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# Three-Frequency Wave Interactions in the Field of 100 fs Ti:Sapphire Laser pulse in PPLN

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The paper contains experimental results of three-frequency parametric conversion in the field of femtosecond laser pulses in periodically poled lithium niobate crystal. The spectral distribution and the power of radiation at the periodically poled lithium niobate output pumped by Ti:sapphire laser were measured. Special attention is paid to realization of parametric amplification at low frequency pumping. In order to interpret the results obtained we used simultaneous phase matching condition of two coupled three-frequency processes.

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## 1. Introduction

Periodically poled nonlinear crystals (PPNCs) are widely used for effective realization of nonlinear optical wave interactions. In such crystals the phase mismatch of interacting waves for the three-frequency process  $\omega_3 = \omega_1 + \omega_2$  is compensated by the reciprocal grating vector  $\mathbf{g}$  of periodically changing nonlinear coefficient of the crystal [1]:

$$\Delta\mathbf{k} = \mathbf{k}_{\omega_3} - \mathbf{k}_{\omega_1} - \mathbf{k}_{\omega_2}, \quad \Delta\mathbf{k} = \mathbf{g}, \quad \mathbf{g} = \frac{2\pi m}{\Lambda}, \quad (1)$$

where  $\mathbf{k}_{\omega_j}$  is the wave number of the wave with frequency  $\omega_j$ ,  $\Delta\mathbf{k}$  is the mismatch of wave numbers,  $\Lambda$  is the period of the nonlinear structure and  $m$  is the quasi-phase matching (QPM) order ( $m = \pm 1, \pm 3, \dots$ ).

Due to realization of quasi-phase matching the largest nonlinear coefficients can be involved, thus high efficiency of frequency conversion may be achieved. It is possible to satisfy two QPM conditions (1) for two different nonlinear optical processes simultaneously by selecting modulation period of nonlinear coefficient for different QPM orders. Such processes may be consecutive or coupled wave

interactions. In this case the nonlinear grating vector compensates the phase mismatches of several nonlinear optical processes [2].

We investigate two coupled processes in PPNC

$$\omega_p = \omega_1 + \omega_2, \quad (2)$$

$$\omega_1 + \omega_p = \omega_3, \quad (3)$$

where  $\omega_p$  is the pump frequency. The first process is parametric down-conversion, the second one is frequency mixing. From the viewpoint of the  $\omega_3$ -frequency generation, this interaction is the parametric amplification at low frequency pumping. We investigated the process (2), (3) in PPLN with  $\Lambda = 16.6 \mu\text{m}$ . Theoretically predicted optimal wavelengths of the interaction waves are the following:  $\lambda_p = 785 \mu\text{m}$ ,  $\lambda_1 = 1315 \mu\text{m}$ ,  $\lambda_2 = 1956 \mu\text{m}$ , and  $\lambda_3 = 492 \mu\text{m}$ . QPM orders are  $m_1 = 1$  and  $m_2 = 3$  for the process (2) and (3), correspondingly.

## 2. Experiment

The efficiency of nonlinear wave interactions is determined by the intensity of interacting waves. Therefore application of ultrashort pulses allows to increase the energy exchange between interacting waves.

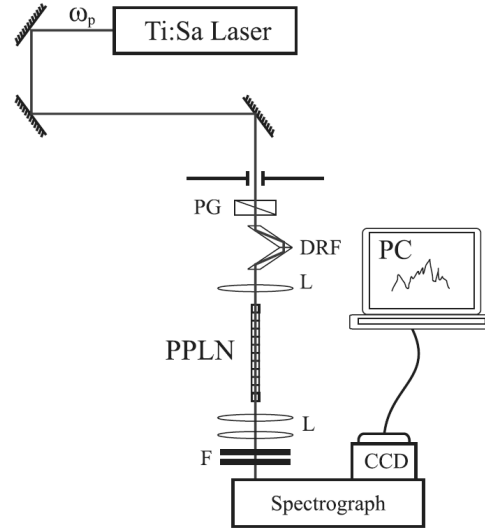


Fig. 1. Experimental setup: PG — polarizing Glan–Taylor prism; DRF — double Fresnel rhomb; L — lenses; PPNL — sample; F — optical filters; CCD — charge-coupled device, PC — personal computer.

