Interference structure of the scattering cone in a laser spark

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(Submitted 7 June 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **58**, No. 2, 73–76 (25 July 1993)

Interference fringes have been observed in a cone laser light scattered in the plasma of a laser breakdown of air. This is the first such observation. An explanation of the observed pattern is proposed: The pattern results from an interference of laser light scattered at two or more self-focusing centers in the plasma of the laser spark in air. The diameter of a focus in the plasma has been found as a function of the gas pressure in the chamber for various wavelengths of the laser light.

A multifocus structure[1,2] of the self-focusing of intense light has been studied experimentally in various nonlinear media, but it has yet to be seen in a laser plasma. With regard to self-focusing in a laser spark, all that has been learned to date, starting in the earliest studies,[3,4] is as follows:[5] Inside the caustic of the lens, which focuses the laser beam into the region of the laser breakdown of the gas, the refractive index of the plasma is nonuniform. The length scale of the variations is small in comparison with the caustic diameter. Behind the spark one observes a cone of scattered laser light with a vertex angle larger than the angular aperture of the focusing lens. In the present study, interference fringes have been detected in the scattering cone for the first time. Their formation may be due to the presence of a multifocus structure of the self-focusing of the laser light in the spark.

In our experiments the scattering cone was detected by photographing a screen illuminated by scattering laser light. This screen was oriented parallel to the axis of the spark and positioned 2–6 mm away from it. The exposure time during the photography was long in comparison with the lifetime of the laser spark. To produce the spark we used light from a pulsed Nd laser operating on a single longitudinal mode, with a wavelength $\lambda_0 = 1.06\ \mu\text{m}$ and a divergence close to the diffraction limit. The energy of the laser pulse was 0.2–4 J in all experiments; the pulse length was ≈ 10 ns, and the beam diameter at the focusing lens was 40 mm. The laser pulse had a relatively short rise time (≈ 1 ns) and a comparatively long trailing edge. The laser light or (after conversion in KDP crystals) its second, third, or fourth harmonic was focused by a long-focal-length lens ($f = 1$ m) into the chamber, in a caustic 2 mm long and 80 μm in diameter. The laser spark at the lens focus was studied at air pressures from 10 to 760 torr in the chamber.

We observed the interference pattern inside the scattering cone (Fig. 1) in experiments with the first, second, and third harmonics of the neodymium laser at comparatively low pulse energies ($\leqslant 0.5$ J) and high pressures ($p \sim 1$ atm). At higher energies and lower pressures, the fringe contrast decreased, or the fringes disappeared completely. The clearest fringes were observed during breakdown of air at $p = 1$ atm by

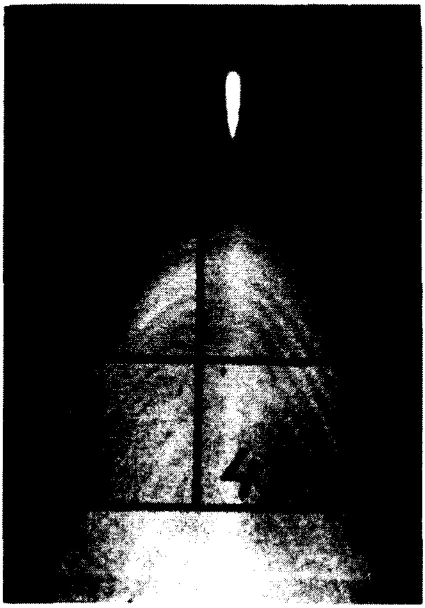

FIG. 1. Time-lapse photograph of a screen illuminated by laser light scattered in a spark. The laser beam is propagating from right to left. Ahead of the scattering cone is an image of the spark. Here $\lambda = 0.353$ μm; $p = 760$ torr; and the distance from the spark axis to the screen is 6 mm. A grid with a side of 1 cm has been applied to the screen.

light with a wavelength $\lambda = 0.353$ μm. In the experiments with the fourth harmonic, we did not observe an interference structure in the light scattered in the spark anywhere in the ranges of experimental conditions studied.

