SURFACE-EMITTED DIFFERENCE FREQUENCY GENERATION IN PERIODICALLY POLED STEP-INDEX PLANAR WAVEGUIDE

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Abstract

It was shown that the periodically poled optical waveguide with period $\Lambda = 2\pi/\beta_s$ of poling (β_s is a propagation constant of nonlinear polarization wave) is capable of emitting the THz-wave difference frequency generation (DFG) in direction normal to the surface of waveguide. The DFG power in cover of periodically poled lithium niobate (PPLN) planar weveguide is numerically calculated. It was shown that efficiency of frequency conversion in the surface emitting geometry is better than for case collinear geometry, especially in THz region where PPLN have a large absorption.

1. INTRODUCTION

The nonlinear difference frequency generation (DFG) of laser sources is a convenient technique to produce a coherent THz-wave radiation, although typically the DFG conversion efficiency is not high [1]. As a rule the materials with high nonlinearity have a large absorption in THz region. For example the widespread $LiNbO_3$ have a coefficient of absorption about a few tens cm^{-1} [2,3]. In addition it is impossible to increase efficiency of DFG by using high concentration of laser radiation in optical waveguide. The point is that thickness of optical waveguide is much less than wavelength of emitted THz-wave, and therefore output THz-beam will have a very large divergence [1]. In modern researches of mid-IR DFG a tapered waveguide [4,5] is usually used for overcoming the above-mentioned problem and for the increases of interaction volume. However this approach can not be applied in case of THz DFG, when wavelength of emitted wave is approximately two order of magnitude more than wavelength of optical stimulant radiation.

In present paper we offer to realize THz-wave DFG in planar waveguide in surface-emitted geometry (SEG). In this case the absorption of emitted wave is determined by the thickness of waveguide which is extremely small. The divergence THz-beam can be also small, because the large area of waveguide's surface determines it. The additional advantage of SEG is a significant increase of generation efficiency due to the possibility of application of resonant cavities both at a pumping

and at a difference frequency. The SEG allows the separate optimization of both optical and THz cavities.

To obtain the THz-wave emission in SEG (in direction normal to the surface of waveguide) we suggest using Cherenkov-type DFG in periodically poled lithium niobate (PPLN) waveguide. In this case each spatial harmonic of the nonlinear polarization wave emits Cherenkov radiation in the direction that is conditioned both by the material dispersion and by the spatial period of PPLN structure, Λ [6,7]. By choosing an appropriate value of Λ the DFG can be obtained in direction normal to the surface of waveguide. All layers of the waveguide to emit THz-wave with the same phase because thickness of the waveguide is much more less than the wavelength of emitted wave, λ. The necessary period Λ and λ are values of the same order, and therefore the such PPLN structure can be easily implemented.

The capability of surface-emitted DFG does not contradict a conversion law of momentum. Indeed, due to uncertainty principle the value of momentum uncertainty in thin waveguide is much more than the momentum of emitted THz-wave. The purpose of this paper is to develop simple theoretical model for surface-emitted DFG in PPLN waveguide.

2. THEORY

Let us consider two waves with frequencies ω_1 and ω_2, which propagate in PPLN (x-cut) planar waveguide as fundamental TE-modes, polarized along the optical z-axis of lithium niobate (Fig. 1). The nonlinear mixing of propagating waves in a slab will induce a nonlinear polarization at the difference frequency $\omega_3=\omega_1-\omega_2$:

$$P_z = 2d(y)E_1(x)E_2^*(x)\exp[i(\Omega t - \beta_s y)]. \tag{1}$$

Here $\beta_s = \beta_1 - \beta_2$, and $E_{1,2}(x)$, $\beta_{1,2}$, are amplitudes and propagation constants of interacting optical waves, respectively. The spatial distribution of the nonlinear coefficient in PPLN is given as:

$$d(y) = \frac{4\varepsilon_0 d_{33}}{\pi}\left(\sin\frac{2\pi}{\Lambda}y + \frac{1}{3}\sin 3\frac{2\pi}{\Lambda}y + \cdots\right). \tag{2}$$

Considering only the first term in (2) and using the condition $\Lambda = 2\pi/\beta_s$ we obtain that the Eq. (1) includes the term which does not depend on the coordinates z and y:

$$P_{z0} = -i4\varepsilon_0 d_{33}\pi^{-1}E_1(x)E_2^*(x)\exp(i\omega_3 t) \tag{3}$$

It means the phase of polarization is the same at any point of the surface of PPLN waveguide. In other words, the induced dipoles oscillate with the same phase throughout the waveguide. Therefore the radiation in direction normal to the waveguide's surface is formed. The situation is similar to the surface-emitted second harmonic generation in counter-propagating wave geometry [8].

