ON THE NONSTATIONARY SELF-ACTION OF THE PROFILED LIGHT BEAMS

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Received September 15, 1988

The interference pattern from one-dimensional on-axis null beams subject to nonstationary thermal blooming in a moving transparent or absorbing medium is examined. In the case of optical propagation through a cloudy medium a noninteracting subbeam structure is found to form, which can deteriorate the performance of the adaptive autofocusing system. It is shown that the thermal blooming effect may result in a beam with a single intensity peak if the initial optical power is above a certain critical value.

As is known, one of the ways to compensate for the nonlinear distortions of a light beam is to profile it, i.e., to choose an optimal amplitude profile. The use of hypergaussian and hypersleeve beams is very promising for this purpose. Such beams experience much less nonlinear distortion when propagating through both clear (see Refs. 1–5) and cloudy media (Refs. 6–8). The efficiency of light energy transport as well as the clearing of a liquid-droplet medium can also be increased by utilizing elliptically shaped beams[9,10]. Thus, the combination of profiling and ellipticity[7] enables one, for example, to compensate for the side shift of the beam's center of gravity in a moving nonlinear medium. In practice it is important to know not only the position of the beam center but also its intensity profile, or, in other words, to know whether the intensity reaches its maximum value at one or several points and what is the ratio of intensities at these points. Just this question of the structure of a beam with the valley of intensity on its axis is considered in this paper (see also Ref. 15).

BASIC EQUATIONS

Propagation of a light beam through a nonlinear regular medium is described by the quasi-optical equation, which is written in terms of nondimensional variable and has the form

$$\frac{\partial A}{\partial z} + i\Delta_{\perp}A - i\alpha\varepsilon_{NA}A = 0. \qquad (1)$$

where A is the complex amplitude normalized by its peak value, z is longitudinal coordinate measured in units of the diffraction length $l_d = 2ka^2$, k is the wave number, a is the characteristic cross-sectional size of the beam, $\Delta_{\perp}$ is the Laplacian transverse operator; ε_{NA} is a nonlinear term of the dielectric constant, which is equal to αT in the case of thermal blooming in clear air and $\alpha T + iW\tau_g$ for a cloudy atmosphere. Here α is the excess of the initial power over the value characteristic for thermal blooming, τ_g is the optical depth of the unperturbed cloud, T is the nondimensional temperature change, W is the water-content of the medium[11,12,13] normalized by its value in the unperturbed medium.

The temperature change in a transparent medium moving along the x-axis perpendicular to the z-axis caused by propagation of a light pulse is described as follows

$$\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x} = |A|^2. \qquad (2)$$

In the case of a water-droplet aerosol one has to solve the following system of equations in T an W[12,13]

$$\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x} = (a_M + (1-\beta_T)\ W)\ |A|^2,$$

$$\frac{\partial W}{\partial T} + \frac{\partial W}{\partial x} = -\gamma\ \beta_T\ |A|^2\ W, \qquad (3)$$

Here (in Eqs. (2) and (3)) t is time normalized by $\tau_v = a/v$, v is the velocity of the transverse movement, of the medium α_M is the coefficient of molecular absorption, β_T is the fraction of energy absorbed by the droplets, γ is the ratio of the initial beam power to that characterizing the vaporization of the droplets.

At the boundary of the cross-sectional region at $t = 0$, the temperature change and the complex amplitude are equal to zero, while the water content $W = 1$. Since numerical simulations of the nonstationary propagation of a light beam which does not possess axial symmetry require much computation time, we consider only slit-shaped beams. In this case the initial distribution of the complex amplitude at $z = 0$ is given as follows

$$A|_{z=0} = 0.5\sqrt{T_p}\ (x-x_0)^m \exp(-2(x-x_0)^m - K_0(t-t_0)^2/Q,$$

$$Q^2 = \int (x-x_0)^{2m} \exp(-4(x-x_0)^m dx \int_0^{T_p} \exp(-2K_0(t-t_0)^2 dt, \qquad (4)$$

where $m = 2$ to 10, T_p is the pulse duration, and $K_0 = 10$. Since in the two-dimensional case beams with distribution (4) are called tubular, we shall use this term also to emphasize the fact that at $x = x_0$ the intensity of a slit-shaped beam vanishes.