The shape of the fringes in Fig. 1 is similar to the interference pattern from two coherent sources on the spark axis, separated by a distance much smaller than the distance from the screen to the axis of the laser beam. If each of the sources is the vertex of a scattered cone, then when these cones are superimposed we should see on the screen interference fringes in the form of a system of nested hyperbolas, as in Fig. 1. The angles between the asymptotes of the dark fringes and the distances between neighboring dark fringes (measured in Fig. 1) lead to an estimate $\approx 50\lambda = 18$ μm between the light sources in this experiment. In experiments with other harmonics, the distances between sources are again estimated to be on the order of 20 μm. This distance is much smaller than the length of the focal region.

The formation of such a structure in a spark can be explained on the basis of a self-focusing in a plasma involving the formation of two or more self-focusing centers. When there are several focusing points, not spaced uniformly, and when these points are furthermore in motion during the laser pulse, the interference pattern should be smeared. If, on the other hand, only two self-focusing points arise, and the distance between them changes only slightly near the crest of the pulse, there is the possibility of detecting the interference by time-lapse photography, as illustrated in Fig. 1. Finally, if only a single self-focusing center arises, there is no interference pattern at all. This conclusion seems to correspond to our experiments with the fourth harmonic. The absence of an observable system of interference fringes in these experiments may be due to a rise in the threshold power for self-focusing with decreasing wavelength.

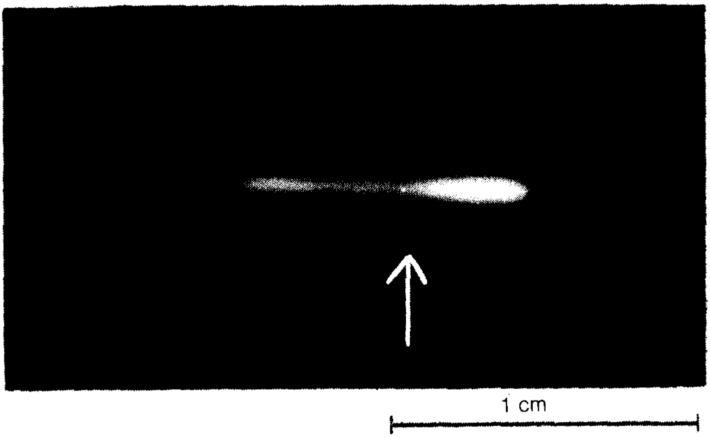

FIG. 2. Time-lapse photograph of a laser spark with a wake left by a focus. The laser beam is propagating from right to left. The arrow shows the position of the focus. The part of the spark to the left of the arrow is formed during the decay of the laser pulse at a velocity of more than 10^8 cm/s. Here $\lambda = 0.265$ μm and $p = 102$ torr.

At the trailing edge of the laser pulse, where the radiant power decreases, and the self-focusing distance increases, it is possible to observe a motion of the self-focusing point outside the original region of optical breakdown if this motion is accompanied by an ionization of the gas. With this possibility in mind, we used an image-converter camera to record the motion of plasma fronts in the light emitted by the plasma itself. These measurements showed that after breakdown of the gas the plasma moves opposite the laser beam at a velocity up to $\sim 10^7$ cm/s. At pressures $p \sim 1$ atm, the plasma undergoes essentially no motion along the line of sight. At lower pressures, however, there is a brief increase in the velocity of the plasma front along the laser beam during the decay of the laser pulse. The increase lasts ≈ 1 ns and results in a value above 10^8 cm/s. Outside this brief time interval, the velocity of the front remains below 10^7 cm/s. The thin "tail" on the spark in Fig. 2 corresponds to a region in which the plasma front is moving at $\geqslant 10^8$ cm/s. These results can be explained[2] as the consequence of an increase in the self-focusing length to values greater than the size of the plasma on the trailing edge of the laser pulse. The point at which the rays of the partially focused beam converge moves along the axis of the beam within the plasma of the spark, forming a thin wake.

