Possibility of using self-focusing for increasing contrast and narrowing of ultrashort light pulses

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Possibility of using self-focusing for increasing contrast and narrowing of ultrashort light pulses

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An investigation is made of the influence of self-focusing on the shape of ultrashort light pulses passing through a stable two-component medium containing an inhomogeneous screen inside the resonator. In this system, the radiation losses decrease with increasing radius of the beam on the screen. It is shown that instantaneous self-focusing increases the contrast and produces a narrow peak at the maximum of an ultrashort pulse.

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INTRODUCTION

It has been established in several papers[1–6] that the self-focusing of radiation plays an important role in the process of amplification and generation of ultrashort light pulses. Self-focusing alters the transverse structure of the field and gives rise to additional losses which depend on the intensity of an ultrashort pulse. Even in the absence of gain saturation, this limits the peak intensities to several gigawatts per square centimeter and distorts the shape of the ultrashort pulses. Changes in the temporal structure of ultrashort pulses due to self-focusing in the active medium of a neodymium-glass laser were investigated in Refs. 5 and 6. It was found that instantaneous self-focusing first began to alter the divergence of the radiation at the maximum of an ultrashort pulse. As a result, the broadening of the beam in the most intense part of a pulse increased the losses on the screen and produced a dip at the maximum of an ultrashort pulse. This process was repeated in successive passages of the pulses across the resonator and it resulted both in the splitting of ultrashort pulses into a series of subpicosecond components and in a reduction of the contrast. In view of this, special measures had to be taken during the generation of high-power single ultrashort pulses to reduce the influence of self-focusing.[2,5]

The present paper considers some possibilities of utilizing self-focusing for reducing the duration and increasing the contrast of ultrashort pulses. The possibility of increasing the contrast by self-focusing is illustrated in Fig. 1. A train of ultrashort pulses travels across a nonlinear medium 1, in which instantaneous self-focusing takes place, and reaches an absorbing screen 2. The divergence of the stronger ultrashort pulses changes considerably because of self-focusing and slight losses occur as a result of the passage through a screen 2 (because the radius of the beam is much greater than the screen size). On the other hand, weaker pulses have a smaller radius on the screen and are absorbed more strongly by it, which results in an increase in the contrast of these pulses.

We shall investigate the generation of ultrashort pulses allowing for the self-focusing of radiation in a resonator containing a screen with an inhomogeneous transverse distribution of the transmission coefficient

$$K(r)=K(0)\exp(r^2/a^2), \tag{1}$$

where $K(0)$ is the transmission coefficient (gain) on the axis of the light beam; r is the distance from the axis. In this system, an increase in the beam radius reduces the losses on the screen. This may result in considerable changes in the temporal structure of the ultrashort pulses due to instantaneous self-focusing. In fact, contrary to the mechanism considered in Refs. 5 and 6, self-focusing in the presence of a screen inside the resonator may not give rise to additional losses but, on the contrary, reduce them. As a result, the losses are found to be lowest near the pulse maximum. This should produce a narrow intense peak at the pulse maximum and increase the contrast.

FORMULATION OF THE PROBLEM

We shall consider the influence of self-focusing on the structure of ultrashort pulses in a stable two-component medium[5] with a spatially inhomogeneous gain $K(r)$ specified in the form of Eq. (1). We shall assume that the medium is excited by a pulse initially of Gaussian form and that the pulse intensity is sufficiently high for a nonlinear filter to become completely bleached so that it does not affect the shape of ultrashort pulses. The saturation of the gain in the medium will be allowed for approximately by assuming that, in the absence of self-focusing, the envelope of a train of ultrashort pulses is Gaussian:

$$I_k=I_{max}\exp(-(k/N-1)^2). \tag{2}$$

Here, I_{max} is the peak intensity at the maximum of a train; I_k is the peak intensity of the k-th pulse in a train; $2N+1$ is the number of pulses in a train (measured at the 1/e level); $k=0, 1, 2, \ldots, 2N$.

