Nonlinear-optical Christiansen filter as an optical power limiter

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We have constructed an optical power limiter based on nonlinear induced scattering in a cell containing crushed glass and a mixture of acetone and carbon disulfide. For 30-ps-long laser pulses the transmitted energy saturates at a value of 6 μJ. We also present the results of a theoretical modeling study that shows how the operating characteristics of such a device can be optimized. © 1996 Optical Society of America

There is great interest in the development of interactions that can be used to construct an optical power limiter, that is, a device that can limit the maximum power transmitted by the device to some fixed value. Several techniques for the construction of optical power limiters have been studied.[1–3] One standard method[4] involves using the absorption of a molecule for which the absorption cross section of the excited state exceeds that of the ground state. Under these circumstances the absorption coefficient of a collection of these molecules will increase with increasing laser intensity; this process will tend to limit the intensity of the transmitted beam to a value comparable with the saturation intensity of the lower transition. Recent research in this area has utilized fullerines[5,6] and organometallic compounds[7] with good success.

Here we describe our theoretical and experimental investigations of a different type of optical power limiter, based on a nonlinear version of the classical Christiansen filter. There is a large body of literature describing the classical Christiansen filter.[8–14] Our device is illustrated in Fig. 1. Here small grains of crushed glass (of characteristic size 100 μm) are mixed with a liquid. The liquid is a nearly 50/50 mixture of carbon disulfide and acetone. We establish the exact concentration experimentally by requiring that the linear refractive index of the liquid be precisely equal to that of the glass grains at the design wavelength, $\lambda_0 = 0.53$ μm in our case. Under these conditions the glass grains disappear into the host liquid, and the slurry becomes optically homogeneous when examined with weak 0.53-μm radiation. However, the nonlinear refractive indices of the solid and liquid constituents are quite different. The nonlinear refractive index of glass is $n_2 = 8.5 \times 10^{-17}$ esu,[15] that of carbon disulfide is 2.8×10^{-14} esu,[16] and that of acetone is 6.1×10^{-16} esu.[17] We estimate the nonlinear refractive index of the liquid solution as $n_2 = 1.5 \times 10^{-14}$ esu. Inasmuch as the nonlinear refractive indices of the liquid and the glass components of the slurry are different, an index mismatch between the two components can be induced by exposure of the material to a high-intensity laser beam. In the presence of such a mismatch the material becomes highly scattering. The attenuation coefficient describing these scattering losses can be calculated in terms of an expression derived by Raman[18] to describe the classical Christiansen filter. This expression, in the form as modified by Sipe[19] to allow for arbitrary fill fraction f of the glass particles, has the form

$$\alpha = f(1 - f)\frac{4\pi^2 d}{\lambda_0{}^2}(n_l - n_g)^2, \tag{1}$$

where d is the characteristic size of the glass particles, λ_0 is the vacuum wavelength of the incident radiation, and n_l and n_g denote the refractive indices (including their nonlinear contributions) of the liquid and the glass components. Because the linear contributions to these indices are equal, we can set $n_l - n_g$ equal to $[n_2^{(l)} - n_2^{(g)}]I = n_2^{(l)}I$, so the attenuation coefficient becomes

$$\alpha(I) = f(1 - f)\frac{4\pi^2 d}{\lambda_0{}^2}[n_2^{(l)}I]^2. \tag{2}$$

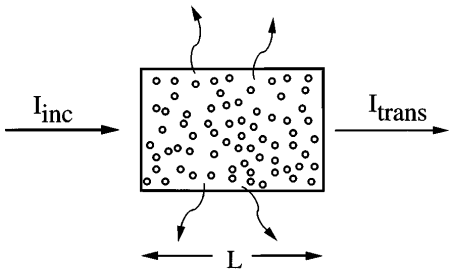

Fig. 1. Nonlinear Christiansen filter of length L consisting of particles suspended in a solution. Light at the index-matched wavelength is transmitted if the incident intensity is low but is scattered for high input intensities.

