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INFLUENCE OF IDLER PULSE ON OPTICAL PARAMETRIC CHIRPED LASER PULSE AMPLIFICATION

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Чирпирланган лазер импульсларини параметрик кучайтиришда салт тўлқини интенсивлиги спектрал тақсимотининг муҳим осцилляцияси зкспериментал аниқланди. Олинган оддий аналитик ечим асосида бундай сигнал импульси ва салт нурланиш интенсивлигининг спектрал ва вақтий тақсимоти осцилляцияси ва ассимметрияси бошланғич салт нурланиш параметрлари сигналдан фарқ қилишини юзага келтирар экан. Чирпирланган импульсли параметрик кучайтирилган кўп каскадли лазернинг кучайтирилган ва компрессланган чиқиш импульсининг вақтий ва спектрал тақсимоти формасининг бузилиш шартлари аниқланди.

Экспериментально обнаружены значительные осцилляции спектрального распределения интенсивности холостой волны в процессе параметрического усиления чирпированных лазерных импульсов. На основе полученного простого аналитического решения показано, что подобные осцилляции и асимметрия спектрального и временного распределения интенсивности импульсов сигнала и холостого излучения обусловлены небольшим отличием параметров начального холостого излучения от сигнала. Определены условия искажения формы временного и спектрального распределения усиленных компрессированных выходных импульсов многокаскадного лазера с параметрическим усилением чирпированных импульсов.

Significant oscillations of the spectral distribution of the idler pulses in the optical parametric amplification of chirped laser pulse have been observed experimentally. On the base of the obtained simple analytical solution we have showed that such oscillations and an asymmetry of the spectral and temporal distributions of the intensities of the signal and the idler were caused by small variations in the parameters of the initial idler in comparison with the signal one. Conditions for distortion of the shape of the temporal and spectral distributions of the amplified compressed output pulses in a multi-stage laser with optical parametric chirped pulse amplification have been determined.

I. INTRODUCTION

There is great current interest in the use of high-power, ultra-short-pulse lasers for a wide range of applications such as the generation of ultrashort x-ray pulses, the generation of high-order harmonics, the generation of plasma beams, the acceleration of electrons, etc. For many years, the main method of obtaining these laser pulses has been the technique of chirped pulse amplification (CPA) according to the scheme: master oscillator – pulse stretcher – high-power amplifier – pulse compressor [1]. However, this technique does not allow one to eliminate the accompanying amplification of spontaneous emission and the dispersing influence of the amplifiers. Moreover, the requirements on the amplifier bandwidth are rather high. These limitations restrict the applicability of the original CPA technique. A major breakthrough in this field was thus the development of optical parametric chirped pulse amplification (OPCPA), first by Vilnius State University [2] and subsequently at the Rutherford Appleton Laboratory [3]. This technique provides a wide amplification bandwidth and in principle an essentially constant coefficient of

amplification, thus allowing the output power to be increased by two orders of magnitude and compact high-power laser systems to be developed. Despite of relative long researches, now a set of theoretical and experimental works is devoted to analysis of the optical parametric amplification of broadband chirped pulses, its optimization, increase of temporary contrast of radiation, use of quasi-phase matching conditions etc. (for example, [4-8]). As a result, to nowadays, the petawatts peak powers of the OPCPA laser systems compare to the CPA ones [9, 10].

In optical parametric amplification (OPA) alongside with amplification of a signal, there is the generation of the idler wave which energy is comparable to energy of the amplified signal. In early works it was shown that the idler phase is inverted to the signal one and the changes in phases of pump and signal are reflected on the idler. Thus, traditionally it is assumed that the idler can bring the negative contribution to the signal gain, and the idler is removed on each cascade of the OPCPA lasers. At the same time, use of the idler at the input of the OPA allows increasing of the factor of 2 practically.

In our work the influence of the initial idler at the input of the OPCPA on the gain, the shape of distributions of the spectral intensities and chirps of the signal and the idler is considered.