The experimental setup is depicted in Fig. 1. For the pumping in our experiments we used tunable Ti:sapphire laser, which produced 100 fs pulses with the average power 1.5 W and spectral width of 11 nm. The beam was focused into the periodically poled lithium niobate (PPNL) sample. The waist of the beam was

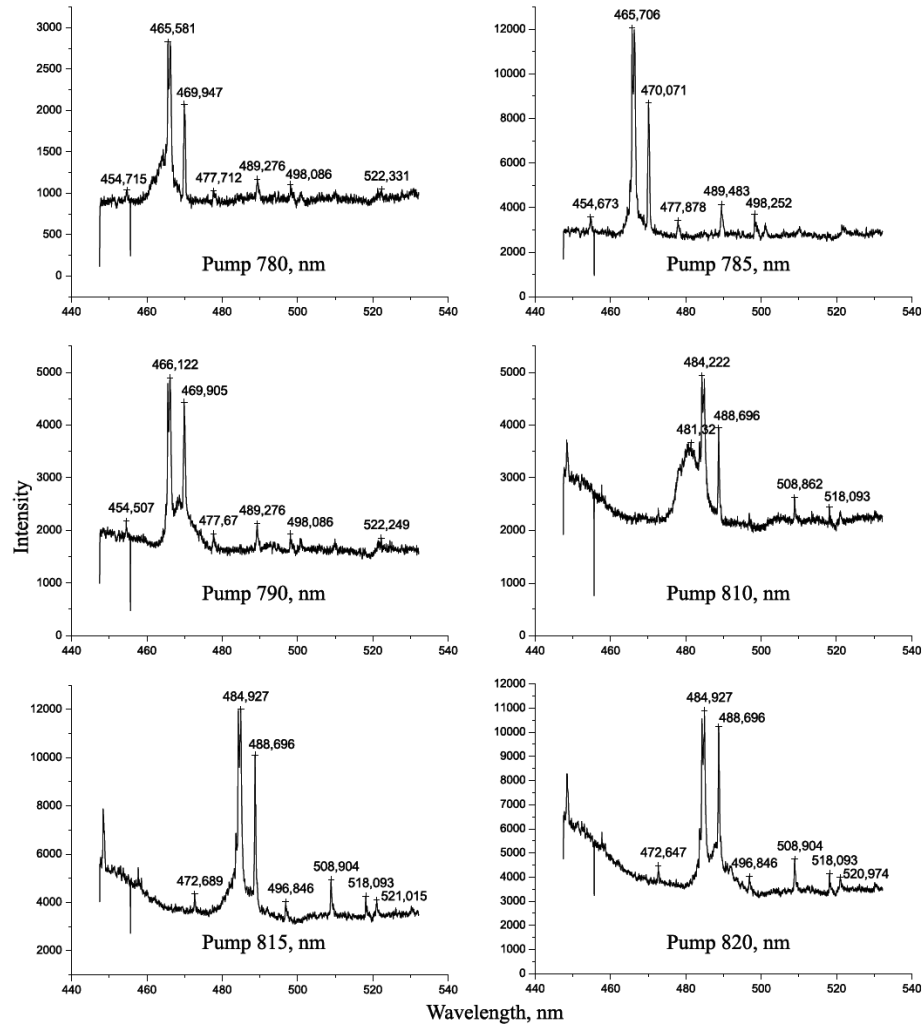


Fig. 2. The spectrum of the signal at the output of the PPLN sample for the different pump wavelengths.

$\approx 100 \mu\text{m}$  in diameter. The maximum average power at focus was  $\approx 350 \text{ mW}$ , which corresponded to a peak intensity of  $\approx 600 \text{ MW/cm}^2$ . Polarizing Glan–Taylor prism was used to ensure an incident linear polarization of the beam, double Fresnel rhomb provided polarization twisting of the pump radiation. The detection system of spectrum consisted of spectrograph, CCD-camera and computer.

The wavelength of pumping was varied in the range of 770–825 nm. The spectral distribution of the radiation near the wavelength of  $\lambda_3 = 492 \mu\text{m}$  was measured. Experimental results shown in Fig. 2 correspond to the parametric amplification at the low frequency pumping. One can see that there are two

intensive components in the generated spectrum and several lower components. The power efficiency of the process was about  $3 \times 10^{-5}$  for the wavelength range shown in Fig. 2.

