Features of the angle-tuned phase-matched OPO with pump beam reflected

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ABSTRACT

The development of compact high efficiency optical parametric oscillators (OPO) which generate widely tunable coherent radiation with small divergence and high angular pointing stability is a currently a topical problem. In the past, many efforts have been made to reduce the spectral bandwidth and the divergence of the OPO output beam. The spatial and spectral properties of a 355nm pumped pulsed ns-BBO OPO were improved by using type II phase matching and pump beam back reflection [1]. In this way the OPO bandwidth was reduced by more than a factor of 20 to less than 0.1nm, and the divergence of the OPO beam was reduced in the phase matching plane by a factor of 5 to 1mrad.

We investigated the spectral properties of the type II BBO OPO and KTP OPO pumped at 532nm and pump beam reflected. It was found, that the OPO bandwidth was reduced by more than a factor of 5 to less than 0.3nm at 680nm and 0.7nm at 1064nm. We determined, that in collinear OPO with inclined nonlinear crystal in the forward direction the output signal beam deviates from the pump beam. After reflection at the OPO out-coupling mirror the signal and pump beams inside crystal are non-collinear. After passing through the crystal in backward direction and reflection at the OPO rear mirror the signal and pump beams inside crystal are again collinear.

Key words: optical parametric oscillator, BBO crystal, KTP crystal, noncollinear phase-matching conditions.

1. REDUCTION OF THE SPECTRAL WIDTH OF THE KTP OPO WITH BACK REFLECTION OF THE PUMP BEAM

The OPO was pumped by the second (532nm) of Q-switched Nd:YAG laser. We used 14-mm long KTP crystal cut at $\varphi = 0°$ and $\theta = 54{,}5°$. OPO resonator optics are coated to make the cavity singly resonant at the signal wavelength and to double pass the pump light. The signal beam is separated from the idler and pump using 45°-dichroic mirrors M_2 coated for HR at the signal wavelength and HT at the pump and idler.

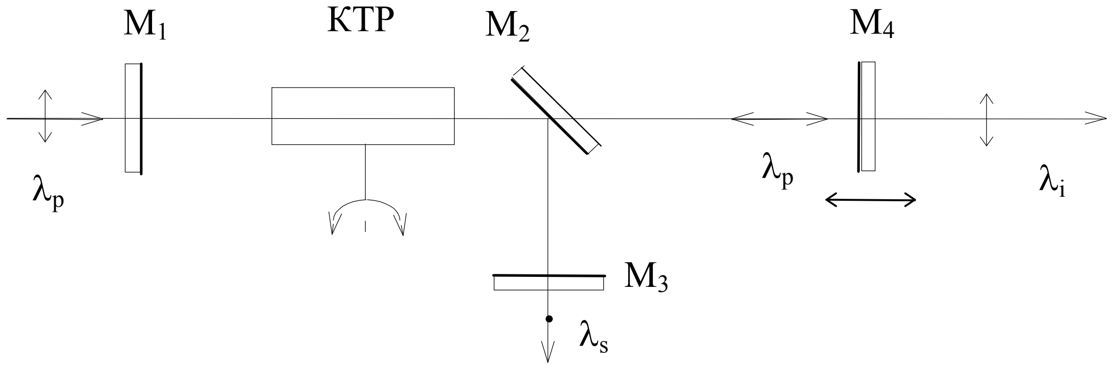

Fig.1. Experimental layout of KTP OPO with back reflection of the pump beam.

We measured spectrum of OPO signal wave when operated with and without pump beam reflection. The spectral bandwidth of KTP OPO without pump beam reflection was ~ 1,8 nm, Fig.2, and with pump beam reflection was ~ 0,4 nm, Fig.3.