In most of the experiments, photographs like that in Fig. 1 can be used to determine the maximum angle through which laser light is scattered in the spark, i.e., the angle α, between the axis of the scattering cone and the generatrix of the cone. We find a completely regular $\alpha(p/N^2)$ dependence, which can be approximated well by $\alpha_0 = 4.4 \times 10^{-2}$ (p/N^2) deg, where p is in torr, and N is an index of the harmonic of the light from the Nd laser (see Fig. 3).

These results can be used to estimate the transverse dimension of the self-focusing

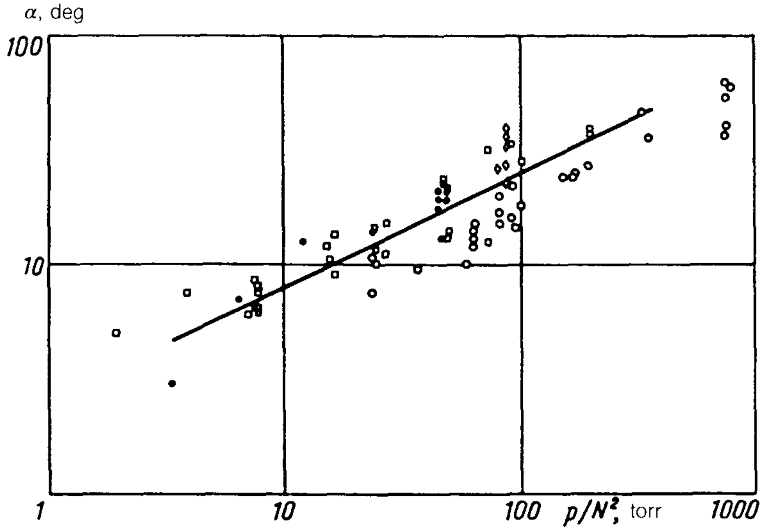

FIG. 3. Maximum angle through which laser light is scattered in the spark, α, in experiments with the Nth harmonic of the laser light, at a pressure p in the chamber. The solid line shows the approximation $\alpha_0 = 2.5 (p/N^2)$ deg, where p is in torr. Open circles—$\lambda = 1.06$ μm; squares—0.53; diamonds 0.353; filled circles—0.265 μm.

region, d, from $\sin \alpha = 1.22\lambda/d$. Using $\lambda = \lambda_0/N$ and the approximation for α_0, we find $d \simeq 30\lambda_0 p^{-1/2}$ (again, p is in torr) in the region $\alpha_0 < 1$. In other words, under our conditions the minimum beam diameter during self-focusing in the plasma does not depend on the laser wavelength, being determined exclusively by the pressure p.

The $d \propto p^{-1/2}$ dependence may have the following explanation. If we assume that a self-focusing with several centers occurs in the plasma, and that a power on the order of the threshold power for self-focusing (P_0) goes into each focus, then we can estimate d^2 from $d^2 \approx P_0/I_{\max}$, where $I_{\max}$ is the intensity of the laser light at a self-focusing center. The intensity $I_{\max}$ is determined from the condition that the ponderomotive pressure created by the laser light exceed the thermal pressure of the plasma, $(n_e/n_{cr})(I_{\max}/c) \approx n_e T_e$. Here n_e is the electron density, which has the value n_{cr} near the critical point, c is the velocity of light, and T_e is the temperature. If the expression $P_0 \approx 2cT_e n_{cr}/r_0 n_e$ holds for the ponderomotive mechanism for self-focusing in a plasma,[6] we find $d \simeq (r_0 n_e)^{-1/2}$, where r_0 is the classical radius of the electron.

On the other hand, the gas in the focal volume in our experiments at intensities $\sim 10^{13}$ W/cm^2 is apparently fully ionized. If so, the pressure p completely determines the electron density n_e (if we ignore the plasma expansion). The approximating function for α_0 becomes $\alpha_0 = 2(n_e/n_{cr})^{1/2}$, and the corresponding expression for d is $d \approx \lambda/\alpha_0 \approx (r_0 n_e)^{-1/2}$. This result agrees with the theoretical prediction derived above. The agreement between the estimate of the focus size found from the experimental data and the result found from a calculation based on the realization of a multifocus focusing in the plasma is a further argument in favor of this proposal.

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Translated by D. Parsons