Features of noncollinear parametric generation light in $LiNbO_3$ crystal pumped by the fundamental radiation of Nd:YAG laser

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ABSTRACT

Theoretical and experimental studies the features of parametric generation light in $LiNbO_3$ with noncollinear phase matching from noncollinear angle i_{23}, i.e. angle between pump wave vector and resonant signal wave vector, are presented. It was shown that at the small angle $i_{23}< 0,3°$ four nonlinear processes can simultaneously take place: these processes are noncollinear parametric conversion of the 1.0642 μm into the signal and an idler waves; second-harmonic generation of the signal; noncollinear difference-frequency mixing of the doubled signal and the idler; parametric conversion of the doubled signal into new pair: the signal and an idler waves.

It is shown that the maximum efficiency of noncollinear OPO takes place for tangential phase-matching at $i_{23} \approx 0,9°$. Spectral broadening of the signal wave of $LiNbO_3$ noncollinear OPO was studied. Theoretically it is shown that the spectral bandwidth of the signal wave depends on the divergency of the signal wave.

Key words: optical parametric oscillator, $LiNbO_3$ crystal, noncollinear phase-matching conditions.

1. INTRODUCTION

2.

The last few years have seen an increased number of scientific publications devoted to optical parametric oscillators (OPO) with noncollinear phase matching. This is due to the fact that at noncollinear phase matching for three-frequency parametric interactions, a marked change is possible in the shape of tuning curves, angular and spectral acceptance [1-3]. Detailed study of the peculiarities of 1.0642-μm pumped pulsed optical parametric oscillator of $LiNbO_3$ with noncollinear phase matching is an urgent problem which solution will make it possible to devise high-efficiency light sources generating radiation in the eye-safe range 1.5-1.8 μm as well as radiation for remote sensing of impurities in the atmosphere in the 2.8-3.5 μm range.

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2. EXPERIMENTAL SET-UP

A type-I noncollinear phase matching $LiNbO_3$ OPO is schematically represented in Fig.1.

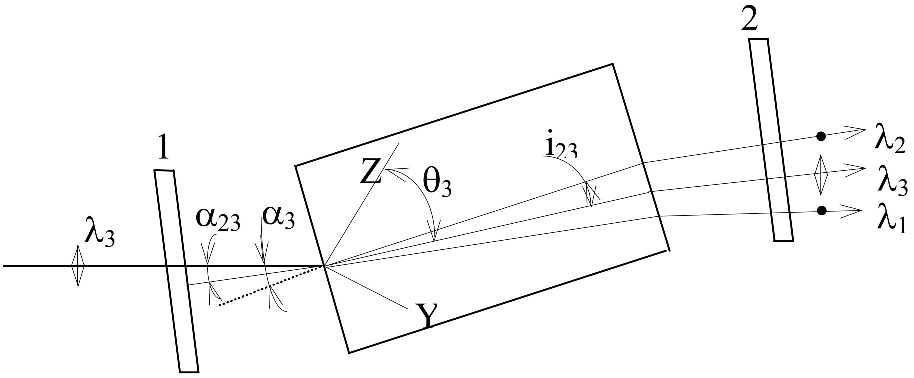

Fig.1

The $LiNbO_3$ crystal was cut at φ=270° and θ=45° relative its optic axis and had dimensions 10mm×20mm×40mm. The OPO cavity consisted of two flat mirrors 1, 2 that reflected the signal wave in the range 1.5-1.7 μm. Both mirrors transmitted the pump and idler waves. The cavity length was 6.5 cm. The mirrors of the OPO resonator were set perpendicular to the YZ plane of the $LiNbO_3$ crystal. The optical axis of the cavity could be rotated with respect to the directions of the pump beam. In experiment the angle α_{23} between the optical axis of the cavity and the pump beam was varied over the range from 0.3° to 2°. Wavelength tuning of this OPO was realized by rotating the nonlinear crystal about the axis perpendicular to the YZ plane of the $LiNbO_3$ crystal. In the noncollinear OPO the idler wave radiation was directed toward a rift of the energy flux of the extraordinary pump wave. The OPO was pumped at 1.0642 μm by a 10 Hz repetition rate Q-switched multimode Nd:YAG laser (Solar LS, model LQ-727). The laser provided ~240 mJ of energy with pulsewidth ~6 ns. The pump beam 5 mm in diameter had a divergence of ~0.8 mrad. The spatial intensity profile of the pump beam polarized in a horizontal plane was close to a rectangular one. The pump radiation intensity was equal to ~200 MW/cm^2. The pump radiation loss with allowance made for the reflection from the input face of the $LiNbO_3$ crystal was ~30%.

