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Degradation of the contrast of a short light pulse in a CPA system

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Abstract. **We have calculated the effect of four-wave mixing of the main radiation pulse with the background radiation components on the value of the output radiation contrast in a chirped pulse amplification system of petawatt laser facilities. Formulae are presented that make it possible to quantify the contributions of two mechanisms, i.e. Kerr nonlinearity of the refractive index of the amplifying medium and gain saturation. For typical values of the nonlinear refractive index, both contributions are comparable. The possibility of mutual quenching of nonlinear contributions is noted. The influence of spectral filtering of radiation on the output pulse contrast is considered.**

Keywords: *pulse contrast, four-wave mixing, Kerr nonlinearity, gain saturation, chirped pulses.*

1. Introduction

Femtosecond laser pulses of petawatt powers and intensities as high as $10^{22}-10^{23}$ W cm^{-2} [1, 2] have become a common tool for studying matter under conditions of extremely high electric and magnetic fields, as well as sources of secondary radiation and high-energy elementary particles [3, 4]. In these fields, the interaction forces of electrons and atomic nuclei are only a small addition to the field strength, the atomic-molecular structure of matter is destroyed and the matter turns into a plasma. The effects of the formation of a plasma and its interaction with the light field markedly depend on the presence of relatively weak (but stretched out temporarily) background radiation, as well as on the prepulses accompanying the main pulse, which are formed during the amplification and propagation of radiation in the laser system [5–7]. Even with a significant (10^9-10^{11}) radiation contrast (the ratio of the peak intensity of the main pulse to the background intensity) and intensities close to 10 W cm^{-2}, the effect of the background on a medium may be sufficient for the emergence of a preplasma before the arrival of the main pulse, which will lead to degradation of the latter [8, 9]. Thus, increasing the radiation contrast is one of the most important tasks for developers of high-power laser systems. This especially applies to the technique of chirped pulse amplification (CPA) [10, 11]. Under conditions of amplification of temporarily stretched pulses, the radiation of the main pulse is superimposed on the radiation of the background and/or post- and prepulses, and the effects of their nonlinear interaction with an amplifying medium contribute to the transfer of the main pulse energy into them, which degrades the radiation contrast. The main mechanisms of the interaction of radiation with an amplifier medium are the Kerr nonlinearity (nonlinear refractive index) and gain saturation. It is known that the action of both nonlinearities can lead to the generation of a prepulse by a postpulse upon chirped pulse amplification [5–7]. In this paper, we analyse another possibility of radiation contrast degradation when the background radiation is amplified as a result of the main radiation energy transfer into pairs of time-delayed symmetric components of background radiation during four-wave mixing with the same nonlinear interaction mechanisms as Kerr nonlinearity and gain saturation. The components of the background field are inevitably present in the output radiation in the form of amplified spontaneous emission. As a result of the stretching of the radiation pulse in the stretcher, symmetric frequency components of the background, $\omega_0 \pm \gamma T$, enter the amplifier medium, where ω_0 is the frequency of the main radiation pulse; γ is the stretcher parameter; and T is the time delay between the background components and the main pulse. In the amplifier medium, field components with frequencies $\omega_1 = \omega_0 + \gamma T$ and $\omega_2 = \omega_0 - \gamma T$ gain energy from fundamental radiation due to the medium nonlinearity, which leads to contrast degradation.

Below we present a calculation of the effect of radiation contrast degradation for each mechanism of amplifier medium nonlinearity.

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2. Calculation

As a result of the stretching of radiation pulses in a stretcher, the field of the main radiation pulse at the entrance to the amplifying medium takes the form of the amplitude spectrum $s_0(\omega)$, where each time moment t has its own frequency $\omega = \omega_0 + \gamma t$:

$$E_0(t) = \sqrt{2\pi\gamma}\exp(-\mathrm{i}\omega_0 t - \mathrm{i}\gamma t^2/2)s_0(\omega_0 + \gamma t). \quad (1)$$

This is a regime of strong temporal stretching. The field maximum moment (1) is taken as the time reference. The parameter $\gamma \approx \Delta\omega/\tau_s$, where $\Delta\omega$ is the radiation spectrum width, and τ_s is the stretched-pulse duration. The spectrum width can be considered close to the inverse duration of the main pulse, $\Delta\tau$, before the stretcher: $\Delta\omega \approx \pi/\Delta\tau$. The fields of two background components separated by $\pm T$ from the main pulse can be represented as random spikes with a duration equal to the inverse width of spectrally filtered amplified spontaneous emission.