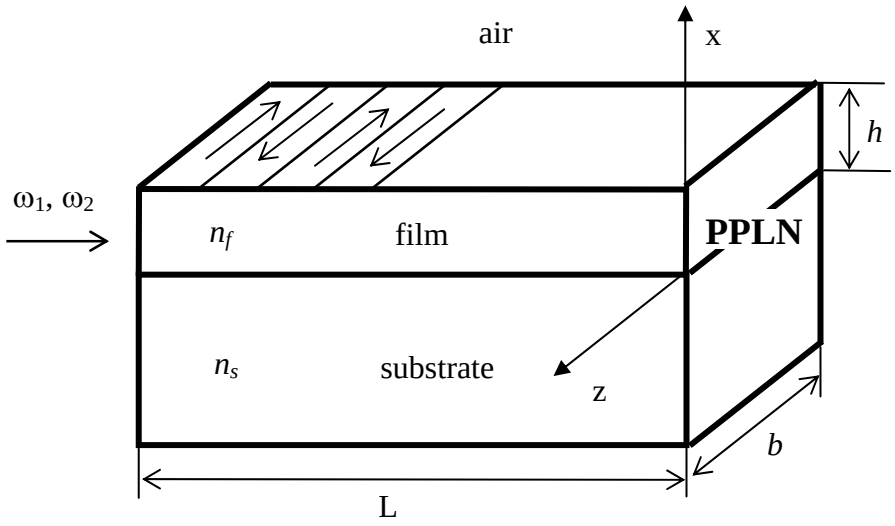

Figure 1. The scheme of surface-emitted DFG in PPLN waveguide.

For calculation of an electrical field of surface-emitted DFG, it is needed to decide a one-dimensional wave equation:

$$\frac{d^2E_z(x)}{dx^2}+\frac{\omega_3^2 n(x)}{c^2}E_z(x)=-\mu_0\Omega^2 P_{z0}(x) \tag{4}$$

in waveguide's substrate (x<0), film (0<x<h) and cover (x>h). For simplicity we assume that a cover is the air (P_{z0} = 0) and refractive indexes of film and substrate is same values.

The solution of Eq. (4) can be written as

$$E_z=\begin{cases} D\,e^{-ik_0(x-h)} & x>h \\ Ae^{-ikx}+Be^{ikx}+rF_f & 0<x<h \\ Ce^{ikx}+rF_s & x<0 \end{cases} \tag{5}$$

where $r = 4k_0^2 d_{33}/\pi$, $k_0 = 2\pi/\lambda$, $\lambda = 2\pi c/\omega_3$ is a wavelength of emitted wave, $k = k_0 n$, n is a refractive index of film and substrate at a wavelength of emitted wave.

The particular solution, rF_f and rF_s, represents the forced field which is generated directly by nonlinear polarization P_{z0} is determined by exiting fields. The fields are

$$E_j=\begin{cases} U_j\cos(\gamma_j h-\varphi_j)e^{-\xi_j(x-h)} & x>h \\ U_j\cos(\gamma_j x-\varphi_j) & 0<x<h \quad j=1,2 \\ U_j\cos\varphi_j e^{\zeta_j x} & x<0 \end{cases} \tag{6}$$

guided TE modes which has the following form:

with

$$tg\varphi_j = \zeta_j / \gamma_j,\ \zeta_j = \sqrt{\beta_j^2 - k_j^2 n_{sj}^2},\ \gamma_j = \sqrt{k_j^2 n_{fj}^2 - \beta_j^2},\ tg(\gamma_j h - \varphi_j) = \xi_j / \gamma_j$$

$\xi_j = \sqrt{\beta_j^2 - k_j^2}$, $k_j = 2\pi/\lambda_j$, n_{fj} and n_{sj} are refractive indexes of film and substrate at the ω_j (λ_j) frequencies.

The constant U_j is determined by power of exiting wave, P_j, and given by

$$U_j = \sqrt{\frac{4\eta_0 P_j}{b h_j n_{jeff}}} \tag{7}$$

where $h_j = h + 1/\xi + 1/\zeta$ is the effective depth for guided TE mode at ω_j frequency, $n_{jeff} = k_j n_{fj} / \beta_j$, $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is the impedance of free space, b is width of the waveguide.