3. EXPERIMENTAL RESULTS

We investigated the spectral characteristics of noncollinear OPO for the case where the angle α_{23} between the cavity axis and the pump beam was small and equal ~ 0.3°. Initially, the $LiNbO_3$ crystal was positioned so that its faces were parallel to the cavity mirrors. In this case, the angle of incidence of the pump beam on the input face of the crystal α_3 ~ 0.3° and OPO generated two waves: a signal λ_2=1.943 μm and an idler λ_1=2.353 μm. When the angle α_3 was varied over the range from 0.43° to 0.86°, the OPO simultaneously generated four frequencies (Table):

α_3, degree	λ_1, μm	λ_2, μm	λ_3, μm	λ_4, μm
0,43	2,380	1,925	0,9625	1,611
0,57	2,424	1,897	0,9485	1,560
0,72	2,450	1,881	0,9405	1,540
0,86	2,485	1,861	0,9305	1,527

When the angle α_3 was varied from 1° to 2° the OPO generated the two waves: the signal λ_2 and the idler λ_1. Fig.2 shows the spectrum of OPO at angle α_3 ~0.55° which generated the signal wave at λ_2=1.917 µm. As the reper line with λ_r=1.598 µm shown in Fig.2, we used the third stokes component of the Raman frequency converter based on a Ba $(NO_3)_2$ crystal.

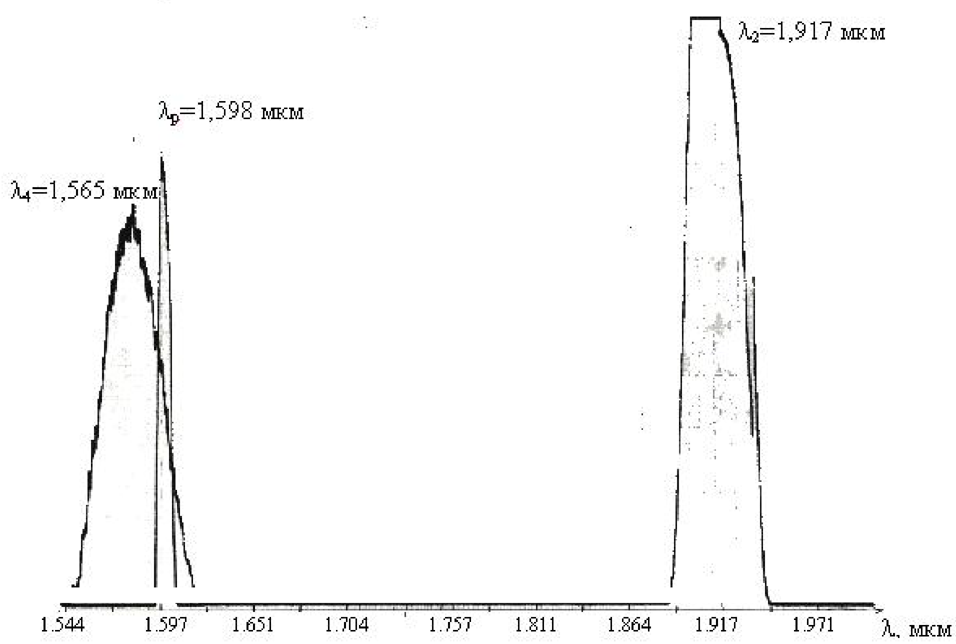

Fig.2

For various values of the angle α_{23}, measurements were made of the spectral linewidth of the signal wave at λ_2=1.572 µm. It has been found that as the angle α_{23} was increased from 0.3 to 2°, the spectral linewidth of the signal wave increased from 6 nm to 18 nm, respectively.

We investigated the OPO efficiency at λ_1=3.294 µm and λ_2=1.572 µm varying the angle α_{23} over the range from 1° to 2°. It has been found that at angles α_{23} in the range from 1.6° to 1.8° the OPO efficiency is maximum and the threshold pump energy is minimum.

4. DISCUSSION

To explain the experimentally observed peculiarities of noncolliniar $LiNbO_3$ OPO we calculated the phase-matching angle-tuning curves

- -for 1.0642 µm-pumped noncollinear OPO;
- -for second-harmonic generation of the signal;
- -for noncollinear difference-frequency mixing of the doubled signal and the idler and
- -noncollinear OPO pumped by the second harmonic of the signal wave.

A vector diagram of vectors satisfying the phase-matching conditions for noncollinear parametric generation of two waves λ_1 and λ_2 is illustrated in Fig.3.