Note, that in studies of beam self-action in a cloudy medium the temperature change due to molecular absorption was not taken into account because for $\beta_T \sim 0.5$[4] this absorption does not alter the qualitative picture of beam self-action. We have made calculations for paths $0 \le z \le 0.2$ and the time interval $0 \le t \le 2.1$; and for values of the parameter running from 1.05 to 4.5. Finally, it is worth noting that (as was shown in Refs. 6 and 8) the weakly diffracted beams of tubular profile can undergo an anomalous increase of the peak intensity and, consequently, the depth of the cleared portion of the path within the medium increases. Therefore the influence of diffraction on this effect is also considered below.

LINEAR MEDIUM

Let us now consider now the case of a linear medium in order to elucidate the influence of diffraction and thermal blooming on the propagation of laser beams which have zero intensity along their axes. According to Ref. 14 at the first stage of propagation a tubular beam ($m = 2$) undergoes focusing, which is focusing confirmed by numerical simulations. The computations showed that the intensities of the side maxima decrease with increase of z while the axial intensity of the beam increases (see solid and dashed lines 2 in Fig. 1). In the case of hypertubular beams ($m > 2$) subbeam structures form with growth of m. Their number and intensity are determined by the value of m and by the properties of the propagation path. Thus, the intensity of radiation between subbeams decreases with increase of m and z. It is important to note that new subbeams are formed in the region of geometrical shadow, to the right and to the left of the initial maxima. The central maximum is formed at the beginning of the propagation path. Thus, the formation of subbeams occurs due to the diffraction of radiation by the two slits. Since the slit irradiation is inhomogeneous, the diffraction picture has no zero maxima. In Fig. 1 solid and dashed lines b illustrate the intensity profiles of a beam with $m = 6$ at cross-sections $z = 0.1$ and 0.2.

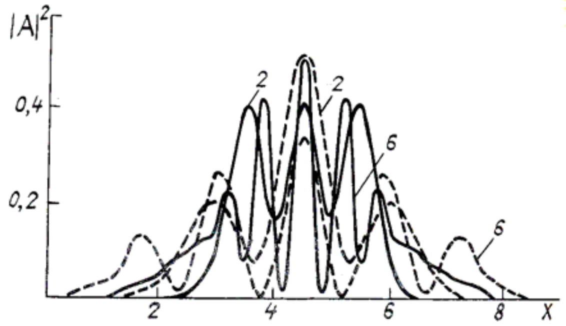

FIG. 1. Profiles of the intensity of the optical radiation propagating through a linear medium for Gaussian-shape pulses at the time $t = 1.19$ and cross-sections $z = 0.1$ (solid curves), $z = 0.2$ (dashed curves). The values of the parameter m are shown near the curves; $x_0 = 4.5$.

CLOUDY MEDIUM

Now let us consider the propagation of light pulses in a cloudy medium with the parameters $\beta_T = 0.75$, $\tau_g = 1$, $\gamma = 10$, and $\alpha = 80$, 150 and 1500. These values of the parameters were chosen to fit those at which the investigation of thermal blooming of profiled beams was carried out in Refs. 1–6 and 15. The computer calculations show that the propagation of the beam has practically the same character at $\alpha = 80$ and 150, at least from the viewpoint of its profile. Note that $\alpha = 80$ corresponds to the conditions of weak thermal blooming now being widely investigated (the effective value of a at which thermal blooming occurs, taking into account the value β_T and the normalization[7,9,10], is 40).

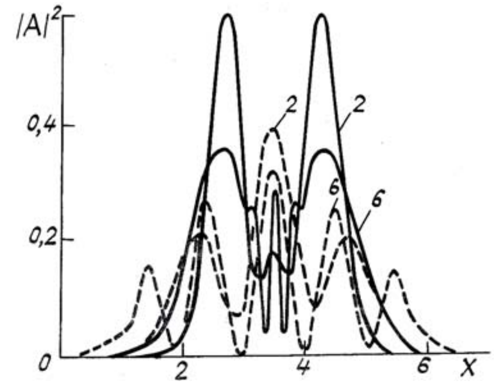

FIG. 2. Analogous to Fig. 1, profiles in a cloudy medium for a Gaussian pulse at $t = 1.19$, $z = 0.05$ (solid curves), $z = 0.15$ (dashed curves), $x_0 = 3.5$. The values of the parameter m are shown near the curves.