### 3. Discussion

Let us consider quasi-phase matching from the viewpoint of spatial spectrum of the nonlinear coupling coefficient, which can be written in the form

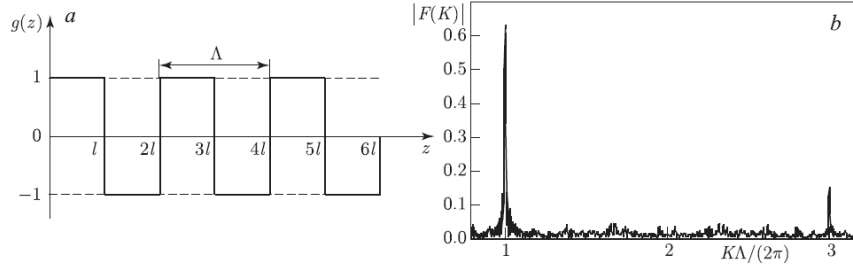


Fig. 3. (a) Function  $g(z)$  ( $\Lambda$  is the modulation period,  $l$  is the domain thickness); (b) spatial spectrum of the function  $g(z)$ .

TABLE

Phase mismatches  $\Delta k$  for LiNbO<sub>3</sub>,  $\mu\text{m}^{-1}$ .

$\lambda_p$ [nm]	780	785	790
$\lambda_3$ [nm]			
465	$ \Delta k_1  = 0.387,$ $ \Delta k_2  = 1.401$	$ \Delta k_1  = 0.386,$ $ \Delta k_2  = 1.404$	$ \Delta k_1  = 0.385,$ $ \Delta k_2  = 1.407$
470	$ \Delta k_1  = 0.385,$ $ \Delta k_2  = 1.345$	$ \Delta k_1  = 0.384,$ $ \Delta k_1  = 1.348$	$ \Delta k_1  = 0.382,$ $ \Delta k_2  = 1.350$
485	$ \Delta k_1  = 0.383,$ $ \Delta k_2  = 1.191$	$ \Delta k_1  = 0.378,$ $ \Delta k_2  = 1.195$	$ \Delta k_1  = 0.377,$ $ \Delta k_2  = 1.198$
489	$ \Delta k_1  = 0.382,$ $ \Delta k_2  = 1.155$	$ \Delta k_1  = 0.379,$ $ \Delta k_2  = 1.158$	$ \Delta k_1  = 0.376,$ $ \Delta k_2  = 1.162$
$\lambda_p$ [nm]	810	815	820
$\lambda_3$ [nm]			
465	$ \Delta k_1  = 0.391,$ $ \Delta k_2  = 1.417$	$ \Delta k_1  = 0.395,$ $ \Delta k_2  = 1.419$	$ \Delta k_1  = 0.400,$ $ \Delta k_2  = 1.421$
470	$ \Delta k_1  = 0.384,$ $ \Delta k_2  = 1.361$	$ \Delta k_1  = 0.386,$ $ \Delta k_2  = 1.363$	$ \Delta k_1  = 0.389,$ $ \Delta k_2  = 1.365$
485	$ \Delta k_1  = 0.342,$ $ \Delta k_2  = 1.218$	$ \Delta k_1  = 0.371,$ $ \Delta k_2  = 1.212$	$ \Delta k_1  = 0.371,$ $ \Delta k_2  = 1.214$
489	$ \Delta k_1  = 0.369,$ $ \Delta k_2  = 1.172$	$ \Delta k_1  = 0.367,$ $ \Delta k_2  = 1.175$	$ \Delta k_1  = 0.368,$ $ \Delta k_2  = 1.178$