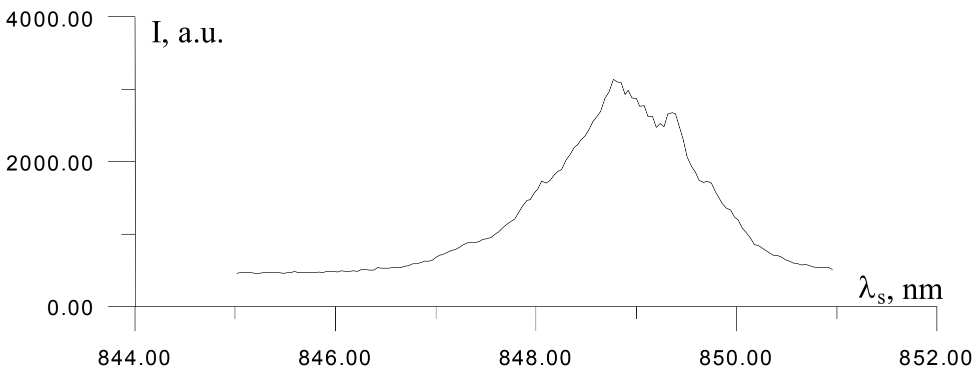

Fig.2. Spectrum of the signal wave of KTP OPO without back reflection of the pump beam.

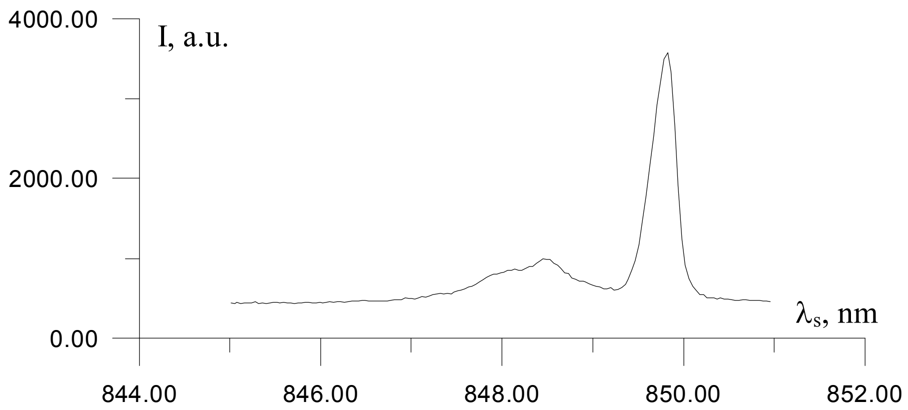

Fig.3. Spectrum of the signal wave of KTP OPO with back reflection of the pump beam.

According to the theory of noncollinear phase matching a divergent beam can be considered as a homogeneous distribution of rays, each with a small noncollinear angle with respect to the direction of the propagating beam [1]. The noncollinear angles of the OPO waves i_{23} are defined as the angles between the directions of the pump wave and the OPO waves. The signs of these noncollinear angles are positive or negative if the propagation of the OPO waves deviates from the direction of the pump beam in clock-wise or counter-clockwise direction, respectively, Fig.4.

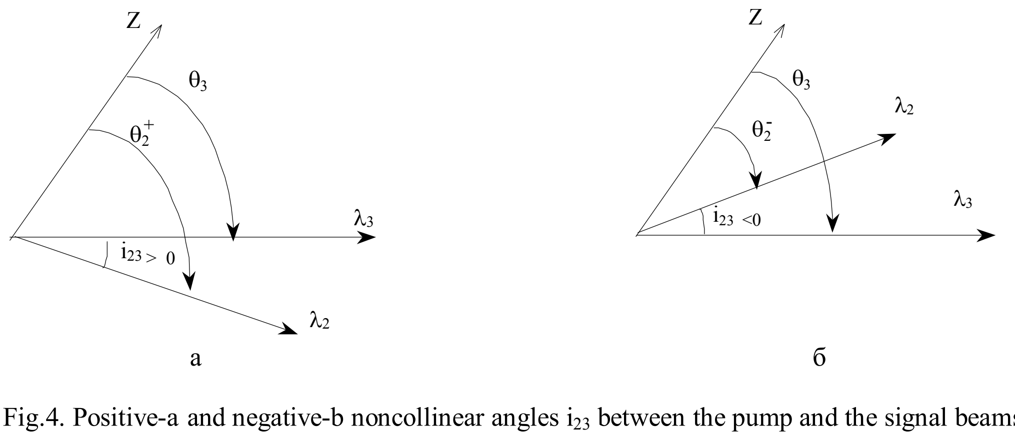

Fig.4. Positive-a and negative-b noncollinear angles i_{23} between the pump and the signal beams.