After the stretcher, these field components also take the form of amplitude spectra of the postcomponent field,

$$E_1(t) = \sqrt{2\pi\gamma}\exp(-i\omega_0 t)$$
$$\times\exp[-i\gamma(t-T)^2/2]s(\omega_0+\gamma(t-T)), \quad (2)$$

and the precomponent field

$$E_2(t) = \sqrt{2\pi\gamma}\exp(-i\omega_0 t)$$
$$\times\exp[-i\gamma(t+T)^2/2]s(\omega_0+\gamma(t+T)). \quad (3)$$

The postcomponent field (2) can also be considered as a postpulse. As the spectrum of background components $s(\omega)$, we can take the spectrum of spontaneous emission (possibly amplified in previous amplification stages), the width of which is limited by spectral filtering to the spectrum width of the fundamental radiation $s_0(\omega)$. In further analysis, we will consider the conversion of only one pair of symmetric background components, because during the four-wave interaction, many symmetrical background components with different delays T do not affect each other due to the difference in frequencies γT characteristic of each pair.

In a nonlinear medium of an amplifier, the radiation field is transformed, acquiring a nonlinear phase and experiencing saturated gain. Both nonlinearities allow the conversion process to be described in the form

$$E_{\rm out}(t) = E(t)K_{\rm r}(I(t))K_{\rm a}(Q(t)), \quad (4)$$

where $E(t)$, $I(t)$ and

$$Q(t) = \int_{-\infty}^{t} I(t')\,dt'$$

are the field, intensity and density of the current radiation energy at the entrance to the amplifier medium (see below). The growth of the nonlinear phase of radiation in (4) is given by the factor

$$K_{\rm r}(I) = \exp\left[i\frac{2\pi}{\lambda}n_2\int_0^L I(t,z)\,dz\right], \quad (5)$$

which depends on the nonlinear refractive index n_2 and on the intensity integral $I(t,z)$ along the amplifying medium length L. The phase in the exponent of expression (5) is known as the B-integral. Here and in formulas (11) and (12) below, we introduce the radiation intensity, which is dependent on the coordinate in the amplifying medium, $I(t,z)$; its value at $z=0$ coincides with the input intensity $I(t)$ used in the text. The saturated gain is given in (4) by the factor

$$K_{\rm a}(Q) = \sqrt{\frac{G\exp[2\sigma Q(t)/\hbar\omega]}{1+G\{\exp[2\sigma Q(t)/\hbar\omega]-1\}}}, \quad (6)$$

where σ is the gain cross section; $G=\exp(\sigma NL)$ is the unsaturated gain; and N is the inverse population of the working levels. Expression (6) follows from the well-known equation [12]*

$$\exp[2\sigma Q_{\rm out}(t)/\hbar\omega]-1 = G\{\exp[2\sigma Q(t)/\hbar\omega]-1\}, \quad (7)$$

which for the radiation intensity takes the form

$$I_{\rm out}(t)\exp[2\sigma Q_{\rm out}(t)/\hbar\omega] = GI(t)\exp[2\sigma Q(t)/\hbar\omega], \quad (8)$$

and for the field is expressed as

$$E_{\rm out}(t) = \sqrt{G}\,E(t)\frac{\exp[\sigma Q(t)/\hbar\omega]}{\exp[\sigma Q_{\rm out}(t)/\hbar\omega]}$$
$$= E_{\rm in}(t)\sqrt{\frac{G\exp[2\sigma Q(t)/\hbar\omega]}{1+G\{\exp[2\sigma Q(t)/\hbar\omega]-1\}}}. \quad (9)$$

Here and in formulae below, we will use the approximation of a low energy density at the amplifier input: $2\sigma Q_{\rm in}(t)/\hbar\omega \ll 1$. For Ti:sapphire amplifiers ($\hbar\omega = 2.5\times 10^{-19}$ J and $\sigma = 4\times10^{-19}$ cm^2) this approximation is justified for first amplification stages: $Q_{\rm in}(t) \ll \hbar\omega/2\sigma = 0.3$ J cm^{-2}. Then

$$K_{\rm a}(Q) \approx \sqrt{\frac{G}{1+2\sigma GQ(t)/\hbar\omega}}. \quad (10)$$

Relations (7) and (8) allow one to restore the dependence of the radiation intensity in the amplifier medium on the coordinate z along its axis,

$$I(t,z) = I(t)\frac{\exp(\sigma Nz)\exp[2\sigma Q(t)/\hbar\omega]}{1+\exp(\sigma Nz)\{\exp[2\sigma Q(t)/\hbar\omega]-1\}}, \quad (11)$$

and calculate the integral over the amplifier medium length, included in (5):

$$\int_0^L I(t,z)\,dz = I(t)\frac{L(\tilde G-1)}{\ln G}$$
$$\times\frac{\exp[2\sigma Q(t)/\hbar\omega]2\sigma Q(t)/\hbar\omega}{\exp[2\sigma Q(t)/\hbar\omega]-1} \approx I(t)\frac{L(\tilde G-1)}{\ln G}. \quad (12)$$

Here $\tilde G$ is the saturated gain. The factor $(\tilde G-1)/\ln G$ takes into account an increase in the radiation intensity as it propagates in the amplifier medium. It makes it possible to estimate the contribution of the nonlinear refractive index of the amplifying medium to the B-integral. Note that the value of integral (12) is greater than that of $LI(t)$, but less than that of $LGI(t)$.