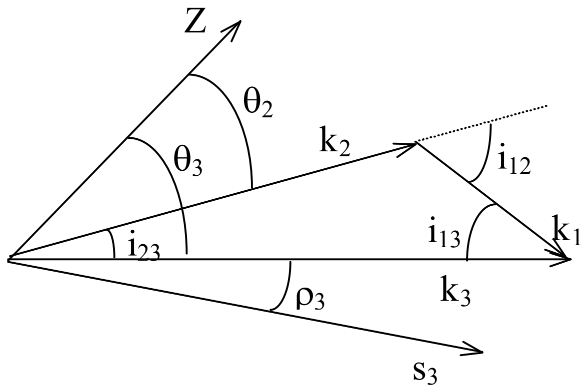

Fig.3

Here the following notations are used: i_{23}-angle between the wave vectors of the signal wave k_2 and the pump wave k_3, i_{13}-angle between the wave vectors of the idler wave k_1 and the pump wave k_3 , i_{12}- angle between the wave vectors of the signal wave k_2 and the idler wave k_1, ρ_3 -walk-off angle of an extraordinary polarized pump beam, θ_3-angle between the vector k_3 and the optical axis Z, θ_2-angle between the vector k_2 and the optical axis Z, s_3-Pointing vector of the extraordinary pump beam. The curves are calculated using the refractive indices by the Sellmeier dispersion equations for stoichiometric melt (mole ratio Li/Nb=1,000) $LiNbO_3$ [4].

The calculated phase-matching angle-tuning curves for 1.0642 μm-pumped noncollinear OPO and second-harmonic generation of the signal as a function of the wavelength of the signal in the 1.7-2.1 μm range are pesented in Fig.4. The angle-tuning curves for the noncollinear OPO and the second-harmonic generation intersect in the range of angles i_{23} from 0° to 0.25°.

For example, at the angle i_{23}=0.11° in the direction of θ_2=44.73° the simultaneous occurence of two nonlinear processes:
-noncollinear parametric generation 1.0642 μm → 1.897 μm ⊕ 2.424 μm and
-second-harmonic generation 1.897 μm → 0.9485 μm.

The presence of the doubled signal may lead to the appearance of two new processes:
-noncollinear difference-frequency mixing 0.9485 μm - 2,424 μm → 1.5582 μm ° and
-new parametric generation 0.9485 μm → 1.560 μm ⊕ 2.420 μm .

Fig.5 shows the calculated phase-matching angle-tuning curves for 1.0642 μm-pumped noncollinear OPO and angle i_{23}=0.11°-1, and for 0.9485 μm- pumped noncollinear OPO and angle i'_{23}=0.04°-2. With the presence of the doubled signal the second noncollinear parametric process can in principle become possible.

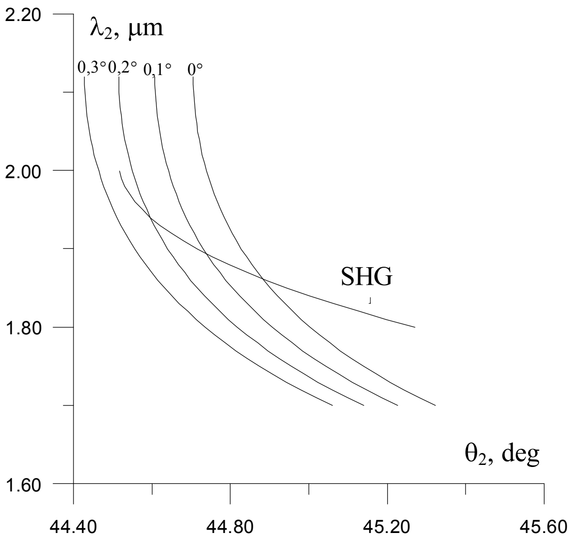

Fig.4

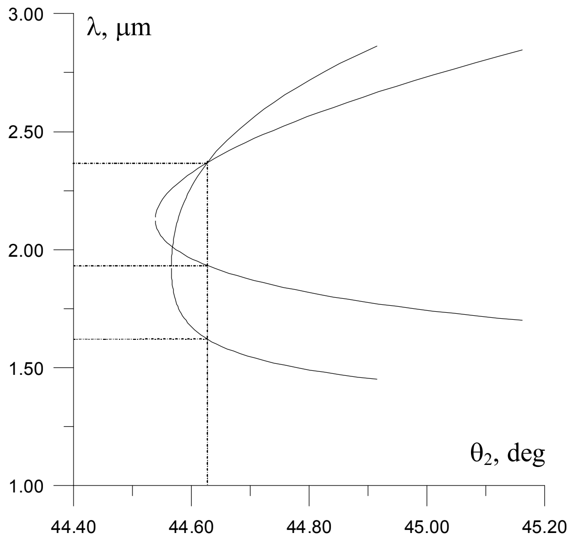

Fig.5

It should be noted that in [5] it is shown that for 1.0642 μm-pumped $LiNbO_3$ OPO there is a specal case in which additional difference-frequency mixing of the doubled signal and the idler take place. The obtained results point to the possibility of simultaneous existence of four nonlinear processes.