II. EXPERIMENTAL

The experiments were carried out on the set-up using modified multi-cascade Nd:glass laser with the wavelength of 1053 nm. The set-up consists from the two channels. For the OPCPA in a degenerate mode, the diode pumped femtosecond fiber ytterbium laser (YFO-40, Avesta Project) was used as a signal oscillator in the first signal channel of a starting complex (Fig. 1). The passive mode locking laser generated pulses with repetition rates of 40 MHz. The FWHM bandwidth of a signal pulse was 8.2 nm (Fig. 2, curve *1*). At the output of this laser, the pulses got phase modulation and the duration made 12 ps. The measured pulse duration after the compensating compressor was 172 fs. These measurements were carried out by autocorrelator on the base of a step-by-step technique of second harmonic generation. Then in the first signal channel of a starting complex, the radiation passed through stretcher which served for the further phase modulation of the signal resulting to its pulse prolongation up to 452 ps.

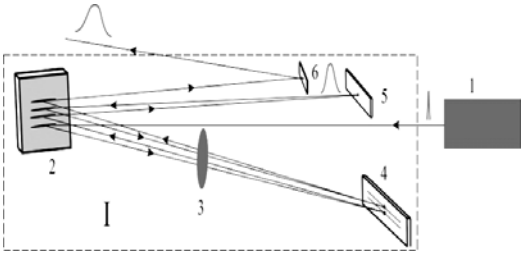


Fig. 1. Scheme of signal channel. I – stretcher; 1 – fs fiber laser; 2 –grating; 3 – lens; 4,5,6 – mirrors.

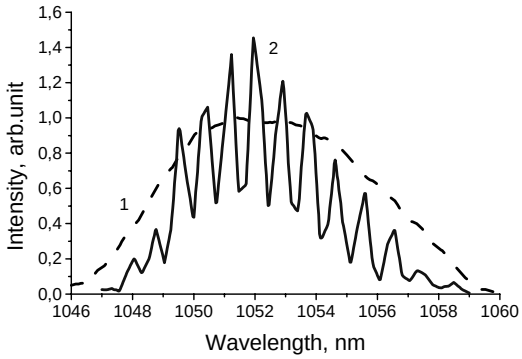


Fig. 2. Spectral distributions of the input signal (dashed curve) and the output idler (solid line) pulses.