The self-focusing of a pulse in a nonlinear medium with a refractive index $n=n_0+n_2E^2$ will be described in the aberration-free approximation. We shall assume that the field at the entry to the medium ($z=0$) is a Gaussian beam

$$\tilde{E}(r,0,t)=E_0(t)\exp[-{}^1\!/_2(1/r_0^2(t)+ik/R_0(t))r^2+i\varphi(t)] \tag{3}$$

with an amplitude $E_0(t)$, beam radius $r_0(t)$, and wavefront radius $R_0(t)$. After passing through the nonlinear medium, the field amplitude can be expressed in the form[7,8]

$$\left.\begin{aligned} E(r,l,t)&=\frac{E_0(\tau)}{f}\exp\left(-\frac{r^2}{2r_0^2(\tau)f^2}\right),\\ f^2&=\left[\frac{1}{R_0^2(\tau)}-\left(\frac{n_2E_0^2(\tau)}{n_0r_0^2(\tau)}-\frac{1}{k^2r_0^4(\tau)}\right)\right]l^2+\frac{2l}{R_0(\tau)}+1.\end{aligned}\right\} \tag{4}$$

Here, f is the relative width of the beam; $\tau=t-l/v$; l is the length of the medium; v is the group velocity of a pulse in the medium; k is the wave number.

After passing through a screen of the kind described

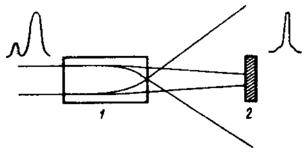

FIG. 1. System for increasing the contrast of ultrashort pulses by self-focusing.

above the beam radius increases:

$$r_a'(t)=r_a(t)/(1-r_a^2(t)/a^2). \tag{5}$$

Here, $r_a(t)$ and $r_a'(t)$ are, respectively, the radii of the beam before and after passing through the screen. The beam remains Gaussian after passing through the screen if

$$r_a(t)<a. \tag{6}$$

Changes in the radiation field resulting from the propagation of a pulse in the resonator are described by the well-known formulas of the theory of Gaussian beams.[9]

When a pulse travels in the self-focusing medium in the resonator, its shape (dependence of the beam power on time) does not change

$$I(l,t)=\frac{c}{8\pi}\int_0^\infty E^2(r,l,t)\,2\pi r\,dr=\frac{c}{8\pi}E_0^2(\tau)r_0^2(\tau)\equiv I_0(\tau). \tag{7}$$

However, the pulse shape changes as a result of the passage of the beam through the screen with an inhomogeneous transmission described by Eq. (1):

$$I(l,t)=\frac{c}{8\pi}\int_0^\infty E^2(r,l,t)K(r)\,2\pi r\,dr=K(0)I_0(\tau)/(1-f^2r_0^2(\tau)/a^2). \tag{8}$$

These relationships allow us to calculate the change in the shape of an ultrashort pulse and in the transverse structure of a Gaussian beam during successive passages of the pulse through a stable two-component medium.

INFLUENCE OF SELF-FOCUSING ON THE SHAPE OF ULTRASHORT PULSES IN A TRAIN

We shall report calculations carried out for a stable two-component medium in the form of neodymium glass. The self-focusing of picosecond pulses in this glass is instantaneous: $n_2=10^{-13}$ cgs esu (Ref. 11). We shall ignore the nonlinearity of the refractive index of the filter (screen) because the nonlinearity of the glass is more important.[1] For simplicity, we shall consider a ring resonator with one spherical mirror (radius of curvature $R=10$ m) and assume that the other mirrors are plane. The resonator length is $L=1.5$ m and the length of the nonlinear medium is $l=20$ cm. The screen is located at the entry into the medium. The initial radius of the beam r_0 for a pulse exciting the medium ($k=0$) is assumed to be equal to the radius of the dominant resonator mode ($r_0=0.66$ mm). The number of pulses in a train is assumed to be 60 (at the I_{max}/e level).

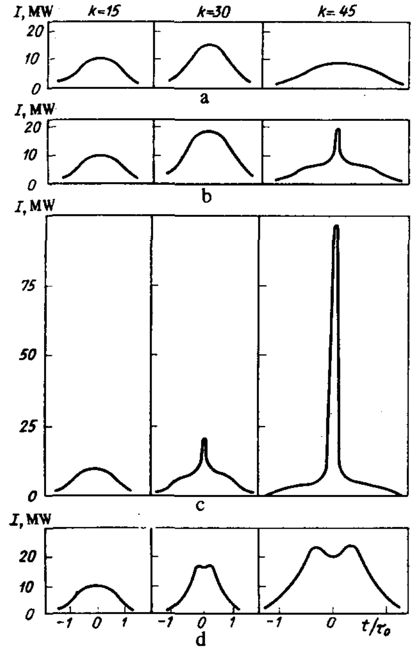

FIG. 2. Changes in the shape of 15th, 30th, and 45th ultrashort pulses in a train with $I_{max} = 1$ GW/cm^2 produced by a screen of different radii (cm): a) 10; b) 2; c) 1; d) 0.8.

