Optik 123 (2012) 896–900

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Theoretical analysis of electromagnetic field distribution and Cerenkov second harmonic generation conversion efficiency based on lithium niobate ion-implanted channel waveguide

G.L. Du*, G.Q. Li, S.Z. Zhao, T. Li, X. Li

School of Information Science and Engineering, Shandong University, Jinan 250100, PR China

ARTICLE INFO

Article history:
Received 3 October 2010
Accepted 10 February 2011

Keywords:
Ion-implantation
Channel waveguide
Cerenkov SHG
Nonlinear optics

ABSTRACT

Cerenkov type second harmonic generation (CSHG) is proposed in ion-implanted Z-cut lithium niobate ($LiNbO_3$) channel waveguides. We have obtained exact analytical solutions for the field distribution and the power of second-harmonic waves. Conditions for attaining higher conversion efficiency are discussed on the basis of numerical calculations.

1. Introduction

The nonlinear optics phenomenon of second harmonic generation (SHG) is much of interest in the area of high density optical data storage, color image processing, and optical measurements. CSHG occurs when the nonlinear second harmonic polarization wave generated in the nonlinear medium has a phase velocity faster than that of the free second-harmonic wave in the material. For this case, phase matching is automatically satisfied. So it has large tolerances for fabrication and work conditions, which is a very important advantage especially in SHG of semiconductor laser light source. [1–10].

This Cerenkov scheme of SHG was first proposed and used by Tien et al. in a ZnS–ZnO slab waveguide [1]. Theoretical analyses of CSHG have been reported by several authors. They use several approaches, such as the antenna theory [1], the dipole radiation theory [2], or the coupled mode theory [3,4]. CSHG from a planar waveguide was analyzed in our previous paper [5]. In slab waveguides, an approximate can be applied as the transverse dimensions are larger than the thickness while in channel waveguide the width is limited. Almost all optical waveguides used as coupler or modulator in integrated optics technology can be considered to be channel waveguides. However, to our knowledge, no paper attempts to explain the general characteristics of CSHG in ion-implanted channel waveguides.

In this paper, we have obtained exact analytical solutions for the field distribution and the power of second-harmonic waves in ion-implanted channel waveguides. Higher efficiency CSHG of channel waveguides will be attainable when parameters are well matched.

2. Theory

Fig. 1 illustrates a typical CSHG configuration, as a representative of devices using channel waveguides. The channel is assumed to be parallel to one of the optical principal axes of the waveguide material, and the axis is taken as the z axis of the coordinate system. We treat only the case of a z-cut substrate, in this geometry only TM pump is possible for CSHG.

In the notation of field and refractive indices, the subscripts f and h imply fundamental and harmonic field. Besides, the subscripts 1, 2, and 3 denote the waveguide, the substrate, and the cladding, respectively.

The geometrical effect plays an important role in CSHG, and our calculation for channel waveguides takes into account the whole area surrounding the guiding layer which contains most of the energy radiated by CSHG.

* Corresponding author.
E-mail address: guolongdu@gmail.com (G.L. Du).

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doi:10.1016/j.ijleo.2011.02.035

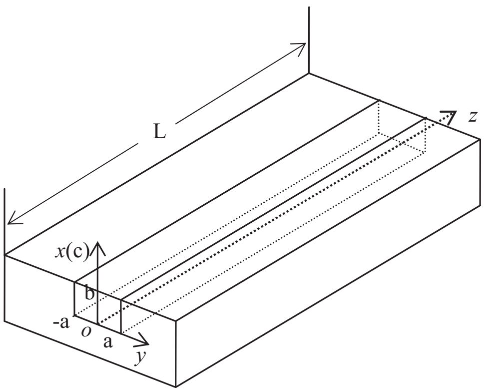

Fig. 1. Configuration of the channel waveguide with respect to the crystal axes.