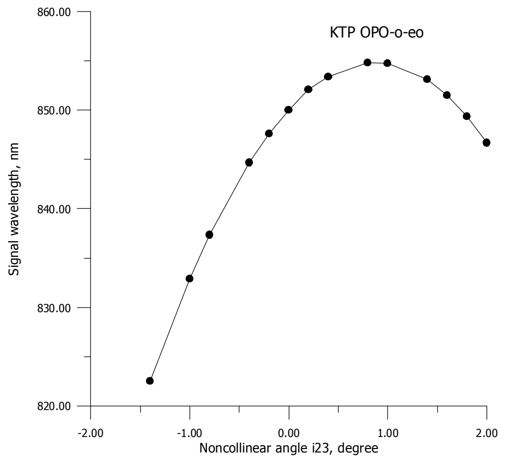

Fig.5. Wavelength of the signal wave calculated for type-II KTP OPO pumped at 532nm as a function of the noncollinear angle i_{23}.

A deviation of the direction of propagation of the OPO waves from the phase matching angle $\theta_3 = \theta_{pm}$ causes a phase mismatch. This phase mismatch is compensated by a change in OPO wavelength. For type II o-eo phase matching KTP OPO, the e-polarized signal wave causes an asymmetric change of the OPO wavelength, Fig.5. In this example a signal wavelength of λ_{20} = 850 nm for collinear phase matching is assumed.

From Fig.5 it is obvious that the divergence of the resonant OPO wave causes a spectral broadening of the OPO bandwidth.

According to our calculations, λ_2 = 848.9 nm at the angle i_{23} =–0,1°, and λ_2 = 851.1 nm at the angle i_{23} =+0,1°. It is evident, that at divergence of the resonant signal beam ~ 3.5mrad the spectral broadening of signal wave is ~ 2.2 nm.

Due to the asymmetry of the wavelength–shift–curve and different sign of the noncollinear angle i_{23} for wave travelling in forward or backward direction, the gain is at different wavelengths for the forward and backward passes, Fig.6.

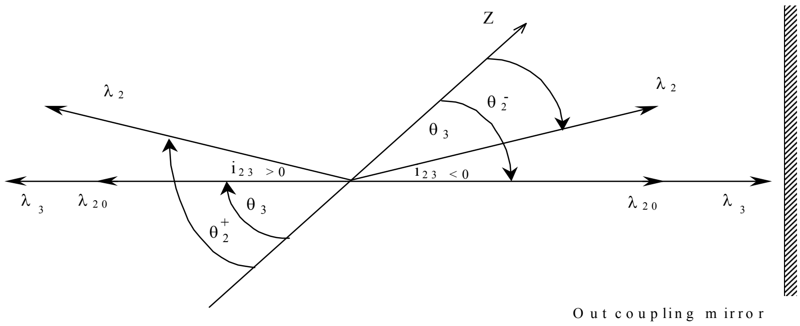

Fig.6. Change of the sign of the noncollinear angle i_{23} between the pump and the signal beams after reflection at the OPO out-coupling mirror.