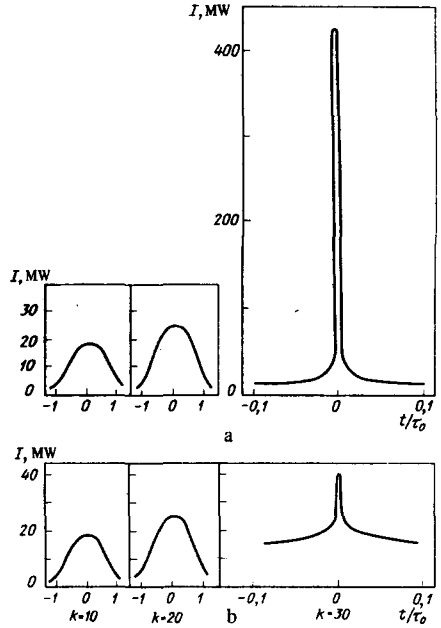

FIG. 4. Changes in the shape of the 10th, 20th, and 30th ultrashort pulses in a train with $I_{max} = 2$ GW/cm^2 due to the presence of a screen of 10 cm (a) and 5 cm (b) radius.

The self-focusing of ultrashort pulses in neodymium glass becomes important at peak power densities of the order of 1 GW/cm^2 (corresponding to $n_2E^2 \approx 8 \times 10^{-7}$).[4] As pointed out in the Introduction, the self-focusing process in the presence of an inhomogeneous screen may reduce losses near the pulse maximum. The rate of reduction of the losses depends on the degree of inhomogeneity of the transmission coefficient, i.e., on the screen radius. This radius (a) is the quantity which is varied in our calculations. Figure 2 shows the dependences obtained for ultrashort pulses with a peak intensity $I_{max} = 1$ GW/cm^2 at the maximum. When the screen radius is sufficiently large ($a > 2$ cm, Figs. 2a and 2b), the distortions of the shape of ultrashort pulses because of self-focusing remains slight. The screen is practically homogeneous and the losses are not reduced by self-focusing. There is an optimal value of the screen radius which ensures the most effective formation of a strong peak at the maximum of an ultrashort pulse and a considerable reduction in the duration of the pulse ($a = 1$ cm, Fig. 2c). Figure 3 shows how, in this case,

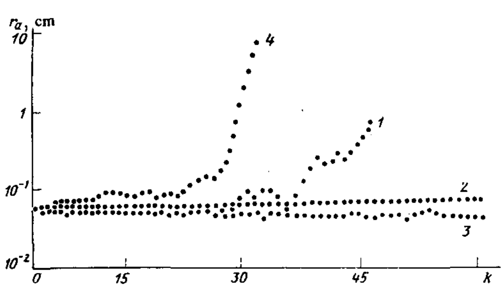

FIG. 3. Dependences of the beam radius on the screen r_a on the number of passages k of an ultrashort pulse through the resonator.

the beam radius on the screen varies at the pulse maximum as a result of successive passages of an ultrashort pulse through the resonator (curve 1). For comparison, the same figure includes the corresponding dependence in the absence of self-focusing (curve 2). Curve 1 in Fig. 3 stops at $k = 46$; this is due to the fact that, at high values of k, the condition (6) is no longer obeyed (the beam ceases to be Gaussian and its intensity rises away from the axis). Calculations indicate that, when the screen radius is $a < 0.8$ cm (Fig. 2d), a peak is not formed at all at the maximum of an ultrashort pulse but, instead, a dip is observed. It is clear from Fig. 3 (curve 3) that, in this case, self-focusing reduces the beam radius on the screen in the central part of the pulse. The losses on the screen increase and a dip forms at the center of a pulse.

Similar dependences are obtained for a peak ultrashort pulse intensity $I_{max} = 2$ GW/cm^2 at the train maximum (we recall that I_{max} is the intensity in the absence of self-focusing). It is found that the optimal value of the screen radius depends on I_{max}. If $I_{max} = 2$ GW/cm^2, the optimal screen radius is $a = 10$ cm (Fig. 2a). The dependence of the beam radius on the screen on the number of passes through the resonator is represented by curve 4 in Fig. 3. It is clear from Figs. 3 and 4 that as the peak intensity I_{max} is increased, the narrowing of the peak at the center of a pulse becomes greater, the intensity of the peak rises considerably, and the beam radius on the screen becomes larger.