The experimentally observed increase in the efficiency of OPO is due to the increase in the angular pump wave acceptance of the noncollinearly phase-matched type I OPO [6].

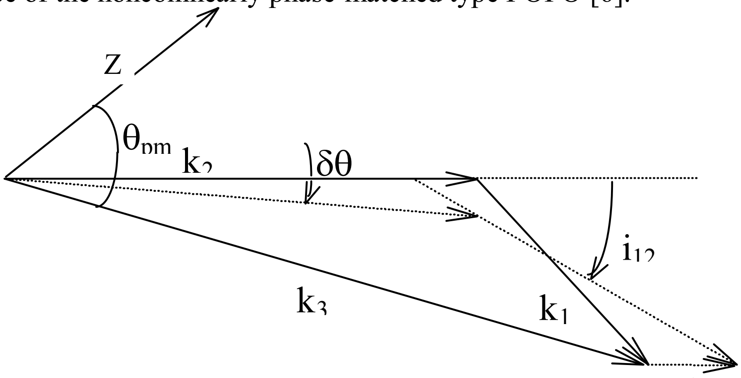

Fig.6.

By using the vector diagram (Fig.6) it is easy to obtain the expression for the angular acceptance $\Delta\theta_{pm}$:

$$\Delta\theta_{pm} = -\left|\frac{a}{b}\right| + \left[\left(\frac{a}{b}\right)^2 + \frac{1.772\lambda_3}{|b|L}\right]^{1/2}.$$

where $a = \frac{\partial n_3}{\partial\theta}\left(\cos i_{23} + \mathrm{tg}\, i_{12}\sin i_{23}\right) + n_3\left(\cos i_{23}\,\mathrm{tg}\, i_{12} - \sin\alpha_{23}\right)$, $b = \frac{1}{2}\left(\frac{\partial^2 n_3}{\partial\theta^2} + \frac{\lambda_1 n_2 n_3 \cos i_{23}}{\lambda_2 n_1 \cos i_{12}}\right)$.

For small angles i_{12} and i_{23} and taking into account $\frac{\partial n_3}{\partial\theta} = -\rho_3 \cdot n_3$ expression $a \approx n_3\left(i_{12} - i_{23} - \rho_3\right)$.

When $i_{12} = i_{23} + \rho_3$ and the Pointing vector s_3 of the extraordinary pump beam coincides with the wave vector k_1 of the idler wave, coefficient a becomes zero and the angular acceptance $\Delta\theta_{pm}$ reaches its maximum $\Delta\theta_{pm}^{max} = \left(\frac{1.772}{|b|}\frac{\lambda_3}{L}\right)^{1/2}$. The calculated curve of angular acceptance $\Delta\theta_{pm}\cdot L$ as a function of angle i_{23} is shown in Fig.7.

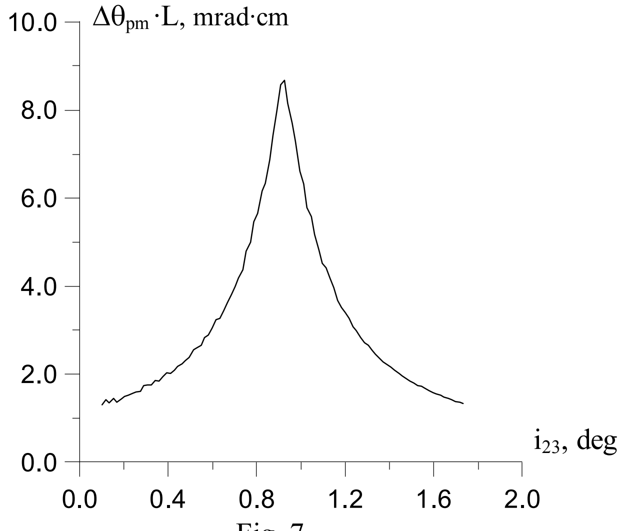

Fig. 7.

