Loss of spatial coherence and limiting of focal plane intensity by small-scale laser-beam filamentation

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(Received 6 August 2011; published 18 November 2011)

We describe a nonlinear optical mechanism that leads to a decrease of the degree of (transverse) spatial coherence of a laser beam as a function of propagation distance. This prediction is in direct contrast with those of the van Cittert-Zernike theorem, which applies to propagation through a linear, homogeneous material. The mechanism by which coherence is lost is the growth of small phase irregularities initially present on the laser wave front. We develop a detailed theoretical model of this effect and present experimental results that validate this model. The practical importance of this result is that by being able to controllably decrease the spatial coherence of a laser beam, one can limit the maximum intensity that is produced in its focal region. By limiting the intensity, one can prevent laser damage to bulk optical components or to sensitive photodetectors. This mechanism thus provides an alternative to current approaches of sensor protection based on optical power limiting.

DOI: 10.1103/PhysRevA.84.053837 PACS number(s): 42.65.Jx

I. INTRODUCTION

The ability to focus a light beam to a small spot is intimately related to the spatial-coherence properties of the beam. A fully coherent beam of wavelength $\lambda = 2\pi c/\omega$ and diameter D can be focused by a lens of focal length f to a spot size of approximately $f\lambda/D$, as given by the usual Rayleigh criterion. A beam with limited spatial coherence cannot be focused so tightly. To a good approximation, the spot size in this case is given by the Rayleigh criterion, but with the beam diameter replaced by the transverse coherence length l_{coh} of the light beam. Thus, the ability to control the coherence properties of a light beam can lead to important implications for the nature of the intensity distribution within the focal region, including the maximum intensity that can be produced.

It is well known that thermal radiation is highly incoherent, but nonetheless light from a distant star possesses a high degree of spatial coherence when the light arrives at the earth. This thought is quantified by the van Cittert-Zernike theorem [1], which states that light fields become spatially more coherent as they propagate away from their source. Nonetheless, there are counterexamples for this sort of behavior. One such situation is in the propagation of light though atmospheric turbulence, in which case the random refractive index variations induced by the turbulence leads to a decrease in the coherence of the light field and the blurring of the resulting image [2]. In the present paper, we describe another example of such behavior, in which propagation through a nonlinear optical material leads to a loss of spatial coherence.

II. THEORY

The mechanism by which an intense light field can lose coherence as it propagates through a nonlinear optical medium is intimately related to the mechanism that leads to small-scale laser-beam filamentation [3], as described by Bespalov and Talanov [4] and observed by many others [5–10]. According to this mechanism, small irregularities present initially on the laser wave front become amplified by four-wave mixing processes as the beam passes through a material characterized by an intensity-dependent refractive index of the form $n = n_0 + n_2 I$. It has been shown that, in fact, even the relatively weak quantum fluctuations present in any light field can serve as the irregularities that initiate the filamentation process [11]. It is well established that the exponential amplitude gain experienced by a weak harmonic perturbation of transverse wave vector q is given by the gain parameter [12]

$$g = \sqrt{\beta(2\gamma - \beta)}, \tag{1}$$

where $\gamma = n_2 k_0 I$, $k_0 = \omega/c$, ω is the angular frequency of the light wave, and $\beta = q^2/(2n_0 k_0)$ [13].

We note that the total gain $G = gL$ experienced upon propagation though a nonlinear medium of length L must exceed some threshold value $G_0(q)$ in order for perturbations of transverse wave vector q to become appreciable. For nonlinear optical processes that grow from noise, such as stimulated Brillouin scattering, this threshold value is often in the range of 25–30 [14,15]. However, a value of 5 is more likely relevant in the present context in which the process is initiated by technical noise on the laser wave front. We thus conclude that the gain given by Eq. (1) must be at least as large as $g_0(q) = G_0(q)/L$ in order for perturbations with wave vector q to become appreciable. We now calculate the maximum value of q, which we call q_{max}, for which the gain is this large. (We determine the maximum value of q because we are interested in determining the smallest distance over which transverse coherence is maintained.) We define the corresponding value of β to be $\beta_{\text{max}} = q_{\text{max}}^2/(2n_0 k_0)$. Equation (1) thus becomes $g_0(q_{\text{max}}) = [\beta_{\text{max}}(2\gamma - \beta_{\text{max}})]^{1/2}$. We solve this for β_{max} to find that