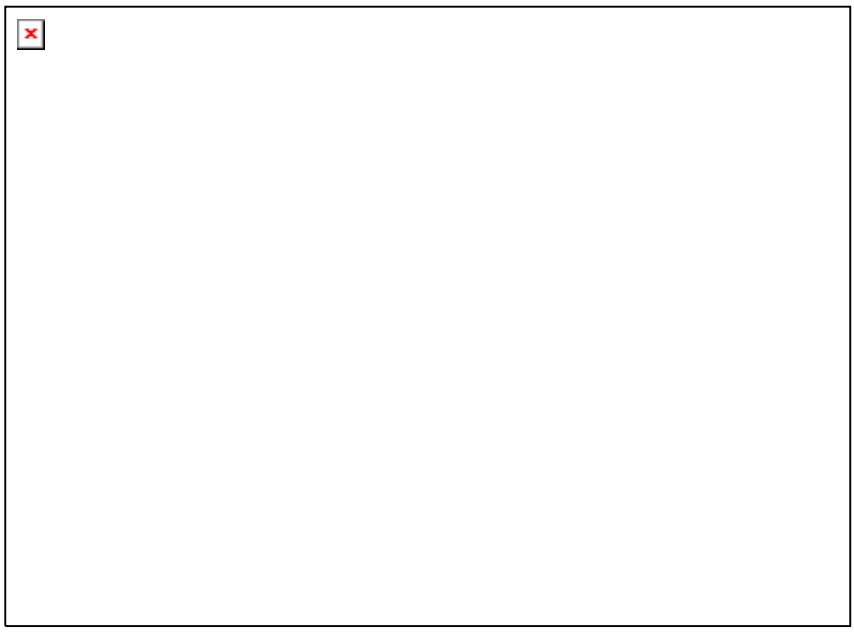


Fig. 3. Scheme of pump channel. I – scheme of ns oscillator; II – scheme of the pulse shaping; III – regenerative oscillator; IV – amplifiers; 1, 21 – fibers; 2, 20 – lenses; 3, 19 – Nd:YLF active rods; 4, 8, 15 – Pockels cells; 5 – Glan prism; 6, 18 – spherical lenses; 7, 14, 16 – prisms; 9, 10, 11, 12, 13, 17, 22, 23, 24, 25, 27, 28 – mirrors.

As the oscillator of the second pump channel, the oscillator on the diode pumped Nd:YLF active element was used (Fig. 3, I). The pulse duration was 3 ns. The value of pulse duration and synchronization was provided by two Pockels cells (4 and 9). The electric pulses of the cells were synchronized with the femtosecond laser by the high-speed block of synchronization (Picker). Thus, there was the simple and safely synchronization of the laser with cavity dumping and passive mode locking laser with jitter down to 15 ps. Then the radiation of the second channel amplified in regenerative amplifier on the diode pumped Nd:YLF active element (II). After the regenerative amplifier, the radiation was directed to the two linear two-passed lump pumped amplifier (Nd:YLF, ∅10 mm). At the output of the amplifying cascade the laser pulse duration was 2.4 ns with energy of 235 mJ.

Then the radiation was frequency doubled in a KDP crystal with efficiency of 62%. This radiation at the wavelength of 527 nm served as pump of two crystals of the parametric amplifier. The FWHM bandwidth of the second harmonic was less than 1.5 nm. Two nonlinear-optical crystals, two crystals KDP ($40\times40\times40$ mm^3), were used as the OPA. The crystals were cut for the I-type of an interaction. The angle between pump and signal beam was 2 degree. Two crystals of the parametrical amplifier were unwrapped from each other for decreasing of the lateral walk-off.

The measurements of a spectrum of a pulse of parametric wave radiations were carried out by HR4000 spectrometer (Ocean Optics). The resolution of the spectrometer and time of integration were 0.5 nm and 4 ms, respectively. The OPA gain was estimated at a level 5×10^4. The energy instability of the amplified signal did not exceed 18%. In Fig. 2 the spectral distributions of the integrated signal before amplification (*a*) and the

idler intensity after two crystals of the OPA (*b*) are presented. From this figure one can see that the spectral distribution of the idler becomes oscillatory. The period of oscillations was ~0.85 nm. The FWHM bandwidth of the idler was 6.7 nm.

The oscillations were observed in the spectrum of amplified signal also. However they were not so essential on an integrated background signal train. The appearance of such oscillations effects on subsequent pulse compression. This can result in prolongation of output pulse and decrease of peak power of the multi-cascade OPCPA lasers.

III. THEORY AND DISCUSSION

To analyze the OPCPA, the solution obtained in the framework of the spectral domain was considered. Despite the existing dispersion theory [11] which describes the interaction of short laser pulses in different approximations with high accuracy, it is necessary to use approximations of the third and higher orders to describe the interaction of broadband laser pulses. This is due to the fact that approximate formulas for the refractive index of the medium with limited accuracy are used to calculate the dispersion parameters. As the order of approximation of the dispersion theory grows, the accuracy of calculating such parameters decreases, which affects the analysis of the interaction of broadband laser pulses [12]. We note that sometimes the spectral model [13] is understood as the replacement of the time amplitude in truncated equations obtained in the first or second approximation of the dispersion theory by the spectral amplitude

$$E(t) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} E(\omega) \exp(i\omega t) d\omega .$$