For the central ray with wavelength λ_{20} the wave mismatch is equal to zero both in “direct” and “back” directions, i.e. $\Delta k^-(\lambda_{20}) = \Delta k^+(\lambda_{20})$=0. For the forward travelling ray with wavelength λ_2 and angle i_{23} < 0° the wave mismatch in “direct” direction is equal to zero, $\Delta k^-(\lambda_2)$=0. After being reflected at the out-coupling mirror the angle i_{23} > 0° and wave mismatch is not equal to zero, $\Delta k^+(\lambda_2) \neq 0$, Fig.5. It is clear, that only collinear rays experience gain at the same wavelength for both passes through the nonlinear crystal. Therefore, double-passing the pump beam will reduce the divergence and spectral bandwidth of the resonant signal wave. The angular acceptance in the phase matching plane is about 0.7 mrad and the bandwidth acceptance is about 0,43 nm at λ_{20} = 850 nm for collinear type-II 532nm pumped OPO with 14-mm long KTP crystal. The close agreement of the measured spectral width with the calculated bandwidth acceptance clearly indicates that the OPO bandwidth is now mainly determinated by the gain bandwidth of the parametric process.

2.ANGLE DEVIATION OF THE SIGNAL BEAMS OF ANGLE TUNED BBO OPO

Lets consider the angle tuned collinear OPO, which contained two plane mirrors and, nonlinear crystals cut at the angle of θ_c to the optic axis. And lets the axis of resonator and axis of pump beam with wavelength λ_3 coincide and pumping is performed through “rear” mirror, Fig.7.

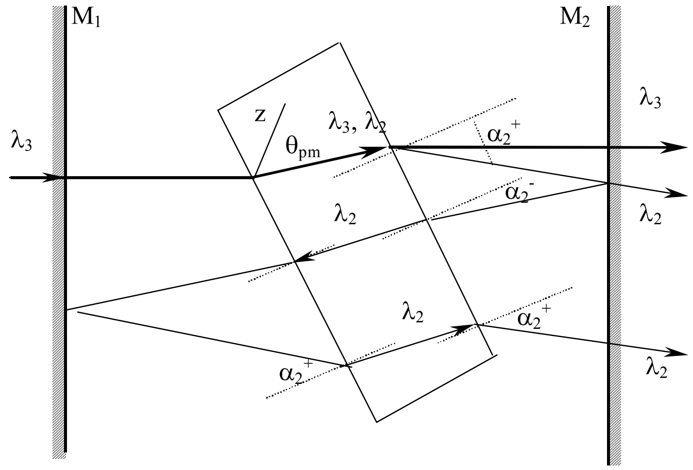

Fig.7. The position of the pump and the signal beams in inclined crystal in OPO with one-passing the pump.

In normal position of nonlinear crystal the signal and idler waves are generated with λ_{20} and λ_{10} respectively, which propagates in one direction with pump beam at the angle θ_c to the optical axis and perpendicular to the crystal faces. Outside the crystal these beams propagates perpendicular to the mirrors of resonator.

When the crystal is tilted, the two other signal and idler waves with λ_2 and λ_1 respectively are generated. Inside the crystal they propagates in one direction with pump beam at the angle $\theta_{pm} \neq \theta_c$. After refraction, the output beams are deviated at different angles: $\alpha_1^+ = \arcsin(n_1 \cdot \sin(\theta_{pm} - \theta_c))$, $\alpha_2^+ = \arcsin(n_2 \cdot \sin(\theta_{pm} - \theta_c))$ and $\alpha_3 = \arcsin(n_3 \cdot \sin(\theta_{pm} - \theta_c))$, where n_1, n_2, n_3 – refractive indexes at λ_1, λ_2 and λ_3 , respectively.

Outside the crystal the pump beam is incident perpendicular to the mirror M_2. The signal beam is incident on the mirror M2 at the angle $\alpha_{23} = \alpha_2^+ - \alpha_3$, Fig.7. After being reflected at the mirror M_2 the signal beam is incident on the crystal face at the angle $\alpha_2^- = 2\alpha_3 - \alpha_2$. Upon refraction on the crystal face the signal beam propagates to the optic axes at the angle $\theta \neq \theta_{pm}$. After being reflected at the mirror M_1 the signal beam is incident on the crystal face at the angle α_2^+.