To calculate the fields of weak background radiation components at the amplifier output, it is advisable to select in (4) small corrections caused by the background components $E_1(t)$ and $E_2(t)$ and restrict our consideration to first-order corrections. For the input field, we have $E(t) = E_0(t) + E_1(t) + E_2(t)$, which gives

$$I(t) = |E_0(t)+E_1(t)+E_2(t)|^2$$
$$\approx I_0(t) + \{E_0^*(t)[E_1(t)+E_2(t)] + \text{c.c.}\},$$

i.e., the correction for substitution in $K_{\rm r}(t)$ takes the form:

$$\delta I(t) = E_0^*(t)[E_1(t)+E_2(t)] + \text{c.c.} \quad (13)$$

Subscripts 0 indicate the parameters of the fundamental radiation. For the current energy density, we have

*The propagation of light pulses in amplifying media was considered in detail in a review by P.G. Kryukov and V.S. Letokhov [13], where, in particular, they analyzed the role of gain nonlinearity in reducing the pulse duration and in superluminal propagation of the maximum of the pulse envelope.

$$Q_{\rm in}(t) = \int_{-\infty}^{t} |E_0(t') + E_1(t') + E_2(t')|^2 {\rm d}t'$$

$$\approx Q_0(t) + \int_{-\infty}^{t} \delta I(t'){\rm d}t',$$

and the correction for the substitution in $K_{\rm a}(Q)$ is

$$\delta Q(t) = \int_{-\infty}^{t} \{E_0^*(t')[E_1(t') + E_2(t')] + {\rm c.c.}\}{\rm d}t'. \tag{14}$$

The products of the fields in (14) contain 'rapidly oscillating' factors $E_0^*(t)E_1(t) \propto \exp({\rm i}\gamma tT)$ and $E_0^*(t)E_2(t) \propto \exp(-{\rm i}\gamma tT)$ [see (2) and (3)]. The frequency of these oscillations is much higher than the repetition rate of pulses being stretched out temporally. In this regard, when calculating the integral by parts in (14), we can leave only the dominant terms:

$$\delta Q(t) \approx E_0^*(t)\left[\frac{E_1(t)}{{\rm i}\gamma T} + \frac{E_2(t)}{-{\rm i}\gamma T}\right] + {\rm c.c.}$$

$$= \frac{\rm i}{\gamma T}E_0^*(t)[E_2(t) - E_1(t)] + {\rm c.c.} \tag{15}$$

Small corrections to the factors $K_{\rm r}(I)$ and $K_{\rm a}(Q)$, taking into account (13) and (15), are expressed as:

$$\frac{\delta K_{\rm r}}{K_{\rm r}(I_0)} \approx {\rm i}\frac{2\pi n_2 L}{\lambda}\frac{\delta I(t)}{\ln G}\frac{\ln[1 + 2\sigma(G-1)Q_0(t)/\hbar]}{2\sigma Q_0(t)/\hbar\omega}, \tag{16}$$

$$\frac{\delta K_{\rm a}}{K_{\rm a}(Q_0)} \approx -\delta Q(t)\frac{\sigma G/\hbar\omega}{1 + 2\sigma G Q_0(t)/\hbar\omega}. \tag{17}$$

Expressions (16) and (17) allow one to estimate the ratio of the contributions of the Kerr nonlinearity and saturated gain to the formation of background field components. The contribution of the Kerr nonlinearity (16) has a characteristic value

$$\frac{2\pi n_2 L}{\lambda}\frac{\delta I_{\max}}{\ln G}\frac{\ln[1 + 2\sigma(G-1)Q_0(t)/\hbar\omega]}{2\sigma Q_0(t)/\hbar\omega}$$

$$\approx \frac{2\pi n_2 L}{\lambda}I_{\max}\frac{\tilde G}{\ln G}\frac{\delta I_{\max}}{I_{\max}}, \tag{18}$$

where

$$\tilde G \approx \frac{1}{2\sigma Q_{\max}/\hbar\omega}\ln(1 + 2\sigma G Q_{\max}/\hbar\omega).$$