$$\beta_{\text{max}} \equiv q_{\text{max}}^2 \big/ (2n_0 k_0) = \gamma + \sqrt{\gamma^2 - g_0(q_{\text{max}})^2}. \tag{2}$$

We have taken the positive part of the square root because we are seeking the maximum value of q. Note that for $\gamma^2 < g_0^2$, there is no physically meaningful solution to this equation, that is, there is no value of β for which the perturbation sees gain.

We now determine how the transverse coherence length $l_{coh} = \pi/q_{max}$ is limited by the growth of wave-front perturbations. This quantity is given by

$$l_{coh} = \frac{\pi}{\sqrt{2n_0k_0}[\gamma + \sqrt{\gamma^2 - g_0(q_{max})^2}]^{1/2}} \tag{3}$$

for $\gamma^2 > g_0^2$. In the limit of very large laser intensities, this result simplifies to

$$l_{coh} = \frac{\pi}{2\sqrt{n_0 n_2 k_0^2 I}}. \tag{4}$$

In the opposite limit of $\gamma^2 < g_0^2$, the quantity l_{coh} becomes imaginary, implying that there is no decrease of the transverse coherence distance. In this case, and for that of γ not too large, the transverse coherence length is identical to that of the incident laser beam. For a fully coherent beam, the transverse coherence is limited by the beam diameter $2w_0$ itself. In summary, well below the threshold for filamentation, the coherence length l_{coh} is given approximately by the diameter $2w_0$ of the laser beam. Above the threshold for filamentation, the coherence length is given by Eq. (3), and well above the threshold for filamentation it is given by Eq. (4). These results summarize our theoretical model.

III. EXPERIMENTAL INVESTIGATIONS

We have performed a series of experiments to confirm the predictions of the model just described. These experiments were performed using the 25-ps duration, 532-nm wavelength output pulses of a commercial, mode-locked, frequency-double, Nd:YAG laser system operating at a pulse repetition rate of 10 Hz. These pulses were focused into a 10-mm-long optical cell containing carbon disulfide, and the transmitted beam was examined both at the output of the cell and in the far field. Representative experimental results are shown in Fig. 1 for several values of the pulse energy ranging from 100 nJ to 5.0 μJ. For this set of experiments, a lens with 700-mm focal length was used to focus the 6-mm-diameter laser beam

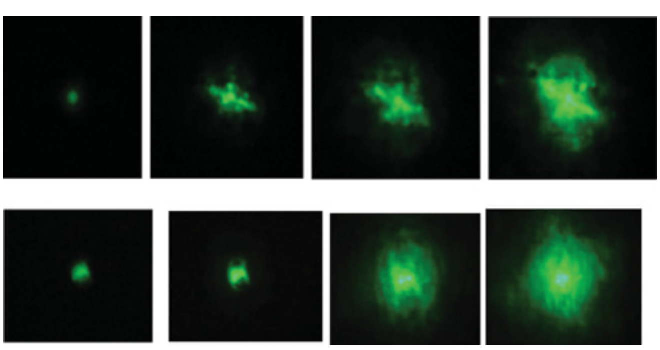

FIG. 1. (Color online) Demonstration of small-scale filamentation (beam breakup into multiple filaments) in carbon disulfide. Top row: Near-field distribution at the output of the interaction region. Bottom row: Far-field intensity distributions. Pulse energies increase left to right: 100 nJ, 0.69 μJ, 2.2 μJ, and 5.0 μJ in a 25-ps pulse. The diameter of the lowest-energy, near-field spot is 80 μm, and the diameter of its far-field pattern is 0.5 degree. One sees that under these experimental conditions, the spatial-coherence properties of the laser light are strongly diminished by the filamentation process.