The propagation of a light pulse a through medium under conditions of weak thermal blooming is in many respects analogous to its propagation in a linear medium. Thus, for $m = 2$ at $z = 0.05$ the third maximum begins to form at the center of the beam with an intensity 3.2 times lower than the side maxima (see the appropriate solid curve in Fig. 2). The transmission profiles, determined according to the rule $1 - W$, and the temperature profiles have similar gaps at the centers. The clearing depth increases with time monotonically, and the value W reaches 0. 1 by the end of the pulse at the points of the initial intensity maxima of the beam and 0.55 at its center. The integral shift of the water content profile is about 0.75, in nondimensional units.

While for the beam with $m = 4$ the propagation picture is analogous to the above, in the case $m = 6$ the propagation picture changes drastically. First, the shift of the windward boundary of the cleared channel is about 20% smaller than for the beam with $m = 2$ (see solid line b in Fig. 2). Secondly, at the center of the beam in the intensity valley there appears a narrow maximum at which the intensity is 1.2 times lower than at the side maxima. It is also important that within the internal region of the beam (in contrast to a linear medium) there appear two local maxima due to the reflection of radiation from the clearer and hence optically less dense parts of the medium. The nonlinear character of the beam self-action is also manifested by the asymmetry in the temporal behavior of the peak intensity, i.e., the trailing edge of the pulse becomes more mildly sloping. The values of the water-content at the transmission maxima and minima are larger than in the case $m = 2$, being equal to 0.2 and 0.63 respectively. As the comparison of quantitative characteristics of the beams with $m = 2$ and 6 shows the largest difference between the beam powers received by an aperture $R_a = 2$ beam widths is about 10% of the maximum power level of the optical radiation with $m = 2$.

The aberration picture of the beam continues to develop with further propagation of the beam. Thus, in the beam with $m = 2$ there are formed three maxima of the intensity and the transmission (see dashed curve 2 in Fig. 2). Nonlinear absorption of light results in a decrease of the intensity peaks and their equalization. The width of the transmission channel increases with increase of z and its asymmetry appears. This asymmetry is observed as the better clearing of the region initially subtended by the second intensity maxima with respect to the movement of the medium. The intensity profile becomes more stratified at larger (up to 6) m values, and it involves, e.g., at $z = 0.1$, five local maxima, which are preserved up to the cross-section $z = 0.15$ (see Fig. 2). It is worth noting that between the two central maxima the intensity value is very close to zero. The diffraction results in the blooming of not only the individual subbeams but of the whole beam. But at the same time the subbeam structure is preserved during the propagation and the subbeams do not overlap. Then at the cross-section $z = 0.2$ the number of subbeams increases to seven (there were five in the linear medium) and the light intensity between subbeams vanishes (to less than 5×10^{-3}), which is caused by a strong absorption of light due to weak clearing of the cloud medium between the subbeams. As a result the nonlinear absorption stabilizes the structure of the subbeams.

The character of the propagation does not change with increase of the value of α up to 150. Differences are observed only in shifts of the beam center, as well as in a larger broadening of the subbeams and in increase of their peak intensities due to nonlinear refraction and due to the difference of the intensities of the side maxima. In these cases the beam structure is in fact determined by the diffraction. Owing to the movement of the medium, its inhomogeneities are displaced in the region of small beam intensity and do not strongly effect the propagation of subbeams because the pulse duration is approximately equal to the transit time of the medium across the beam. As a result the shift of the center of gravity of the Gaussian pulse duplicates its shape. But in the case of a pulse with rectangular temporal profile ($K_0 = 0$) of the same energy as the Gaussian pulse the character of its propagation is slightly different. Thus, clearing of the medium is weaker and the value of the peak intensity is lower and increases toward the end of the pulse. The most essential difference is connected with the beam center shift, although it is seven times smaller than for the Gaussian pulse. At first, the center shifts in the direction counter to the medium movement for $t \le 0.6$ (depending on the beam profile). The optically denser uncleared part of the medium then captures some individual subbeams and they shift together with the medium until the pulse ends.