The contribution of saturation gain nonlinearity (17) is

$$\delta Q_{\max}\frac{\sigma G/\hbar\omega}{1 + 2\sigma G Q_{\max}/\hbar\omega}$$

$$\approx \frac{\sigma G Q_{\max}/\hbar\omega}{1 + 2\sigma G Q_{\max}(t)/\hbar\omega}\frac{\Delta\tau}{\pi T}\frac{\delta I_{\max}}{I_{\max}}, \tag{19}$$

where we make allowance for

$$\delta Q_{\max} \approx \frac{1}{\gamma T}\delta I_{\max} = \frac{\tau_{\rm s}\Delta\tau}{\pi T}\delta I_{\max}$$

and $Q_{\max} = \tau_{\rm s} I_{\max}$. The scales of nonlinearities are related as

$$\frac{2\pi n_2 I_{\max} L}{\lambda}\frac{\tilde G}{\ln G} \quad \text{to} \quad \frac{\Delta\tau}{2\pi T}$$

or

$$\frac{I_{\max}}{2\times 10^{10}}\frac{\tilde G}{\ln G} \quad \text{to} \quad \frac{\Delta\tau}{T}, \tag{20}$$

where $n_2 = 10^{-16}$ cm^2 W^{-1}; $\lambda = 0.8$ μm; $L = 1$ cm; and $I_{\max}$ [W cm^{-2}] is the maximum radiation intensity of the main pulse at the amplifier input after stretching in a stretcher.

Further calculations were performed separately for each nonlinearity.

2.1. Kerr nonlinearity

In this case, we have an expression for the output field with first-order additions for small background components $E_1(t)$ and $E_2(t)$:

$$E_{\rm out}(t) = [E_0(t) + E_1(t) + E_2(t)][K_0(I_0) + \delta K_{\rm r}]K_{\rm a}(Q_0)$$

$$\approx K_{\rm r}(I_0)K_{\rm a}(Q_0)\left[E_0(t) + E_1(t) + E_2(t) + E_0(t)\frac{\delta K_{\rm r}}{K_{\rm r}(I_0)}\right]. \tag{21}$$

where the field of the main pulse is $E_0(t)K_{\rm r}(I_0)K_{\rm a}(Q_0)$; the postcomponent field is

$$\{E_1(t)[1 + {\rm i}I_0(t)M_{\rm r}(t)] + {\rm i}E_2^*E_0^2M_{\rm r}(t)\}K_{\rm r}(I_0)K_{\rm a}(Q_0); \tag{22}$$

and the precomponent field is expressed as

$$\{E_2(t)[1 + {\rm i}I_0(t)M_{\rm r}(t)] + {\rm i}E_1^*E_0^2M_{\rm r}(t)\}K_{\rm r}(I_0)K_{\rm a}(Q_0). \tag{23}$$

In (22) and (23), we introduced the notation

$$M_{\rm r}(t) = \frac{2\pi n_2 L}{\lambda}\frac{1}{\ln G}\frac{\ln[1 + (2\sigma/\hbar\omega)(G-1)Q_0(t)]}{(2\sigma/\hbar\omega)Q_0(t)}. \tag{24}$$

The product of the fields

$$E_1^*E_0^2 \propto \exp[{\rm i}\gamma(t-T)^2/2]\exp(-{\rm i}\gamma t^2)$$

$$= \exp[-{\rm i}\gamma(t+T)^2/2]\exp({\rm i}\gamma T^2)$$

in (23) has a phase structure of the precomponent field, despite the origin from the postcomponent; therefore, this term is assigned to the precomponent. Accordingly, the term with

$$E_2^*E_0^2 \propto \exp[{\rm i}\gamma(t+T)^2/2]\exp(-{\rm i}\gamma t^2)$$

$$= \exp[-{\rm i}\gamma(t-T)^2/2]\exp({\rm i}\gamma T^2)$$

in (22) is assigned to the postcomponent. When calculating the total energy densities of the components at the amplifier output

$$Q_1 = \int[|E_1(t)|^2 + (|E_1|^2 + |E_2|^2)I_0^2M_{\rm r}^2(t)]K_{\rm a}^2(Q_0){\rm d}t, \tag{25a}$$

$$Q_2 = \int [|E_2(t)|^2 + (|E_1|^2 + |E_2|^2) I_0^2 M_r^2(t)] K_a^2(Q_0)\,dt, \quad (25b)$$

we took into account that the phases of the field components $E_1(t)$ and $E_2(t)$ are random, and the terms with their product in integrands are zeroed. Then, in the case of equal energies of the background components $|E_1|^2 = |E_2|^2$, we obtain the radiation contrast before amplification,

$$\frac{\int |E_1(t)|^2\,dt}{\int |E_0(t)|^2\,dt} = \frac{Q_1}{Q_{max}},$$

and after it:

$$\frac{\int [1 + 2I_0^2 M_r^2(t)] |E_1(t)|^2 K_a^2(Q_0)\,dt}{\int |E_0(t)|^2 K_a^2(Q_0)\,dt}. \quad (26)$$