In nonlinear-optical medium, the change in the spectral amplitude of nonlinear waves is due only to absorption and nonlinear effects, while dispersion effects affect its phase. The degree of influence of the absorption effects and the nonlinear interaction on the spectral amplitude will be the same as for the field amplitude. If the method of slowly varying amplitudes, which reduces the order of the wave equation, is applicable to the field amplitude, then it is even more applicable to the spectral amplitude. In this case, the following system of integro-differential equations can be derived for the spectral amplitudes of the shifted components $E_k(\omega, z) = A_k(\omega, z) \exp\left[-ik(\omega + \omega_k)z\right] / 2 + \text{c.c.}$ for the OPA $\omega_p \rightarrow \omega_s + \omega_i$ (here the indexs *p*, *s* and *i* correspond to the pump, signal and idler wave, respectively):

$$\begin{aligned}
&\frac{\partial A_s(\omega, z)}{\partial z} = -i \int_{-\infty}^{\infty} \gamma_s(\omega) A_p(\omega') A_i^*(\omega + \omega') \exp\left\{-i\left[k(\omega' + \omega_p) - \right.\right. \\
&\left.\left. - k(\omega - \omega' + \omega_i) - k(\omega + \omega_s)\right] z\right\} d\omega' - \frac{\alpha(\omega + \omega_s)}{2} A_s(\omega, z), \\
&\frac{\partial A_i(\omega, z)}{\partial z} = -i \int_{-\infty}^{\infty} \gamma_i(\omega) A_p(\omega') A_s^*(\omega + \omega') \exp\left\{-i\left[k(\omega' + \omega_p) - \right.\right. \\
&\left.\left. - k(\omega - \omega' + \omega_s) - k(\omega + \omega_i)\right] z\right\} d\omega' - \frac{\alpha(\omega + \omega_i)}{2} A_i(\omega, z), \\
&\frac{\partial A_p(\omega, z)}{\partial z} = -i \int_{-\infty}^{\infty} \gamma_i(\omega) A_s(\omega') A_i(\omega - \omega') \exp\left\{i\left[k(\omega + \omega_p) - \right.\right. \\
&\left.\left. - k(\omega - \omega' + \omega_s) - k(\omega' + \omega_i)\right] z\right\} d\omega' - \frac{\alpha(\omega + \omega_p)}{2} A_p(\omega, z),
\end{aligned} \tag{1}$$

where $k(\omega)$ and $\alpha(\omega)$ are the wave number and absorption coefficient, respectively, $\gamma_s(\omega,\omega') = \pi d_{eff}(\omega,\omega')(\omega_s+\omega)^2 / k(\omega_s+\omega)c^2$ is the nonlinear coupling coefficient, $d_{eff}(\omega,\omega')$ is the effective second order nonlinearity.

Thus, changes of the spectral components are determined by the total amplitude and phase distributions of the interacting pulses. The presence in the general case of a phase mismatch redistributes the intensities in the spectrum and decreases the conversion efficiency.

In the general case, the system of integro-differential equations (1) is solved by numerical methods. However, in the case of narrow-band pump radiation, system (1) can be reduced to a system of differential equations. Indeed, for the bandwidth of the pump radiation spectrum $\Delta\omega_p << \Delta\omega_{s,i}$, the spectral amplitude can be represented as a δ-function. Then, with the initial intensity of the pump radiation W_p (the square of the field-amplitude modulus), the first two equations of system (1) can be reduced to the form:

$$\begin{aligned}
\frac{\partial A_s(\omega,z)}{\partial z} &= -iG_s(\omega)A_i^*(\omega)\exp\left\{-i\left[k(\omega_p)-k(\omega+\omega_i)-k(\omega+\omega_s)\right]z\right\} - \frac{\alpha(\omega+\omega_s)}{2}A_s(\omega,z) \\
\frac{\partial A_i(\omega,z)}{\partial z} &= -iG_i(\omega)A_s^*(\omega)\exp\left\{-i\left[k(\omega_p)-k(\omega+\omega_s)-k(\omega+\omega_i)\right]z\right\} - \frac{\alpha(\omega+\omega_i)}{2}A_i(\omega,z)
\end{aligned} \tag{2}$$

where $G_k(\omega) = \gamma_k(\omega)\sqrt{W_p}$ and $\chi^{(2)}(\omega)$ is second order nonlinear susceptibility.