Tangential phase-matching increases the angular acceptance of the 1.0642 μm-pumped type I $LiNbO_3$ OPO from ~1mrad·cm (for collinear phase-matching) to ~9mrad·cm.

Let us discuss the causes of the experimentally observed broadening of the spectral linewidth of the signal wave. It is known [7] that for collinear phase-matching OPO the spectral linewidth of the signal wave is due to both crystal dispersion $\Delta\nu' = 2\pi/(\beta_{21}L)$ and the pump beam divergence $\delta\theta_3$ $\Delta\nu'' = 2\rho_3\delta\theta_3/\beta_{21}$, where

$$\beta_{21} = \left|\frac{\partial(\omega_1 n_1)}{\partial\omega_1} - \frac{\partial(\omega_2 n_2)}{\partial\omega_2}\right|.$$

For $LiNbO_3$ OPO away from the degeneration point $\beta_{21}\approx 0.1$, estimation gives the following values of the spectral linewidth: $\Delta\nu'$=2 cm^{-1} and $\Delta\nu''$=6 cm^{-1} per 1 mrad of the pump beam divergence [7], which are an order of magnitude smaller than the experimental ones. An increase in the spectral linewidth is due to the fact that at noncollinear phase-matching there appears an additional mechanism of broadening: the dependence of the spectral width $\Delta\nu'''$ from the signal beam divergence $\delta\theta_2$.

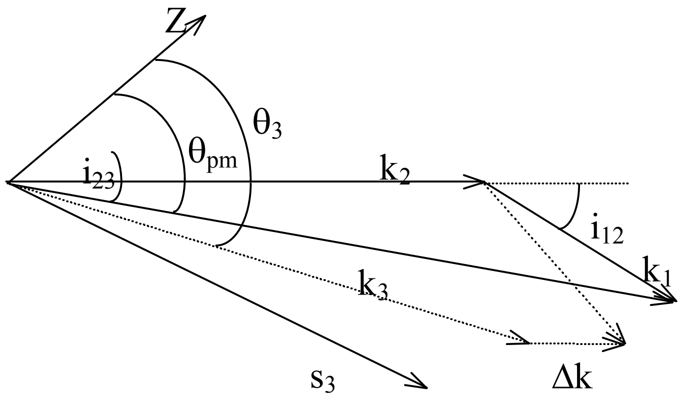

Fig.8.

The signal beam divergence $\delta\theta_2$ leads to the appearance of additional phase detuning Δk_2 calculated on the basis of the vector diagram (Fig.8):

$$\Delta k_2 = k_3(\theta)\cos i_{23} - k_1 \cos i_{12} - k_2 \cos(\delta\theta_2),$$

$$k_3 \sin i_{23} = k_1 \sin i_{12} + k_2 \sin(\delta\theta_2).$$

Since k_3=const and the wave vectors k_1 and k_2 change in both the direction and modulus, then differentiating with respect to w_1, w_2, i_{12} and $\delta\theta_2$, we obtain the following expression for the spectral linewidth $\Delta\nu'''$:

$$\Delta\nu''' = \frac{2k_2k_3}{k_1} i_{23} \frac{\delta\theta_2}{g_{21}}.,\ \text{where}\ g_{21} = \beta_{21}.$$

For collinear phase-matching (i_{23}=0), the broadening under consideration is absent.

For noncollinear phase-matching (i_{23}=1°) estimation gives $\Delta\nu''' \approx 65$ cm^{-1} per 1 mrad of the signal beam divergence. Thus, at the angle i_{23}=1° spectral linewidth of the signal wave $\Delta\nu'''$, which is due to the signal beam divergence, is about an order of magnitude larger than the spectral width $\Delta\nu_2''$, which is due to the pump beam divergence.

5. CONCLUSION

It has been found that in a 1.0642 μm-pumped type I noncollinear $LiNbO_3$ OPO four nonlinear processes can simultaneously take place for a smal angle between signal and pump beams. These processes are noncollinear parametric conversion of the 1.0642 μm into the signal and an idler waves; second-harmonic generation of the signal; noncollinear difference-frequency mixing of the doubled signal and the idler; parametric conversion of the doubled signal into new pair: the signal and an idler waves.

It is shown that the maximum efficiency of noncollinear OPO takes place for tangential phase-matching, when the Pointing vector of the extraordinary pump beam coincides with the wave vector of the nonresonant idler wave.

It has been found that in noncollinear OPO there appears an additional mechanism of broadening of spectral linewidth of the signal wave, which is due to the signal beam divergence.

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