Relations (25) are suitable for a quantitative description of the generation of a prepulse by a postpulse. Assuming $|E_1|^2 \neq 0$ and $|E_2|^2 = 0$, we obtain the total energy density of the prepulse at the amplifier output:

$$Q_2 = \int I_0^2 M_r^2(t) |E_1(t)|^2 K_a^2(Q_0)\,dt$$

at a total energy density of the amplified postpulse

$$Q_1 = \int [1 + I_0^2 M_r^2(t)] |E_1(t)|^2 K_a^2(Q_0)\,dt.$$

The effects under consideration are determined by two integrals:

$$\int |E_0(t)|^2 K_a^2(Q_0)\,dt = \int I_0(t) \frac{G}{1 + 2\sigma G Q(t)/\hbar\omega}\,dt$$

$$= \frac{\hbar\omega}{2\sigma} \ln(1 + 2\sigma G Q_{max}) \equiv \tilde{G} Q_{max},$$

$$\int I_0^2(t) M_r^2(t) I_1(t) K_a^2(Q_0)\,dt$$

$$= \left(\frac{2\pi n_2 L}{\lambda} \frac{\hbar\omega}{2\sigma\tau_s}\right)^2 Q_1 \frac{G}{(\ln G)^2} f_K(F), \quad (27)$$

where $F = (2\sigma/\hbar\omega) G Q_{max}$, and $f_K(F)$ is the 'universal' part of integral (27) without normalising factors. In particular, the radiation contrast is converted during amplification from the initial value Q_1/Q_{max} to

$$\frac{Q_1}{Q_{max}}\left[1 + \left(\frac{2\pi n_2 L}{\lambda} \frac{\hbar\omega}{2\sigma\tau_s}\right)^2 \frac{1}{(\ln G)^2} \frac{2G}{\tilde{G}} f_K(F)\right]. \quad (28)$$

The main factor $f_K(F)$ in (27) was calculated numerically under the assumption of a Gaussian shape of the field spectra (1)–(3). The calculation result in the form of the function $2Gf_K(F)/\tilde{G}$ is presented in Fig. 1. The main value that sets the scale of the output contrast is

$$\frac{2\pi n_2 L}{\lambda} \frac{\hbar\omega}{2\sigma\tau_s} \approx 0.025,$$

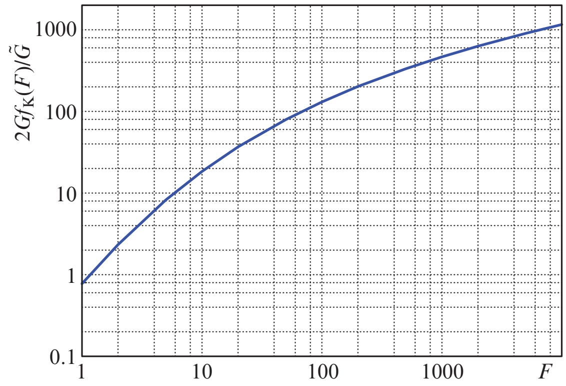

Figure 1. Factor $2Gf_K(F)/\tilde{G}$ for the Kerr nonlinearity, calculated by relation (27) for Gaussian pulses $(Q/\tau_s)\exp(-\pi t^2/\tau_s^2)$ with total energy Q and duration τ_s at a level of 0.456 of the maximum intensity.

where in the course of assessment we additionally assumed that $\hbar\omega = 2.5 \times 10^{-19}$ J, $\sigma = 4 \times 10^{-19}$ cm^2 and $\tau_s = 100$ ps.

The resulting relation (28) makes it possible to estimate the radiation contrast degradation for various parameters of the fundamental radiation and background components. A noticeable change in contrast will occur at $F > 20$, i.e., at $GQ_{max} \geqslant 100$ J cm^{-2}. In the primary amplification stages of a multistage laser setup, where $\tilde{G} I_{max} \tau_s \leqslant 1$ mJ (with a beam diameter of ~1 mm and $\tau_s = 100$ ps), the contribution of the Kerr nonlinearity is hardly comparable with the contribution of saturation ($\Delta\tau/T \approx 1-0.1$). Even at a total pulse energy density of 100 ps duration, close to the optical breakdown of a Ti:sapphire medium (~10 J cm^{-2}), the B-integral per single pass of the medium does not exceed 0.15 rad.