In the fixed field approximation, from system (2) the solutions for the spectral amplitudes of the idler and signal pulses follow:

$$\begin{aligned}
A_s(\omega,z) &= A_{s0}(\omega)\cosh[\gamma(\omega,\omega_s)z] - iG_s(\omega)A_{i0}^*(\omega)\frac{\sinh[\gamma(\omega,\omega_s)z]}{\gamma(\omega,\omega_s)} \\
A_i(\omega,z) &= A_{i0}(\omega)\cosh[\gamma(\omega,\omega_2)z] - iG_i(\omega)A_{s0}^*(\omega)\frac{\sinh[\gamma(\omega,\omega_i)z]}{\gamma(\omega,\omega_i)}
\end{aligned}; \tag{3}$$

here $A_{s0}(\omega)$ and $A_{i0}(\omega)$ are the initial distribution of spectral amplitudes of the signal and the idler, respectively, $\gamma^2(\omega,\omega_k) = \gamma_s(\omega)\gamma_i(\omega)W_p - \left(\frac{\Delta k_d(\omega)}{2}\right)^2 - \alpha^2(\omega+\omega_k)$, $\Delta k_d(\omega) = k(\omega_p) - k(\omega_i+\omega) - k(\omega_s+\omega)$ is the phase mismatch.

It should be noted that (3) is analogous to the solution for the OPA in the time domain [13]. However, (3) differs in the possibility of analyzing parametric amplification of broadband radiation. It is follows from analysis of system (3) that under conditions of weak energy exchange in the presence of a seed signal and pump radiation at the input, the spectrum of the signal pulse remains constant at a constant phase mismatch and the absence of a strong dispersion of the absorption. In this case, the intensity of the signal at the output of the crystal-amplifier is determined by the ratio between the gain $\Gamma_0^2(\omega) = \gamma_s(\omega)\gamma_i(\omega)W_p$, the phase mismatch, and the absorption coefficient.

If $\Gamma_0^2(\omega) > \left(\Delta k_d(\omega)/2\right)^2 + \alpha^2(\omega+\omega_s)$, the signal is amplified exponentially with the length of the crystal-amplifier or the square of the power density of the pump radiation. In the opposite case, the intensity of the parametric waves will periodically change from the input value to zero, i.e. the signal will not be amplified.

In the presence of a significant dispersion of the refractive index, more precisely the phase mismatch, or the absorption coefficient, the crystal-amplifier can be represented as a certain frequency filter. Depending on the magnitude of the dispersion and its nature, the certain frequencies can be identified in the signal spectrum and the idler pulse. With complex dispersion dependences, the form of the spectral distribution of the signal intensity and the idler pulse can oscillate. In particular, with a quadratic dependence, the appearance of two maxima in the spectral distribution of amplified signals is possible.

In calculations we used a hyperbolic-secant (HS) spectral shape of the signal and the idler with phase modulation

$$A_{k0}(\omega) = A_k^0 \exp\left(iD_k\omega^2 / 2\right) \operatorname{sech}\left(\omega / \Delta\omega_k\right), \tag{4}$$

where $\Delta\omega_k$ is the bandwidth, D_k is the linear chirp value, A_k^0 is the maximal spectral amplitude.

From Eq. (2) and (3), it is follows that the Fourier image of the amplified signal (or idler) completely repeats its shape at the OPA output. In other words, the temporal and frequency distributions of the signal and the idler completely conform to each other, respectively.

According to our calculations, parameters of which were close to experimental ones, when there was the initial signal at the OPA input, the spectrum of the amplified signal was the HS as well as the spectrum of the initial signal. The temporal distribution of the amplified signal was the HS also. This HS dependence is presented in Fig. 4 by curve 1. In this case parameter of phase modulation of the initial signal was 4.5×10^{-24} s^2. So, the duration of the chirped signal pulse was stretched in ~2500 times in comparison with Fourier transformed one. The refractive indices of a KDP crystal were calculated by Sellmeier equations at various wavelengths [14]. The idler has the same intensity level and similar spectral and temporal distribution of the intensity. The phase mismatch effects significantly on the frequency distribution of the signal and idler at the larger bandwidth and lengths of the crystals.