2.1. Mode distribution of fundamental wave

By applying Maxwell's equations, we can obtain the expression of field E_{fx},

$$E_{fx} = \begin{cases} N_f n_{fe1}^2 \cos \rho_f y \cos(\sigma_f b + \phi_f) e^{-r_{fa}(x-b)} & (-a < y < a, x > b; \quad \text{in cover}) \\ N_f \cos \rho_f y \cos(\sigma_f x + \phi_f) & (-a < y < a, 0 \le x \le b; \quad \text{in waveguide}) \\ N_f \left(\dfrac{n_{fe1}^2}{n_{fe2}^2}\right) \cos \rho_f y \cos \phi_f \, e^{r_{fx} x} & (-a < y < a, x \le 0; \quad \text{in substrate}) \\ N_f \cos \rho_f a \cos(\sigma_f x + \phi_f) e^{-r_{fy}(y-a)} & (a \le y < \infty, 0 \le x < b) \\ N_f \cos \rho_f a \cos(\sigma_f x + \phi_f) e^{r_{fy}(y+a)} & (-\infty < y \le -a, 0 \le x < b) \end{cases} \tag{2.1.1}$$

with the dispersion equations for propagation and decay constants as follows:

$$r_{fy}^2 = (n_{fe1}^2 - n_{fe2}^2) k_f^2 + \sigma_f^2 \left[\left(\frac{n_{fe2}}{n_{fo2}}\right)^2 - \left(\frac{n_{fe1}}{n_{fo1}}\right)^2 \right] - \rho_f^2$$

$$r_{fx}^2 = \left(\frac{n_{fo2}}{n_{fe2}}\right)^2 \left[(n_{fe1}^2 - n_{fe2}^2) k_f^2 - \left(\frac{n_{fe1}}{n_{fo1}}\right)^2 \sigma_f^2 \right]$$

$$r_{fa}^2 = (n_{fe1}^2 - 1) k_f^2 - \left(\frac{n_{fe1}}{n_{fo1}}\right)^2 \sigma_f^2$$

$$\beta_f^2 = n_{fe1}^2 k_f^2 - \rho_f^2 - \left(\frac{n_{fe1}}{n_{fo1}}\right)^2 \sigma_f^2$$

The continuity of the field E_{fz} at the boundaries $x = b$ and $x = 0$ as well as H_{fz} at $y = a$ leads to eigenvalue equations:

$$\sigma_f b = m\pi + \arctan\left(\frac{r_{fa}}{\sigma_f} n_{fo1}^2\right) + \arctan\left(\frac{r_{fx}}{\sigma_f}\left(\frac{n_{fo1}}{n_{fo2}}\right)^2\right)$$

$$(m = 0, 1, 2, 3, \ldots) \tag{2.1.2}$$

$$\rho_f a = m\pi + \arctan\left(\frac{r_{fy}}{\rho_f}\right) \quad (m = 0, 1, 2, 3, \ldots) \tag{2.1.3}$$

For the TM pumping situation, the fundamental wave power then can be written as

$$P_f = \frac{N_f^2 ab}{4\mu_0 \omega_f \beta_f} c_f \tag{2.1.4}$$

With

$$c_f = \left(1 + \frac{\sin 2\rho_f a}{2\rho_f a}\right)(c_{f1} + c_{f2})$$

$$c_{f1} = \left(\frac{n_{fe1}^2}{n_{fe2}^2}\right)^2 \cos^2 \phi_f (k_f^2 n_{fe2}^2 - \rho_f^2) \frac{1}{r_{fx} b}$$

$$c_{f2} = (k_f^2 n_{fe1}^2 - \rho_f^2) \left[1 + \frac{\sin 2(\sigma_f b + \phi_f) - \sin 2\phi_f}{2\sigma_f b}\right]$$