Using Eq. (6) for particular solution of (4) we find

$$F_f = \frac{U_1 U_2}{2}\left[\frac{\cos(\gamma_+ x - \varphi_+)}{k^2 - \gamma_+^2} + \frac{\cos(\gamma_- x - \varphi_-)}{k^2 - \gamma_-^2}\right] \tag{8}$$

$$F_s = \frac{U_1 U_2 \cos\varphi_1 \cos\varphi_2 \exp(\zeta_+ x)}{k^2 + \zeta_+^2} \tag{9}$$

where

$$\zeta_+ = \zeta_1 + \zeta_2,\quad \varphi_\pm = \varphi_1 \pm \varphi_2,\quad \gamma_\pm = \gamma_1 \pm \gamma_2. \tag{10}$$

In Eq. (5) the coefficient A, B, C and D can be determined by using the requirements of continuity of both electrical field and its first derivative at the interfaces $x = 0$ and $x = h$. So for DFG power in cover we obtain

$$P_3 = \frac{Lb}{2\eta_0}|D|^2 = \frac{512\eta_0 d_{33} L P_1 P_2}{(n+1)^2 n_{1eff} n_{2eff} b \lambda^2} V \tag{11}$$

where

$$V = \frac{1}{h_1 h_2 U_1 U_2}[k^2(f_{sf}^2 + f_h^2) + g_{sf}^2 + g_h^2 - 2k(g_h f_{sf} - g_{sf} f_h)\sin(kh) + 2(f_{sf} f_h k^2 + g_{sf} g_h)\cos(kh)] \tag{12}$$

and $f_{sh} = F_s(0) - F_f(0)$, $f_h = F_f(h)$, $g_{sf} = \dot{F}_s(0) - \dot{F}_f(0)$, $g_h = \dot{F}_f(h)$.

The comparison powers of DFG generated in both ordinary collinear and surface emitting geometry we will lead using well known formula:

$$P_{30} = \frac{512\eta_0 d_{33} P_1 P_2 (1-e^{-\alpha L/2})^2}{(n+1)^2 n_1 n_2 \lambda^2 \alpha^2 ba} \tag{13}$$

where P_{30} is the power of DFG in collinear geometry, α is the power absorption coefficient at emitted wavelength, a is the size of spot of exiting beams, n_1 and n_2 are refractive indexes of bulk PPLN at frequencies ω_1 and ω_2.

3. RESULTS AND DISCUSSION

The physical mechanism of surface-emitted DFG can be easy explained. Under the condition $\Lambda=2\pi/\beta_s$ the nonlinear polarization wave accumulates the phase shift equal to π after the passage through each domain. At the same time, it gets additional phase shift to π due to the reversal of the sign of nonlinear coefficient in the adjacent domain (Fig.2). So the nonlinear polarization does not change its sign and according to Fourier transform it contains the constant in space component. It means that the elementary dipoles of the surface oscillate with the same phase and therefore can radiate a field only in direction normal to the surface. It should be noted that PPLN with such spatial period $\Lambda= 2\pi/\beta_s$ can be easy fabricated. For THz-wave DFG the value $\beta_s = \beta_1-\beta_2$ can be presented as $\beta_s \approx \Omega n_g / c$ because the frequency $\Omega << \omega_1,\omega_2$. Here $n_g = [n + \omega(dn/d\omega)]_{\omega 2}$ is refractive index of the group velocity of light. Using this we obtain $\Lambda \approx \lambda/n_g$, where a wavelength of THz-wave λ typically lies in region 30-300 μm.

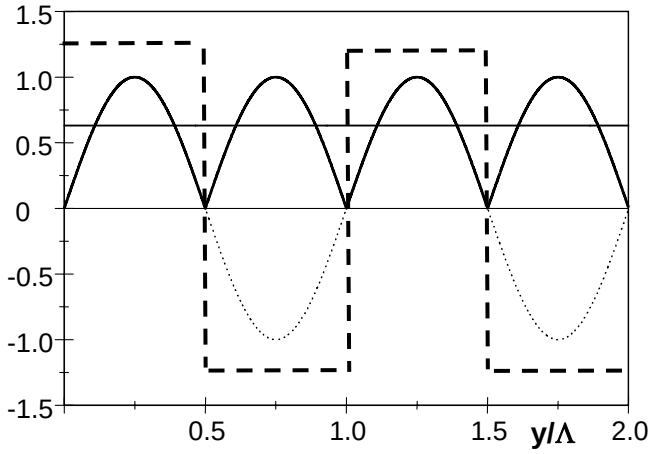

Figure2. Nonlinear polarization (solid) and nonlinear coefficient (---) versus the distance y/Λ.