In our experimental conditions, a two-crystal OPA circuit is used. In this case, because of the differences in group velocities in crystals, the divergence of the beams, or the displacement of the central wavelength, the maxima of the intensity distribution of a signal and an idler may not coincide with each other at the input of the second OPA crystal.

In Fig. 4 the spectral distribution of the idler intensity is shown by curve 2 when there are idler and signal pulses at the input of the 4-cm-long KDP crystal of the OPA. The parameters of the pump radiation and the signal were the same as in previous case. The initial level of the idler intensity was in 16-times lower than the signal one. At the crystal input the idler pulse had the same phase modulation as the signal, but its central spectral line shifted by 1.3×10^{-2} nm. From this figure one can see, that such small shift of the idler spectrum at low its intensity can substantially change the spectral distribution of the idler at the OPA output. The spectral distribution of the signal at the OPA output repeats practically the idler one, i.e. the signal intensity becomes oscillated also. The gain of the signal was at the same level on the average maintained as in the case of idler absence at the OPA input. From the analysis of this curve, one can see a slight asymmetry of this dependence. We note that the shape of the temporal distributions of the signal and the idler corresponds to the spectral ones. Such oscillations of these distributions occur when the phase mismatch effects on the process also.

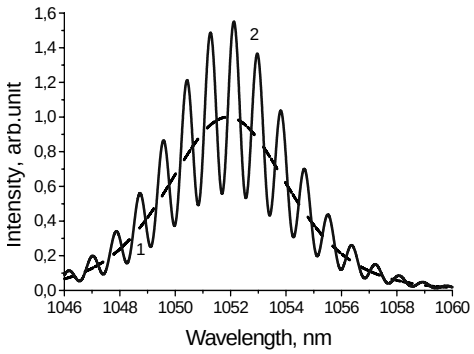


Fig. 4. Calculated spectral distributions of the input signal (dashed curve) and the output idler (solid line).

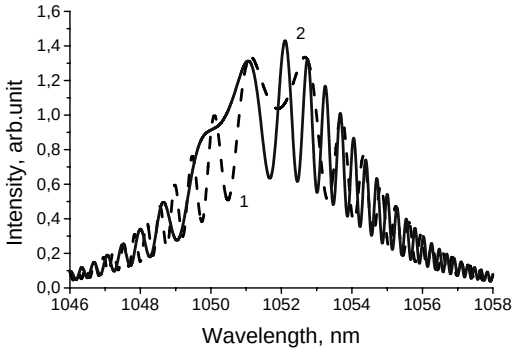


Fig. 5. Calculated spectral distributions of the output signal at difference in the parameters of phase modulation (dashed curve) and the central wavelengths (solid line) between the initial idler and signal pulses.

It should be noted that in these calculations the FWHM bandwidth of the signal was 6.7 nm. This value was less experimental one in 1.2 times. At this value of the FWHM bandwidth, the calculated dependencies fit to experimental one only. This disagreement can be explained by inhomogeneities in the spectral distribution of the signal. Nevertheless, the FWHM bandwidth of 6.7 nm corresponds to the Fourier transformed pulse duration of 170 fs.