2.2. Gain saturation

In this case, for the output field with first-order additions for small background components $E_1(t)$ and $E_2(t)$ we have the expression

$$E_{out}(t) = [E_0(t) + E_1(t) + E_2(t)][K_a(I_0) + \delta K_a] K_r(Q_0)$$

$$\approx K_r(I_0) K_a(Q_0)\left[E_0(t) + E_1(t) + E_2(t) + E_0(t)\frac{\delta K_a}{K_a(I_0)}\right], \quad (29)$$

where the postcomponent field is

$$\{E_1(t)[1 + iI_0(t)M_a(t)] + iE_2^* E_0^2 M_a(t)\} K_r(I_0) K_a(Q_0), \quad (30)$$

and the precomponent field is

$$\{E_2(t)[1 - iI_0(t)M_a(t)] - iE_1^* E_0^2 M_a(t)\} K_r(I_0) K_a(Q_0). \quad (31)$$

Here we also introduce the notation

$$M_a(t) = \frac{1}{\gamma T} \frac{\sigma G/\hbar\omega}{1 + 2\sigma G Q_0(t)/\hbar\omega}. \quad (32)$$

Subsequent formulae for the new contrast and prepulse coincide with the case of Kerr nonlinearity with $M_r(t)$ replaced by $M_a(t)$. For estimates, we need the integral

$$\int I_0^2(t) M_a^2(t) I_1(t) K_a^2(Q_0)\,dt = Q_1 \left(\frac{1}{2\gamma T \tau_s}\right)^2 G f_a(F). \quad (33)$$

The factor $f_a(F)$ in this integral is calculated numerically under the assumption of a Gaussian shape of the field spectra (1)–(3). The function $2Gf_K(F)/\tilde{G}$ is shown in Fig. 2. The radiation contrast is converted during amplification from the initial value Q_1/Q_{max} to

$$\frac{Q_1}{Q_{max}}\left[1+\left(\frac{1}{2\gamma T\tau_s}\right)^2\frac{2G}{\tilde{G}}f_a(F)\right]. \qquad (34)$$

The main value that sets the scale of the output contrast is

$$\frac{1}{2\gamma T\tau_s} \approx \frac{\Delta\tau}{2\pi T}.$$

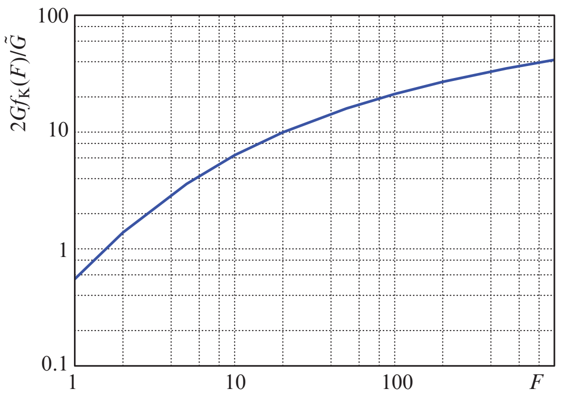

Figure 2. Factor $2Gf_a(F)/\tilde{G}$ for the saturated gain, calculated by relation (33) for Gaussian pulses (see the legend to Fig. 1).

The resulting relation (34) makes it possible to estimate the radiation contrast degradation for various parameters of the fundamental radiation and background components. A noticeable change in contrast will occur at $F > 10$, i.e., at $GQ_{max} \geqslant 30$ J cm^{-2}.

A comparison of the data in Figs 1 and 2 shows that with other conditions being the same, the effect of saturated gain nonlinearity can exceed the influence of the Kerr nonlinearity. In this case, in contrast to the Kerr nonlinearity, the influence of saturated gain decreases with increasing interval T as $1/T^2$.

3. Discussion

The presented estimates show that the quantitative effects of the Kerr nonlinearity and the saturated gain nonlinearity on the value of contrast can be comparable [see (18)–(20)]. An important difference between the saturation nonlinearity is that its contribution, depending on T, is significant near the main pulse and decreases as $1/T^2$ away from it.

In the radiation contrast diagram, this contribution takes the form of a λ-pedestal (Fig. 3). Figure 3 shows the calculated contrast curve, where the saturation parameters determine the position of the λ-pedestal along the vertical scale rather than its shape.