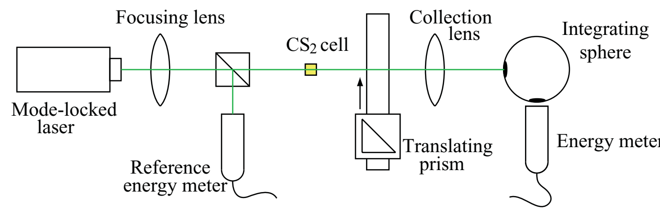

FIG. 2. (Color online) Schematic diagram of the optical configuration used to study the transmission of a 532-nm laser pulse through a 10-mm-long CS_2 cell.

into the cell. The beam diameter at the entrance to the cell was thus of the order of 80 μm, and the Rayleigh range was of the order of 30 mm. The far-field images were recorded at a distance of 900 mm from the cell. At the lowest pulse energy, no discernible nonlinear effects are present. As the pulse energy is increased, the beam is seen to break up into multiple filaments at the output of the cell and to increase in the far-field divergence angle. The increase in the divergence angle demonstrates a decrease in the spatial coherence of the beam, as predicted by the theory described above.

We have also performed experiments to study more quantitatively the loss of spatial coherence of the transmitted laser beam. The setup for these measurements is shown in Fig. 2. A prism mounted on a computer-controlled translation stage serves as a knife edge, and the energy collected by a lens and integrating sphere is recorded as a function of the position of the knife edge for each laser shot. In our experimental method, we set the gain of the laser amplifier to a fixed value and allow the fluctuations in the oscillator output to provide a range of pulse energies. These energies are monitored using the reference energy meter in Fig. 2. The transmitted energy versus knife-edge position was sorted based on the input reference energy, and put into bins of 200 points each, with a 100-data-point overlap between successive bins. For each bin, the transmission versus knife-edge position is fitted to the expected functional form (the error function of variable width) to determine the beam width for that particular pulse energy. The results of these measurement are shown in Fig. 3. Here the measured far-field diffraction angle (the half angle measured to the $1/e^2$ intensity point) is plotted as a function of the pulse energy. The estimated error is approximately the diameter of the circle. The beam diameter obtained for each energy interval was used to calculate the far-field diffraction angle using the following formula:

$$\theta = \arctan[2w(z_1)/z_1], \tag{5}$$

where $z_1 = 207$ mm is the distance from the focus to the knife edge, and $w(z)$ is the radius where the beam intensity is $1/e^2$ of its axial value at that distance z. Under none of our conditions did we observe a decrease in the total energy of the pulse leaving the cell; only transverse reshaping was observed.

The red curve in Fig. 3 is a fit of the data to the prediction $\theta = 2\lambda/(\pi l_{coh})$, where l_{coh} is given by Eq. (3), with g_0 and the coefficient relating γ to the pulse energy taken as fit parameters. The beam-waist parameter w_0 was measured to be equal to 50 μm from a similar experiment performed with no cell present. The fit shown in the figure was obtained for the

