QUANTUM FLUCTUATIONS AS THE ORIGIN OF LASER BEAM FILAMENTATION

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According to traditional theories, the filamentation[1] of a laser beam as it passes through a nonlinear material is a consequence of the spatial growth[2,3] of weak wavefront perturbations initially present on the beam. To a certain extent these perturbations can be removed by passing the beam through a spatial filter before it enters the medium. However, quantum fluctuations in the field amplitudes of the transverse side modes impose perturbations that cannot be removed by spatial filtering. These quantum fluctuations can lead to the filamentation of a beam with an otherwise perfect wavefront. We study the growth of these fluctuations and predict the nonlinear phase shift at which this process will become significant. We find that quantum-initiated filamentation imposes a fundamental limit to the intensities that can be propagated through a nonlinear material without beam breakup.

To model this behavior, we begin by expanding a monochromatic field in its transverse modes as

$$\hat{E}^{(+)}(\mathbf{r},t) = \left[\mathcal{E}_0 + \int d^2q \sqrt{\hbar\omega_0 k_0 / 4\pi^2}\ \hat{a}(\mathbf{q},z)\ e^{i\mathbf{q}\cdot\mathbf{r}}\right] e^{i\gamma z}\ e^{ik_0 z - i\omega_0 t} \tag{1}$$

where $\mathcal{E}_0$ represents the incident plane-wave laser field, $\hat{a}(\mathbf{q},z)$ is the amplitude of the side mode with transverse wavevector $\mathbf{q}$, and γz is the nonlinear phase shift. We assume that all of the side modes are initially in the vacuum state. Using the paraxial wave equation and linearizing the resulting equations in the amplitude of the perturbation, we have obtained an expression for the total intensity I_{sm} of the side modes as a function of the nonlinear index of refraction of the medium, the length of the medium, and the applied field intensity. In the regime where γz is large, this expression can be reduced to

$$I_{sm} = I_0^{vac}\ e^{2\gamma z} \tag{2}$$

where $I_0^{vac} = (nc/8\pi^2)\hbar\omega_0 k_0^2\gamma$. According to the present model, filamentation is unimportant if I_{sm} is much smaller than the intensity of the incident laser beam. This condition places a limit on the size of the quantity $\gamma z = k_0(n_2/n_0)I_0 z$. For any given nonlinear optical medium, there is thus a fundamental limit on the intensity of a laser beam that can propagate without the occurrence of filamentation.

We have also performed numerical simulations of the transverse intensity pattern that is formed as the filaments begin to develop. To do so, we model the vacuum fluctuations by introducing a half photon, with random phase, per mode. The simulations show the growth of large transverse intensity fluctuations from small initial perturbations. An example of such a simulation is shown in Figure 1.

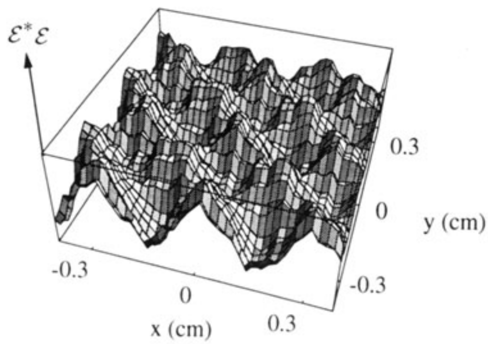

Figure 1. Transverse intensity distribution of a laser beam after passing through a nonlinear optical medium for which $\gamma z = 14.2$.

In summary, we have shown that, even in the absence of classical wavefront perturbations, a laser beam propagating through a nonlinear optical medium is subject to breakup through the process of filamentation initiated by quantum mechanical vacuum fluctuations.

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1. V.I. Bespalov and V.I. Talanov, Filamentary structure of light beams in nonlinear liquids, *JETP Lett.* 3:471 (1966)
2. R.Y. Chiao, P.L. Kelley, and E. Garmire, Stimulated four-photon interaction and its influence on stimulated Rayleigh-wing scattering, *Phys. Rev. Lett.* 17:1158 (1966)
3. E.S. Bliss, D.R. Speck, J.F. Holzrichter, J.H. Erkkila, and A.J. Glass, Propagation of a high-intensity laser pulse with small-scale intensity modulation, *Appl. Phys. Lett.* 25:448 (1974)