Thus, our calculations show that the introduction of a spatially inhomogeneous screen into a stable two-component medium allows us to use the self-focusing effect for the reduction of the duration of ultrashort pulses, increase of their peak power, and improvement of the contrast. It should be pointed out that the screen need not be absorbing. An amplifying medium with an inhomogeneous gain can also be used as a screen. We recall that additional losses resulting from the self-focusing (diffraction losses and nonlinear scattering) are ignored in the calculations. The diffraction losses can be reduced by increasing the aperture in the medium (it is necessary to ensure that the radius of the limiting diaphragm exceeds considerably that of the screen a and the beam radius).

It follows from the reported calculations that when the peak intensities at the maximum of an untrashort pulse train are $I_{max} \geq 2$ GW/cm^2, apertures greater than 10 cm are needed for the optimal compression of ultrashort pulses and this is difficult to achieve in practice. However, it is quite realistic to expect the optimal compression of ultrashort pulses for $I_{max} = 1$ GW/cm^2 because the optimal screen radius is then $a = 1$ cm. Thus, the requirements in respect of the aperture depend strongly on the peak intensity at the maximum of an ultrashort pulse train. The optimal compression of ultrashort pulses in a two-component medium can be achieved by varying the parameters of the medium (such as the gain) and selecting a value of I_{max} such that the self-focusing is significant but does not yet increase greatly the beam divergence ($r_a \lesssim 1$ cm).

The losses due to the nonlinear scattering increase considerably when a beam collapses in a self-focusing medium. It follows from the results obtained that the collapse should not occur in the cases examined here but when the peak intensity I_{max} is raised, such a collapse is likely. Thus, two factors, one of which is the need to increase considerably the aperture and the other is the possibility of the collapse of a beam in the focusing medium, set the upper limit in respect of I_{max} to the proposed method.

As pointed out earlier, the calculations are based on the aberration-free approximation, which considerably simplifies the calculations. The validity of this approximation is considered in Refs. 12 and 13. It is shown in Ref. 13 that, far from a focusing medium (at distances considerably exceeding the diffraction length, $z \gg kr_a^2$), aberrations are important even at powers lower than the critical self-focusing power. Our calculations apply to ultrashort pulse powers much greater than the critical value. An analysis given in the Appendix shows that aberration-induced distortions of a Gaussian beam due to a single passage through the resonator are small if the inequality $lL/l_f^2 \ll 1$ is satisifed (here, l_f is the self-focusing length). In the problem under consideration, the value of lL/l_f^2 is varied, depending on the beam radius r_a, within the range $10^{-5}-10^{-1}$, i.e., the distortions of the beam due to one passage through the resonator are small. The aberration distortions increase during successive passages of the pulses through the resonator and the aberration-free approximation is obviously inapplicable when a beam collapses in the medium. In the calculations reported above, the collapse does not occur because it is prevented by a considerable increase in the beam radius and a corresponding increase in the self-focusing length due to successive passages of ultrashort pulses through the resonator. In view of this, there are grounds for assuming that aberrations do not alter significantly the results obtained.

Our results are valid subject to the condition that the width of the ultrashort pulse spectrum is small compared with the width of the gain band because the frequency dependence of the gain is ignored in the calculations. The dispersion of the medium is allowed in the calculations only in the first approximation. In this situation, the pulse self-modulation of ultrashort pulses does not affect the amplitude modulation.

Changes in the temporal structure of ultrashort pulses were investigated in Ref. 6 allowing for the finite width of the gain band and for the dispersion of the medium; more recently, this was done in Ref. 11. The results reported in these papers are contradictory. It is shown in Ref. 6 that without allowance for self-focusing, the phase self-modulation does not alter significantly the shape of the ultrashort pulses, whereas in Ref. 11 it is reported that in this case the ultrashort pulses split up into subpicosecond components. The mechanism of formation of the subpicosecond structure in ultrashort pulses in a neodymium glass laser has not yet been established experimentally. When the resonator contains a screen with inhomogeneous transmission, the mechanism discussed in Refs. 5 and 6 should not occur and it should be possible to determine which of the proposed mechanisms (Ref. 5, 6, or 11) is the most important.