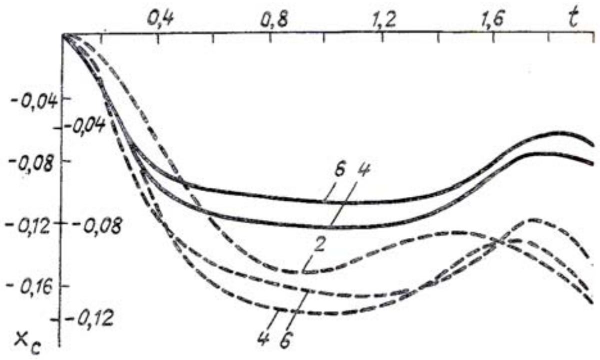

FIG. 3. The position of the beam's center of gravity x for the case of a rectangular pulse as a function of time at the cross-section z = 0.2 for α *= 1500 in a cloudy medium (solid line, the scale is shown on the outer side of the* x_c *axis); and for* α *= 150 in a transparent medium (dashed curves; the scale is shown on the inner side of the* x_c *axis). The pulse propagates in a transparent medium with thermal mechanism of nonlinearity. The values of the parameter m are shown on the curves.*

Neither further increase of α up to 1500, nor increase of the beam power, nor decrease of β_T (provided the value of $\gamma\beta_T$ remains constant) change the structure of subbeams in the rectangular pulse. The intensity of the two subbeams which are the farthest from the center is 15% lower than the intensity of the three proceeding ones. In contrast to the case of $\alpha = 150$, the center of gravity of the beam always moves in the direction counter to the medium movement. Thus, for example, at the cross-section $z = 0.2$ (see Fig. 3, a solid curve) the deviation of the beam from the z axis first increases for $t \le 1$ and then decreases for $1 \le t \le 1.8$ and afterwards increases again. Obviously the oscillations of the beam center of gravity continue for $t > 2.1$. This is caused by the action of two opposing mechanisms of nonlinearity, i.e., thermal blooming and beam focusing due to the reflections from the optically denser uncleared part of the cloudy medium. The maximum shift of the beam center does not exceed 0.13 in nondimensional units.

For the Gaussian beam (see above) and $\alpha = 1500$ the shift of the beam center can reach 0.8 in the middle of the pulse. The shift is in the direction counter to the medium movement and duplicates the pulse shape. It is important to note that at $t = 1.05$ there appears a narrow Intensity peak in the light pulse. The intensity of this peak is 4 to 5 times greater than the intensity of the other maxima, and it is strongly shifted towards the wind. In this case the structure of nonoverlapping subbeams is formed only at the beginning and at the end of the pulse, when the nonlinearity is still weak. Nonlinear self-action taking place in the middle of the pulse yields the formation of the intensity distribution with a narrow maximum.

