, the effective index of the guided mode at 2ω equals that of the radiation mode at ω , so that the former can be easily determined from the coupling angle of the latter. Preliminary results obtained by applying such method to a multi-mode RPE waveguide realized in lithium niobate are presented and discussed.

Operation principle

The method exploits the second harmonic generation process schematically reported in Fig.1, where the fundamental (ω) field is given by prism-coupled radiation modes of a RPE waveguide while the second harmonic (2ω) field by guided modes. The key point of the operation principle is that phase-matching between ω radiation and 2ω guided modes can be satisfied in lithium niobate if the former present an ordinary polarization and the latter an extraordinary one. When such a birefringence phase matching occurs, the effective indices of the interacting modes are the same, i.e. $n_{\text{eff}}^{\omega} = n_{\text{eff}}^{2\omega}$, so that the n_{eff} of the 2ω guided modes can be determined from the coupling angle θ of the ω radiation modes. It is worth pointing out that a direct prism-coupling of the guided modes of RPE waveguides is very often not possible in the case of the lowest order modes, whose field does not superimpose the evanescent field tail generated by total reflection below the prism base. On the contrary, by use of radiation modes, which deeply extend inside the substrate, a sufficient fields overlap is achieved, even with the most confined modes.

The method thus exploits an interaction between two orthogonally polarized modes through the d_{31} nonlinear coefficient of lithium niobate. In order to achieve phase matching it is worth pointing out that, since ω and 2ω modes are respectively guided and radiation-like modes, the n_{eff} at ω is lower than the substrate ordinary index, i.e. $n_{\text{eff}}^{\omega} < n_o^{\omega}$, while the n_{eff} at 2ω is higher than the substrate extraordinary index, i.e. $n_{\text{eff}}^{2\omega} > n_e^{2\omega}$. As a consequence, phase matching occurs only if $n_e^{2\omega} < n_{\text{eff}}^{2\omega} < n_o^{\omega}$. If the ω frequency corresponds to a wavelength $\lambda^{\omega} = 1.55\mu\text{m}$, one has $n_e^{2\omega} = 2.1788$ and $n_o^{\omega} = 2.2112$ [6]: therefore, every guided mode at 2ω can be phase-matched provided that the index change does not exceed ~ 0.033 . The latter is a commonly satisfied condition for α -crystallographic phase waveguides [7]. The method thus proves suitable for the full characterization of most RPE waveguides, and, furthermore, it allows one to obtain directly the n_{eff} at a wavelength $\lambda^{2\omega} = 0.775\mu\text{m}$, which is particularly useful when the poling period of waveguides designed for nonlinear processes in the telecom bandwidth are to be designed [3].

Before going into the details of the experimental set-up and results, two further remarks emerge from the operation principle: i) the interaction length of the process is necessarily limited to the dimensions of the coupling region and the effective interaction area suffers from the poor overlap between ω and 2ω fields, thus resulting in a modest conversion efficiency. However, this interaction is not aimed to the best conversion efficiency but to characterization purposes, and, moreover, it involves a new interesting configuration where guided modes are pumped by radiation modes; ii) as in the Cerenkov second harmonic generation process [8], phase matching is very easy to achieve since radiation modes are characterized by a continuous range of effective indices;

Experimental set-up

The experimental set-up is sketched in Fig.1. The laser source is a parametric amplifier pumped by a 10Hz duplicated Nd:Yag laser providing pulses about 20ps long. The energy-per-pulse is kept below $10\mu\text{J}$ before the coupling prism by means of additional filters. A beam-splitter (Bs), a diaphragm (D) previously aligned with the laser beam, and an InGaAs photo-detector (Pd1) are used to obtain the orthogonality between the beam and the prism, so to fix the zero angle for the following rotations. A cylindrical lens (L) having $f=100\text{mm}$ provides a focusing in the plane of the waveguide, so to increase the energy density in the interaction region without affecting the mode-selectivity of the prism coupling technique. A silicon diode placed just at the end of the waveguide

In order to verify the reliability of the method, the n_{eff} were also determined through an independent measurement. To this aim, a conventional m-lines spectroscopy technique was applied at $0.775\mu\text{m}$ by means of a Ti: sapphire laser, obtaining the n_{eff} reported in the second column of Table I. The agreement between the two sets of n_{eff} is really excellent, even if the comparison is not possible for TM_0 and TM_1 modes, that can not be directly coupled by prism due to the lack of a sufficient fields overlap. The method thus proves as the only mean to capture the n_{eff} of the lowest order modes, and particularly of the TM_0 mode, whose knowledge is of the uppermost importance for the design of poling periods of all-optical devices based on χ^2 processes in RPE waveguides. Further measurements are currently in progress on other waveguides realized with different fabrication parameters in order to achieve a comprehensive investigation of the reverse-proton-exchange process.

Conclusions

A new configuration for the second harmonic generation process, involving fundamental ordinary radiation modes and second harmonic extraordinary guided modes, has been proposed and demonstrated in RPE waveguides in lithium niobate, which are nowadays the most efficient guiding structures for all-optical nonlinear processes.. This method proved very effective for an accurate determination of the effective refractive indices of the guided modes, even of the lower order ones.

References

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