If we turn to the well-known CPA systems of high-power laser systems, then direct estimates of the degree of radiation contrast degradation by the presented relations are difficult due to the lack of data on the unsaturated gain G of a medium. As a rule, only the saturated gain $\tilde{G}$ is known. An indicator of the significant contribution of four-wave mixing to contrast degradation can be the ratio of the energies a postpulse Q_1 and a generated prepulse Q_2:

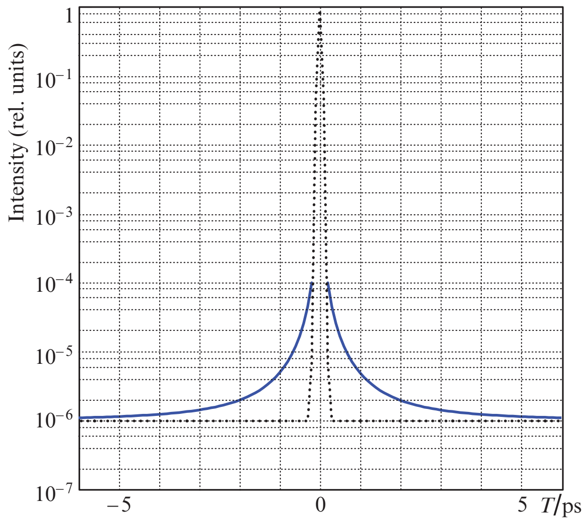

Figure 3. Pedestal of background radiation at the CPA system output, caused by gain saturation and calculated by the relation $10^{-6}[1 + (\Delta\tau/T)^2 \times 400]$ (solid curves). Shown also is the shape of the main Gaussian pulse with a duration of $\Delta t = 100$ fs (dotted curve).

$$\frac{Q_2}{Q_1-Q_2}=\left(\frac{2\pi n_2 L}{\lambda}\frac{\hbar\omega}{2\sigma\tau_s}\right)^2\frac{1}{(\ln G)^2}\frac{G}{\tilde{G}}f_K(F) \quad \text{or}$$

$$\frac{Q_2}{Q_1-Q_2}=\left(\frac{1}{2\gamma T\tau_s}\right)^2\frac{G}{\tilde{G}}f_a(F). \qquad (35)$$

A small relative difference in the energies of the pre- and postpulses underlies a significant contribution of four-wave mixing to contrast degradation. At $Q_2 = \frac{2}{3}Q_1$, the four-wave interaction triples the intensity of amplified background components, i.e. reduces the contrast by three times.

It should be noted that the presented description of the four-photon interaction effects takes into account only individual amplifying stages of CPA systems. A complete quantitative description of multipass and regenerative amplifiers requires additional calculations.

The presented formulae for the characteristics of output radiation describe the interaction of the main radiation pulse with the background components when the background components are slightly away from the main pulse ($T \ll \tau_s$). With the growth of the interval T, the re-overlapping of the stretched pulses in the amplifier becomes incomplete. It is convenient to present the qualitative picture of the fields in the amplifier on the spectral time diagram (Fig. 4). Its construction is possible due to the strong stretching of the pulses in a stretcher, when each spectral component acquires a given position on the time scale. The four-wave interaction involves background components in region I. Regions II before the amplifier are not filled with radiation, and after the amplifier, they are filled due to the generation of a prepulse by a postpulse (above) and a postpulse by a prepulse (bottom). One can see that by applying spectral filtering at the amplifier output, the radiation of both regions II can be suppressed. This will slightly improve the radiation contrast. With a small temporal distance T of the background components from the main pulse, this spectral filtering can almost halve the contribution of nonlinearity: in expressions (26), (28), and (34), factor 2, related to the contribution of nonlinearity, becomes unity. As the background components move away from the main pulse ($T \rightarrow \tau_s/2$), this factor also turns to unity without spectral filtering of the output radiation due to incomplete re-overlapping of stretched pulses.

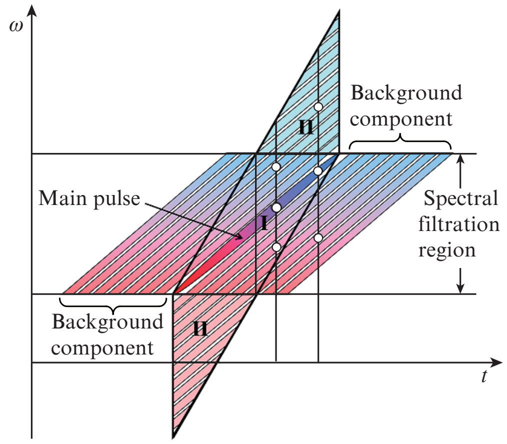

Figure 4. Spectral and temporal regions of interaction of the main pulse with the background components:
I is the region of four-wave interaction; II is the region of the generation of a prepulse by a postpulse (above) and of a postpulse by a prepulse (bottom). Circles indicate the interacting components.