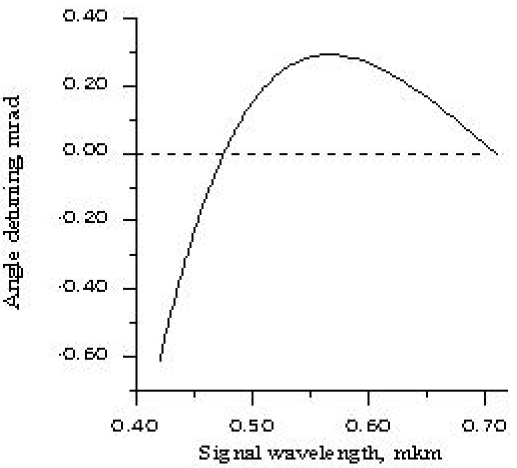

Fig.8. Dependence of an angle deviation of the signal beam α_{23} versus the wavelength in collinear type-I BBO OPO pumped at 355nm. BBO crystal cut at angle of $\theta_c = 29°$.

Thus, at numerous reflections from the mirrors of OPO resonator the signal beam deviates from the pump beam. In the OPO with tilted crystal the deviation angle α_{23} depends on dispersion of crystal’s refraction index and on difference angles $\theta_{pm} - \theta_c$. The calculated values of the angles α_{23} in BBO OPO with the crystal cut at angle of $\theta_c = 29°$ for type I e-oo phase matching and pumped at $\lambda_3 = 354.7$nm, are shown in Fig.8.

The calculations show, that in the normal position of the crystal the deviation angle α_{23}=0° for the signal beam with λ_{20}=475nm; the deviation angle α_{23}= -0.69° for λ_{20}=420nm and the deviation angle α_{23}= +0.29° for λ_{20}=566nm. It is obvious, that in the OPO with one-passing pumping scheme the output signal beam will deviate from the direction of pump beam when BBO crystal is rotated.

Lets consider the angle tuned collinear OPO with two-passing pumping, Fig.9: In this case the gain for wave travelling in forward and backward direction are different.

- In the forward direction inside the crystal the signal beam and the pump beam are collinear and their wave mismatching is equal to zero. After reflection from the output mirror in the back direction inside the crystal the signal beam and the pump beam are noncollinear and their wave mismatching is not equal to zero. After reflection from the rear mirror in the forward direction inside the crystal the signal beam and the pump beam are again collinear and their wave mismatch is equal to zero;
- In the back direction inside the crystal the new signal beam is generated. After reflection from the rear mirror this beam is not amplified. After reflection from the output mirror this beam is amplified again.

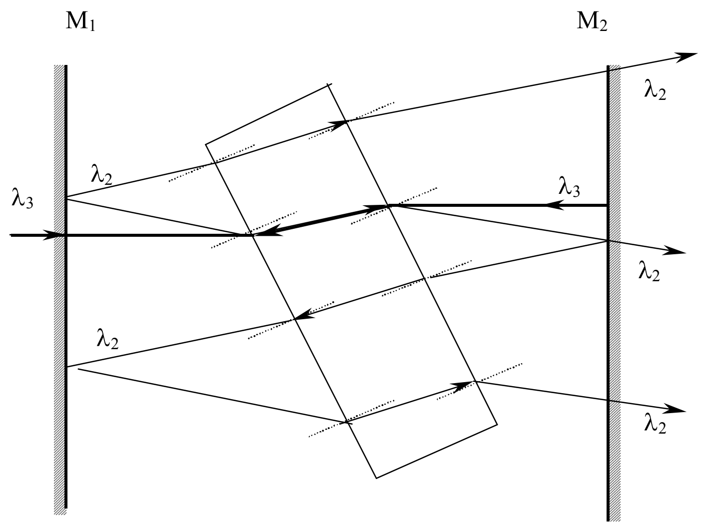

Fig.9. The position of the pump and the signal beams in inclined crystal of OPO with two-passing pumping scheme.

This means, that in OPO with two-passing pumping scheme two signal waves will be generated: one propagates in the forward direction coinciding with the pump direction, and the other propagates in the back direction coinciding with the direction of back-reflected pump beam.

REFERENCES

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