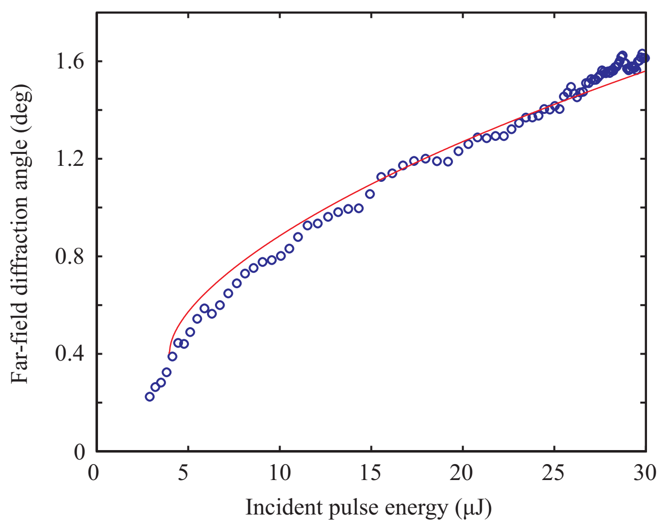

FIG. 3. (Color online) Measured far-field diffraction angle (circles) and the predictions of our theoretical model (solid line) as functions of the incident pulse energy. The square-root dependence on pulse energy predicted by Eq. (4) is evident.

values $g_0 = 1.8\ \text{cm}^{-1}$, and with γ given by $n_2 k_0 I$, with $n_2 = 3.2 \times 10^{-18}\ \text{m}^2/\text{W}$, $k_0 = 2\pi/\lambda$, and $I = 0.144 Q/(\tau\pi w_0^2)$, where Q is the (measured) pulse energy and $\tau = 25$ ps.

IV. DISCUSSION AND IMPLICATIONS

We note from Fig. 3 that for large pulse energies, the far-field diffraction angle increases as the square root of the pulse energy, in agreement with the predictions of Eq. (4). Consequently, the power per unit area in any transverse plane located in the far field remains constant as the input pulse energy increases. If this far-field intensity distribution is itself imaged to a small spot size, the intensity in this region will also remain constant with increasing input energy. This nonlinear process therefore acts as an intensity limiter.

There has been considerable work performed over approximately the past 20 years in developing optical *power* limiters, that is, nonlinear interactions that limit the total power of a transmitted laser beam. Power limiters of this sort hold promise in protecting sensitive optical components, such as optical sensors, from laser damage at high exposure levels. Power limiters have been constructed that operate by means of nonlinear focusing [7,16], reverse saturable absorption [17,18], and other types of nonlinear interactions [19]. The process described in the present work constitutes an alternative to this approach by not attempting to limit the total power, but rather by attempting to limit the more relevant quantity, which is the power per unit area in a focal region. Also, as our process does not deposit energy within the interaction region, it should prevent optical damage to the limiter and should allow for a more rapid recovery after exposure to an intense pulse. Moreover, as this process is nonresonant, it should lead to no intensity loss or visual distortion when low-power pulses are transmitted through the system. We also wish to point out that the study of the interplay between nonlinear optical interactions and the coherence properties of light fields have been studied by others in various contexts [20,21].

Under our experimental conditions, limiting behavior occurs at energies greater than approximately 3 μJ, which for our 25-ps pulses corresponds to a peak power of the order of 100 kW. To good approximation, the filamentation process depends on the intensity (power per unit area) of the incident laser beam. Thus, for longer laser pulses, limiting behavior is still expected to occur at power levels of the order of 100 kW. Through the use of materials with a larger nonlinear coefficient, limiting behavior could be achieved at lower energy and power levels. As an example, we note that the material poly(p-phenylenvinylene) (PPV) possesses a nonlinear coefficient that is 300 times larger than that of carbon disulfide [22]. This material is currently available only in extremely thin films, and would not be suitable for use as an intensity limiter. Nonetheless, the existence of materials such as PPV illustrates that very large values of n_2 are currently available. The use of such a material with an n_2 value this large would lead to limiting behavior for 25-ps pulses as weak as 10 nJ of energy or 300 W of peak power.

In summary, we have shown that the process of laser-beam filamentation can lead to a decrease in the spatial-coherence properties of a laser beam, and that this process leads to a limit of the maximum intensity that can be achieved in the focus of the laser beam. This process may lead to an attractive alternative to current methods for optical power limiting.

ACKNOWLEGMENT

This work was supported by DARPA SBIR Contract No. W31P4Q-10-C-0160.

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