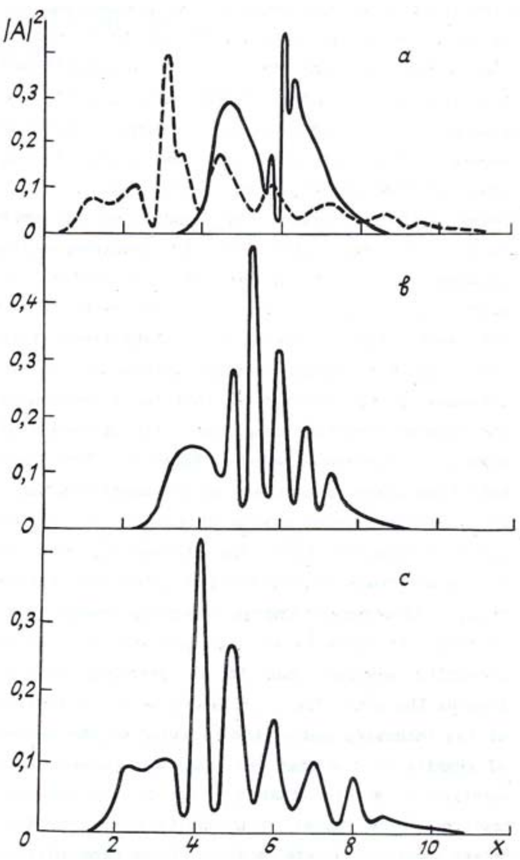

FIG. 4. Intensity profiles for the Gaussian pulse with $m = 6$, in a transparent medium with thermal nonlinearity at the time $t = 1.225$ at cross-sections $z = 0.05$ (solid curve a) and $z = 0.2$ (dashed line a), $z = 0.1$(b), and $z = 0.15$ (c).

THERMAL BLOOMING IN A TRANSPARENT MEDIUM

An investigation analogous to the one discussed above was carried out for the case of thermal blooming in a transparent medium. A detailed discussion of the results of numerical simulations concerning this case cam be found in Ref. 15. In this paper we will discuss only some typical features which distinguish this case from the previous one of a cloudy medium and beam with distribution (4), where $K_0 = 10$, $m = 6$, $x_0 = 6$, $t = 1.05$, and $\alpha = 150$. Thus, in the case of beams with $m = 2$, in contrast to the cloudy medium, a narrow intensity distribution with a sharp maximum is already formed at $z = 0.05$, the maximum intensity value being dependent on m (see Fig. 4a). The intensity of this maximum at first increases with increase of z and then decreases. In time this region divides into two regions the peak radiation intensity of which exceeds the initial maximum.

It should be emphasized that in contrast to cloudy and linear media the formation of subbeams in the transparent medium due to thermal blooming occurs mainly in the internal part of the intensity distribution, the equalizing of subbeam intensities being observed only on the beam periphery. In this case the main maximum is strongly shifted in the direction counters the medium movement (see Fig. 4). The intensity value in the gaps between the subbeams differs significantly from zero.

In the case of rectangular pulses the subbeam structure is more pronounced, i.e. there exist two of equal intensity. In this case the shift of the beam center is approximately equal to that occurring in a cloudy medium with $\alpha = 1500$. There is also an oscillatory behavior in time of the beam's center position and of its peak intensity. Figure 3 illustrates the temporal behavior of the beam's center position (dashed curves).

Note that the subbeam structure is formed again under the conditions of weak self-action, e.g., at $\alpha = 15$. But because of the motion of the medium the beam's center of gravity is greatly shifted in time (up to 0. 14 in nondimensional units). As a consequence, the intensity of light on the receiver axis will periodically increase and decrease.

CONCLUSIONS

The results discussed above allow one to arrive at the following conclusions. The structure of the beam having a gap in the intensity distribution on the axis is determined by the parameter m which characterizes the proximity of the intensity distribution to plateau-shaped function. This structure is also determined by the nonlinearity mechanism, pulse shape, and the excess of the beam power over the characteristic power of thermal blooming. In the case of light beams with $m > 2$ under the conditions of weak self-action the structure of noninteracting subbeams is formed due to the slit diffraction both in transparent and cloudy media. The nonlinear light absorption stabilizes this structure and equalizes the intensity of the subbeams. It should be noted that the formation of the subbeam structure complicates the operation of adaptive - systems which correct for the amplitude-phase distortions of the wavefront since there appear several maxima of equal intensity at the receiving aperture. The thermal blooming of high-power beams stabilizes the intensity profile both in transparent and in absorbing media, i.e. in this case there exists a single we 11-pronounced intensity maximum, but it is strongly shifted towards the wind. The oscillatory behavior in time of the intensity and of the position of the center of gravity of the beam can occur for pulses whose duration is greater than τ_v, due to the optical capture of the radiation intensity maxima by the denser regions of the medium. These are either uncleared regions (in the case of a cloudy medium) or regions which are not heated by optical radiation (the case of a transparent medium).

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