It is of interest to carry out comparison between power of DFG generated in collinear and surface emitting geometry. Using (11) and (13) we obtain $G = P_3/P_{30} = VLa\alpha^2/[1-\exp(-\alpha L/2)]^2$, where P_{30} is a power of DFG in collinear geometry in PPLN, α is a power absorption coefficient at difference frequency and for simplicity we suggested $n_1 = n_{1eff}$, $n_2 = n_{2eff}$. By substituting in Eq. (12) values: n =5.1, $n_{fj} = n_{sj}$ + 0.05, n_{s1} = 2.15474, n_{s2} = 2.15416, λ_1 = 1064 nm, λ_2 = 1075.6 nm we obtain that value V nearly is not depend on thickness of waveguide's film, h, and typically equal to

0.24. Using this and substitute typical values: L = 5 cm, α = 50 cm^{-1} [3], a = 0.5 mm we obtain G = 150. Thus use of surface emitting geometry results in significant increase of output power.

The period of poling of PPLN (needed for surface-emitted DFG) as a function of wavelength of emitted wave is presented on Fig. 3. The dependence of $\Lambda = \Lambda(\lambda)$ is calculated for planar waveguide with thickness of film equal to 1μm and λ_1=1064 nm. The Fig. 3 shows that dependence of $\Lambda = \Lambda(\lambda)$ is approximately linear (with slope $d\Lambda/d\lambda$ equal to 0.33) and the period is changed in the range, which is achievable in practice.

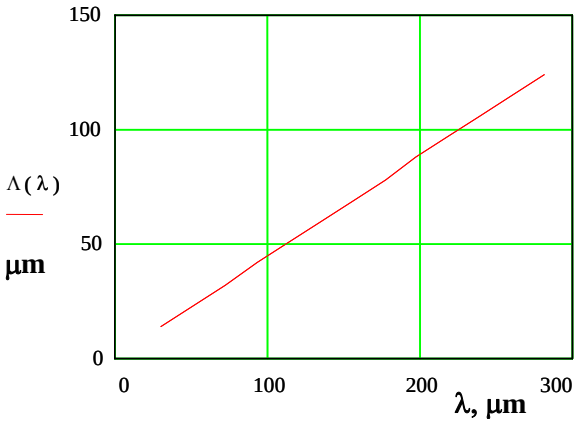

Figure 3.

In contrast to collinear geometry for SE DFG there is no necessity to fabricate a PPLN with strictly given period of poling. The difference between the period of fabricated PPLN structure and required Λ results only in a deflection of the beam from normal direction. The angle of deflection is given by

$$\delta = \frac{\omega_1 N_1 - \omega_2 N_2}{\Omega} \frac{\Delta\Lambda}{\Lambda} \approx n_g \frac{\Delta\Lambda}{\Lambda} \tag{14}$$

So for relative error $\Delta\Lambda/\Lambda$ = 0.01 we have δ = 12°, which is approximately equal to angle of total internal reflection of $LiNbO_3$ at THz-wave.

From Eq. (11) we can get some numerical results for practical case. Using: λ=100 μm, d_{33} = 165 pm/V (from microwave electro-optical data), L = 6 cm, b = 0.3 mm for efficiency of the frequency conversion we obtain $\eta = P_3/P_1P_2 = 1.4\cdot10^{-7}$ W^{-1}. The compact lasers with impulse output power 1 MW and with CW power 300 mW now are commercially available. Therefore the DFG output power can be above 40 mW.

The Eq. (11) indicates that output power is inversely proportional to the width of the waveguide. It is possible to expect about ten-multiple increase of power using channel waveguide instead of planar. The accompanied growth of divergence of THz-beam can be compensated by placing of short-focusing cylindrical lens close to the surface of channel waveguide. The much greater increase of output power can be expected if resonance cavity at the pumping frequency is used [9].

4. CONCLUSIONS

It was shown that the periodically poled optical waveguide with specific period of poling is capable of emitting the THz-wave DFG in direction normal to the surface of waveguide. The general expression was obtained for the power emitted from the PPLN planar waveguide. It was shown that efficiency of frequency conversion in surface emitting geometry is more than for common collinear geometry case, especially in high absorbing nonlinear materials. According to estimation the surface-emitting DFG enables the design of compact solid-state source of THz-waves with the output power, which is sufficient for the practical applications.

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