The influence of two nonlinear processes on the generation of background radiation was considered separately from each other. Under the combined action of Kerr nonlinearity and gain saturation, the contributions of four-wave mixing in the region of precomponents can partially suppress each other. This is indicated by opposite signs in front of the two terms in formulae (23) and (31). Supression occurs when the equality

$$\frac{\Delta\tau}{2\pi T}\sqrt{f_{\mathrm{a}}(F)} \approx \frac{2\pi n_2 L}{\lambda}\frac{\hbar\omega}{2\sigma\tau_{\mathrm{s}}}\frac{\sqrt{f_{\mathrm{r}}(F)}}{\ln G} \tag{36}$$

is fulfilled, which is performed in order of magnitude in a wide range of energies of the main pulse. In the region of the post-component, the contributions of nonlinearities are summed. A possible confirmation of this fact is the results of work [14–16]. By removing a diffraction grating from the amplification channel, Hooker et al. [14, Fig. 2] succeeded in improving the radiation contrast, and the limiting λ-pedestal acquired an asymmetric shape with an enlarged wing in the region of postpulses. A similar asymmetry of the λ-pedestal was also demonstrated by Kalashnikov et al. [15, Fig. 3] and Hong et al. [16, Fig. 4].

4. Conclusions

The presented analysis of the four-wave mixing of the main radiation pulse with the components of the background radiation upon amplification of high-power laser systems in a CPA system shows that the radiation contrast is expected to noticeably degrade when the energy density of the fundamental radiation at the CPA system entrance is $Q_{\max} \geqslant 30/G$ J cm^{-2}. Moreover, the contributions of both nonlinear mechanisms – Kerr nonlinearity and saturated gain nonlinearity – are comparable. The contribution of the Kerr nonlinearity weakly depends on the temporal distance T of the background component from the main pulse (within the stretching time of the radiation pulse in a stretcher), and the contribution of the gain saturation decreases as $1/T^2$. In the region of precomponents, the contributions of two nonlinearities can partially cancel each other, and in the regions of postcomponents, they are added up. Spectral filtering of the output radiation after the amplifier may contribute to some improvement in contrast.

References

1. Yanovsky V., Chvykov V., Kalinchenko G., Rousseau P., Planchon T., Matsuoka T., Maksimchuk A., Nees J., Cheriaux G., Mourou G., Krushelnick K. *Opt. Express*, **16**, 2109 (2008).
2. Yoon J.W., Lee S.K., Sung J.H., Lee H.W., Jeon C., Choi I.W., Shin J., Kim H.T., Hegelich B.M., Nam C.H. DOI: 10.1364/CLEO_SI.2019.STu3E.2.
3. Gonsalves A.J. et al. *Phys. Rev. Lett*., **122**, 084801 (2019).
4. Rockwood A., Wang Y., Wang S., Berril M., Shlyaptsev V.N., Rocca J.J. *Optica*, **5**, 257 (2018).
5. Liu X., Wagner R., Maksimchuk A., Goodman E., Workman J., Umstadter D., Migus A. *Opt. Lett*., **20** (10), 1163 (1995).
6. Didenko N.V., Konyashchenko A.V., Lutsenko A.P., Tenyakov S.Yu. *Opt. Express*, **16**, 3178 (2008).
7. Cupal J., Spinka T., Sistrunk E., Rus B., Haefner C. *Proc. SPIE*, **11034**; https://doi.org/10.1117/12.2524115.
8. Chvykov V., Rousseau P., Reed S., Kalinchenko G., Yanovsky V. *Opt. Lett*., **31**, 1456 (2006).
9. Yanovsky V., Chvykov V., Kalinchenko G., Matsuoka T., Maksimchuk A. https://doi.org/10.1364/CLEO.2009.JTuD35.
10. Damm T., Kaschke M., Noack F., Wilhelmi B. *Opt. Lett*., **10**, 176 (1985).
11. Strickland D., Mourou G. *Opt. Commun*., **56**, 219 (1985).
12. Frantz L.M., Nodvik J. *J. Appl. Phys*., **34**, 2346 (1963).
13. Kryukov P.G., Letokhov V.S. *Sov. Phys. Usp*., **12**, 641 (1970) [*Usp. Fiz. Nauk*, **99**, 169 (1970)].
14. Hooker C., Tang Y., Chekhlov O., Collier J., Divall E., Ertel K., Hawkes S., Parry B., Rajeev P.P. *Opt. Express*, **19**, 2193 (2011).
15. Kalashnikov M., Osvay K., Sandner W. *Laser Part. Beams*, **25**, 219 (2007).
16. Hong K.H., Hou B., Nees J.A., Power E., Mourou G. *Appl. Phys. B*, **81**, 447 (2005).