2.2. Mode distribution of second generation wave

Maxwell's equations for the second-harmonic fields are

$$\nabla \times E_h = -\mu_0 \frac{\partial H_h}{\partial t} \tag{2.2.1A}$$

$$\nabla \times H_h = \varepsilon_0 \varepsilon_h \frac{\partial E_h}{\partial t} + \frac{\partial P}{\partial t} \tag{2.2.1B}$$

The nonlinear polarization which acts as a source for the second harmonic radiation is given by

$$P_x = \varepsilon_0 d_{33} E_{fx}^2, \qquad P_y = 0, \qquad P_z = 0$$

From (2.2.1), we can derive

$$\begin{cases} \left[\beta_h^2 - \left(\dfrac{n_{he}^2}{n_{ho}^2}\dfrac{\partial^2}{\partial x^2} + k_h^2 n_{he}^2 + \dfrac{\partial^2}{\partial y^2}\right)\right] E_{hx} = \dfrac{1}{\varepsilon_0 n_{ho}^2}\dfrac{\partial^2 P_x}{\partial x^2} + \mu_0 \omega_h^2 P_x \\ \left[\beta_h^2 - \left(\dfrac{\partial^2}{\partial y^2} + k_h^2 n_{ho}^2 + \dfrac{\partial^2}{\partial x^2}\right)\right] E_{hy} = \left(\dfrac{n_{he}^2}{n_{ho}^2} - 1\right)\dfrac{\partial^2 E_{hx}}{\partial x \, \partial y} + \dfrac{1}{\varepsilon_0 n_{ho}^2}\dfrac{\partial^2 P_x}{\partial x \, \partial y} \\ E_{hz} = -\dfrac{i}{\beta_h n_{ho}^2}\left(n_{he}^2 \dfrac{\partial E_{hx}}{\partial x} + n_{ho}^2 \dfrac{\partial E_{hy}}{\partial y}\right) - \dfrac{i}{\varepsilon_0 \beta_h n_{ho}^2}\dfrac{\partial P_x}{\partial x} \\ H_{hx} = \dfrac{1}{\mu_0 \omega_h \beta_h}\left[\dfrac{\partial^2 E_{hx}}{\partial x \, \partial y} - \left(\varepsilon_0 \mu_0 \omega_h^2 \varepsilon_{hy} E_{hy} + \dfrac{\partial^2 E_{hy}}{\partial x^2}\right)\right] \\ H_{hy} = \dfrac{1}{\mu_0 \omega_h \beta_h}\left[-\dfrac{\partial^2 E_{hy}}{\partial x \, \partial y} + \left(\varepsilon_0 \mu_0 \omega_h^2 \varepsilon_{hx} E_{hx} + \dfrac{\partial^2 E_{hx}}{\partial y^2}\right)\right] + \dfrac{\omega_h}{\beta_h} P_x \\ H_{hz} = \dfrac{i}{\mu_0 \omega_h}\left(\dfrac{\partial E_{hy}}{\partial x} - \dfrac{\partial E_{hx}}{\partial y}\right) \end{cases} \tag{2.2.2}$$

This is the electromagnetic field distribution of SHG. In TM mode, only *Hy*, *Ex* and *Ez* can propagate. *Hy* and *Ez* can be represented by *Ex*.

The solution to E_{hx} will involve a general solution to the homogeneous equation as well as a particular solution to the inhomogeneous equation. P_x can be obtained by

$$P_x = \varepsilon_0 d_{33} E_{fx}^2 \tag{2.2.3}$$

Then, E_{hx} can be easily obtained through the electromagnetic field distribution of SHG.

$$E_{hx} = \begin{cases} D e^{-k_{h3}(x-b)} & \text{(cover)} \\ A\, e^{-ik_{h1}x} + B\, e^{ik_{h1}x} + s_{11} \cos 2(\sigma_f x + \phi_f) + s_{12} & \text{(waveguide)} \\ C\, e^{ik_{h2}x} + s_2\, e^{2r_{fx}x} & \text{(substrate)} \end{cases} \tag{2.2.4}$$