APPENDIX

We shall now estimate aberrations in one pass through a resonator which contains a medium with cubic nonlinearity. For simplicity, we shall consider a beam with a plane phase front and a Gaussian distribution of the intensity:

$$E(r, 0, t) = E_0(t)\exp[-{}^1/_2(r/r_0)^2]. \tag{A.1}$$

We shall consider the case of powers much greater than the critical value, $E^2 \gg E_{cr}^2 = (2n_0/n_2)(kr_0)^{-2}$, when we can ignore diffraction in the propagation of a pulse in a nonlinear medium. If the length of the medium is much less than the self-focusing length, $l \ll l_f = r_0(2n_0/n_2E_0^2)^{1/2}$, we can obtain an approximate solution of the original parabolic equation which allows for aberrations to within terms of the order of $(l/l_f)^2$.

This solution is of the form

$$E(r, z, \tau) = E_0(\tau)\{1 + (z/l_f)^2(1 - 2r^2/r_0^2)\exp(-r^2/r_0^2)\}\exp[-r^2/(2r_0^2) - i(kz + zE_0 e^{-r^2/r_0^2}/(l_f E_{cr}))]. \tag{A.2}$$

It follows from Eq. (A.2) that the propagation of an initially Gaussian beam in a nonlinear cubic medium results in a redistribution of its intensity in the transverse section and in a distortion of the wave front. The amplitude aberrations are of the order of $(l/l_f)^2$ and the distortions of the wave front shape are of the order of l/l_f. Consequently, during the subsequent propagation of the beam in the resonator, the most important are the aberrations due to the deviation of the wave front from the spherical form.

These aberrations can be calculated by representing the solution for $z>l$ in the form of the Fresnel diffraction integral:

$$E(x,y,z,\tau)=k/(2\pi i(z-l))\exp[-ik(z-l)]\iint E(x',y',l,\tau)\exp\{-ik/(2(z-l))[(x-x')^2+(y-y')^2]\}\,dx'dy'. \quad (A.3)$$

Calculation of the Fresnel integral by the steepest-descent method gives

$$E(r,z,\tau)=\frac{E_0(\tau)}{F}\exp\left\{-\frac{r^2s^2}{2r_0^2}-\frac{ikr^2m^2}{2z'}-i\left[kz+\frac{l}{l_f}\frac{E_0}{E_{cr}}\exp\left(-\frac{r^2s^2}{r_0^2}\right)\right]\right\}, \quad (A.4)$$

where $z'=z-l$; $s^2=\alpha^2(1+2\beta\alpha)$; $m^2=(1-\alpha)(1-\alpha-2\beta\alpha)$;

$$\alpha=il_d/(z'+il_d);$$

$$\beta=\frac{2lz'}{l_f^2};\ F^2=\left\{1-\beta\alpha\left[1-\frac{r^2s^2}{r_0^2}\exp\left(-\frac{r^2s^2}{r_0^2}\right)\right]\right\}\alpha^{-2};$$

$l_d=kr_0^2$ is the diffraction length.

It follows from Eq. (A.4) that the aberration distortions due to deviations of the wave front of the beam from the spherical form are small if $\beta=2lz'/l_f^2\ll 1$. The condition for smallness of the aberrations due to one passage through the resonator is $lL/l_f^2\ll 1$.

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Influence of gain saturation on the frequency pulling of the stimulated emission from linear ring He—Ne lasers

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An investigation was made of the dependences of the intermodal beat frequency of a linear laser and of the difference frequency of a ring laser on the gain of the active medium and the losses in the resonator. These dependences made it possible to determine the reduction in the frequency pulling with increasing output power, relative to the total pulling. A determination of this reduction made it possible to compare the results of experiments carried out under different conditions. A comparison was made of the experimental results with the calculations.

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1. INTRODUCTION

The interaction between waves (here and later, we shall consider traveling waves, but any standing wave in a resonator can be resolved into traveling waves) in the case of inhomogeneous broadening of the $\lambda=0.63\ \mu$ line of an He-Ne laser reduces the pulling of the emission frequency to the line center because the gain of the active medium becomes saturated (this reduction in the pulling is frequently called the frequency pushing). The degree of reduction in the frequency pulling is governed by the intensity of the field in the laser resonator, by the frequency separation between the interacting waves (the frequency separation here means not the difference between the stimulated waves but the difference between the waves in a reference system linked to an active atom), and by the width and form of the natural profile of the transition line. Investigations of the dependence of the frequency pulling on the excitation of the active medium and losses in the resonator, which govern the intensities of the interacting waves, are reported in Refs. 2–5. In a ring laser, a change in the frequency pulling alters the scale factor (the coefficient relating the rotation velocity to the difference between the fre-