There is an oscillation of the spectrum of an amplified signal also when the initial idler has a phase-modulation different from the signal one. Figure 5 shows the spectral distribution of an amplified signal in the OPA with 4-cm-long KDP crystal for a type-I interaction (dashed line). The pump intensity was 3.2 GW cm^{-2}. The amplification was realized at the phase-matching conditions. The bandwidths of the input signal and the idler were 6.7 nm. The signal and idler phase-modulation parameters were 4.5×10^{-24} s^2 and 4.47×10^{-24} s^2, respectively. The initial idler intensity was 25 times lower than the signal one. From this figure one can see that the spectral distribution of the amplified signal becomes oscillated also and dependence is symmetric. The idler spectral distribution has similar oscillations. The temporal distributions correspond to the spectral distribution and oscillated also. Asymmetry of the spectral distributions can appear when initial spectrums of signal and idler are shifted. The solid line in Fig. 5 was obtained by shifting the spectrum of the input idler by one-hundredth of its bandwidth. In this case, there was a strong asymmetry. The depth of these oscillations increases when the relative initial idler intensity grows.

Thus, small inhomogeneities in the spectral distribution of the signal over the beam cross-section can lead to oscillations of the spectral and temporal distribution of the amplified parametric waves under the noncollinear regime that was used in our experiment. These changes can reduce the efficiency of the subsequent temporal compression and radiation power and also increase the pulse duration of multi-stage OPCPA lasers. Our calculations show that the reduction in the compression efficiency occurs with larger differences in the bandwidth or the pulse duration, in the shift of the center of the spectral line or the values of the delay between pulses, in the mismatch of the phase modulation of the signal and the idler, and the comparability of their intensity

values. In particular, with a ratio of initial signal and wave intensities equal to 2:1 and a difference in the parameters of their phase modulation by 4%, a pedestal of the compressed pulse appears with a duration that exceeds the initial signal duration by ~50 times at the level of 0.13 of the maximum signal pulse intensity. However, the use of conformal input signal and idler pulses makes it possible to increase the amplification efficiency.

IV. CONCLUSION

In our work, significant oscillations of the spectral distributions of the idler in the OPCPA laser have been observed experimentally. Based on the developed analytical method for describing the parametric amplification of broadband laser pulses in the field of narrowband pump one, it was established that the oscillation data are due to the spatial inhomogeneities of the spectral distribution of the signal pulse. It is shown that small mismatch in the spectral distributions of the initial signal and idler leads to strong oscillation and asymmetry of the output signal and idler pulses. Such changes can reduce the efficiency of the subsequent temporal compression and radiation power and also increase the pulse duration of multi-stage OPCPA lasers. On the other hand, the observed changes allow one to control the parameters of the output laser radiation.

REFERENCES

1. D. Strickland, G. Mourou, Opt. Commun. **56**, 219 (1985).
2. A. Dubietis, G. Jonusauskas, A. Piskarskas, Opt. Commun. **88**, 437 (1992).
3. I.N. Ross, J.L. Collier, P. Matousek, et al., Appl. Opt. **39**, 2422 (2000).
4. L. Yu, X. Liang, L. Xu, et al., Opt. Lett. **40**, 3412 (2015).
5. D.I. Hillier, S. Elsmere, M. Girling, et al., Appl. Opt. **53**, 6938 (2014).
6. J. Moses, Sh.-W. Huang, J. Opt. Soc. Am. B **28**, 812 (2011).
7. C.R. Phillips, B.W. Mayer, L. Gallmann, et al., Opt. Express **22**, 9627 (2014).
8. Y. Shamir, J. Rothhardt, S. Hädrich, et al., Opt. Lett. **40**, 5546 (2015).
9. X. Zeng, K. Zhou, Ya. Zuo, et al., Opt. Lett. **42**, 2014 (2017).
10. Z. Gan, L. Yu, S. Li, et al., Opt. Express. **25**, 5169 (2017).
11. S.A. Ahmanov, V.A. Vyslouh, A.S. Chirkin. Optics of femtosecond laser pulses (Moscow, Nauka, 1988).
12. S.S. Grechin, Quantum Electron. **35**, 257 (2005).
13. V.G. Dmitriev, L.V. Tarasov. Applied Nonlinear Optics (Moscow, Fizmatlit, 2004).
14. V.G. Dmitriev, G.G. Gurzadyan, D.N. Nikogosyan. Handbook of Nonlinear Optical Crystals (Berlin, Springer-Verlag, 1999).