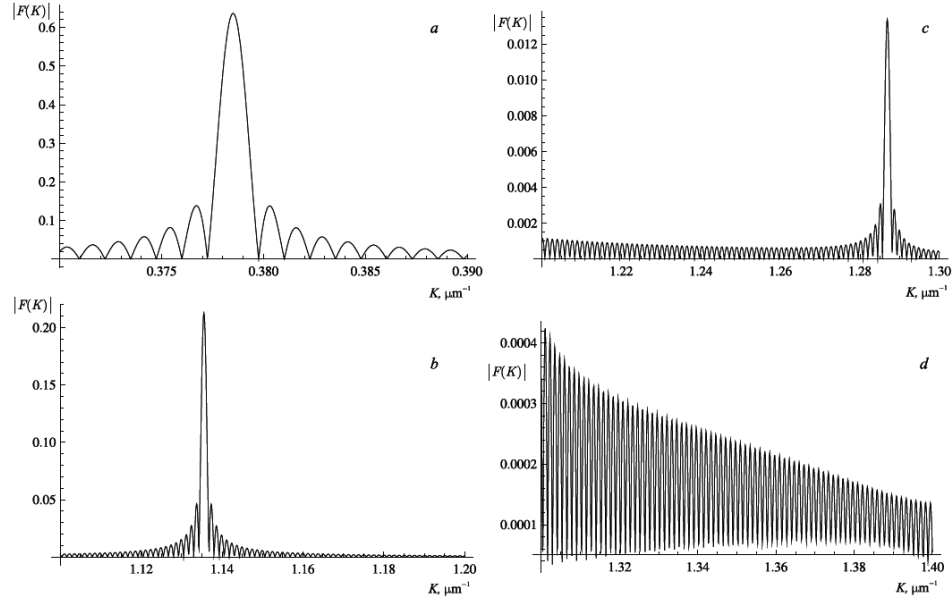


Fig. 4. The spectrum of the function  $g(z)$  with  $\Lambda = 16.6 \mu\text{m}$  and  $L = 0.5 \text{ cm}$  for different ranges of spatial frequencies.

$\chi^{(2)} = d_{\text{eff}}g(z)$ , where  $g(z)$  is the modulation function  $g(z) = \text{sign}(\sin(2\pi/\Lambda))$ , see Fig. 3a. The Fourier transform is defined by the following relation:

$$F(K) = \frac{1}{L} \int_0^L g(z) \exp(-iKz) dz, \quad (4)$$

where  $L$  is the crystals length. It follows from Fig. 3b that if the condition of QPM (1) is fulfilled, then wave interactions can be effectively implemented. It means that spectrum has intensive components for compensating phase mismatch of the process under consideration. In the case of existing a number of intensive spectral components in Fig. 3b, several processes can be effectively realized. To analyze the experimental results we studied the inverse problem. We supposed that  $\omega_p$  and  $\omega_3$  in (2), (3) are fixed and they are measured. Thus frequencies  $\omega_1$  and  $\omega_2$  can be defined and we can calculate phase mismatches  $\Delta k_1 = k_1 + k_2 - k_p$  and  $\Delta k_2 = k_1 + k_p - k_3$  of corresponding processes using dispersion data of lithium niobate crystal [3] (see Table). Then we compared the result obtained with the spectrum of  $g(z)$ .

The spectrum of  $g(z)$  is depicted in Fig. 4. For the convenience of the analysis we separated it into four parts. The process (2) can be eliminated on the QPM order  $m = 1$  (component with  $K = 0.378 \mu\text{m}^{-1}$  has the highest maximum), see Fig. 4a. One can see that there are also maxima near the  $K = 1.287 \mu\text{m}^{-1}$  and  $K = 1.136 \mu\text{m}^{-1}$  which correspond to QPM order  $m = 3$  and  $m = 3.4$ , see Fig. 4b,c. Those maximal values are close to theoretically calculated phase

mismatches for the process (3). We suppose that these components of spectrum provide realizations of the consecutive process. But there is an inconsistency between theoretical and experimental results, it is clear from Fig. 4d. In the range of  $K = 1.3\text{--}1.4 \mu\text{m}^{-1}$  there is no intensive components of the spectrum, although they should be. It can be connected with non-regularity of the nonlinear structure. The modification of the period by  $0.1 \mu\text{m}$ , which is the mean error of the structure, can lead to changing the position of the maximum by the value of  $0.04 \mu\text{m}^{-1}$ . It should be mentioned that the theoretical discussion above corresponds to the case of monochromatic waves and therefore cw pumping. But ultrafast pulses were used for pumping in our experiments. Our calculations showed that we cannot neglect the group velocity mismatches of interacting waves. In PPLN the so-called group length is about  $40 \mu\text{m}$  at pulse duration  $\tau = 100 \text{ fs}$ . Therefore nonlinear optical processes realized are non-stationary ones [4]. More thorough theoretical analysis of this process is the topic of the further investigations.

#### 4. Conclusion

Consecutive nonlinear optical process in the field of femtosecond laser pulses is experimentally realized in PPLN. The spectrum of radiation at the output of the crystal and the efficiency of the process are measured. Parametric amplification at the low frequency pumping has been observed for the first time. The comparison between theoretical estimations and experimental results is carried out.

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