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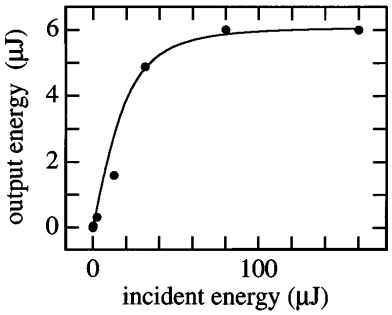

Fig. 2. Experimental data (circles) and theory (solid curve) for a 1-cm-thick Christiansen filter consisting of 100-μm glass particles in a solution of carbon disulfide and acetone. A frequency-doubled Nd:YAG laser pulse with a length of 30 ps was collimated to a diameter of 118 μm at the filter.

Through use of this expression the variation of the laser intensity within the scattering cell can be calculated through

$$dI/dz = -\alpha(I)I\,. \tag{3}$$

Our theoretical predictions for the properties of the nonlinear Christiansen filter are obtained from the solution of Eqs. (2) and (3).

To test the general concept of the nonlinear Christiansen filter we constructed such a device for which the crushed glass particles had a characteristic size $d = 100$ μm and a volume fill fraction $f \simeq 0.5$. The total thickness of the cell was $L = 1$ cm. The nonlinear transmission properties of this filter were studied with 30-ps pulses of the second harmonic ($\lambda_0 = 0.53$ μm) of a Nd:YAG laser. This beam was focused with an $f/200$ optical system to produce a beam that was essentially collimated at a diameter of 118 μm over the 1-cm length of the nonlinear Christiansen filter. The experimental results showing the energy transmitted through the cell are shown in Fig. 2. We see that the output energy initially increases linearly with incident laser energy and eventually saturates at a value of ~ 6 μJ. The solid curve is our best theoretical fit to the data, calculated by a numerical integration of Eq. (3) with $\alpha(I)$ given by Eq. (2). For simplicity, the transverse variation of the laser intensity and the diffractive spreading of the laser beam are ignored, so the theory assumes plane-wave propagation. Also, the time evolution of the laser intensity was modeled as a square-wave pulse. Thus the pulse energy was related to the assumed constant laser intensity through $Q = IAT$, where $A = (\pi/4)d^2$, with $d = 100$ μm and $T = 30$ ps. The calculated transmitted pulse energy was scaled down by a factor of 4 to account for the measured 25% low-intensity transmission of the cell. We believe that the low-intensity transmission was only 25% because the refractive index of the liquid was not precisely matched to that of the glass particles. The agreement between the experimental results and those of the theoretical model is seen to be remarkably good.

We also performed a numerical study to determine how to optimize the performance of the nonlinear Christiansen filter. In performing this study we assumed a pulse duration of $T = 1$ ns, which is more

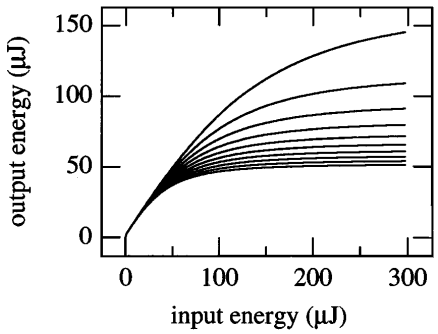

Fig. 3. Modeling of the nonlinear Christiansen filter, assuming 1-ns pulses, a fixed 29-μm beam diameter, and filter thickness ranging from 1 cm (bottom curve) to 1 mm (top curve).

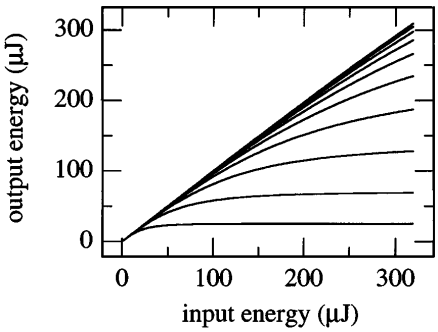

Fig. 4. Modeling of the nonlinear Christiansen filter, assuming 1-ns pulses, a fixed filter thickness of 1 cm, and a beam diameter ranging from 105 μm (top curve) to 15 μm (bottom curve).

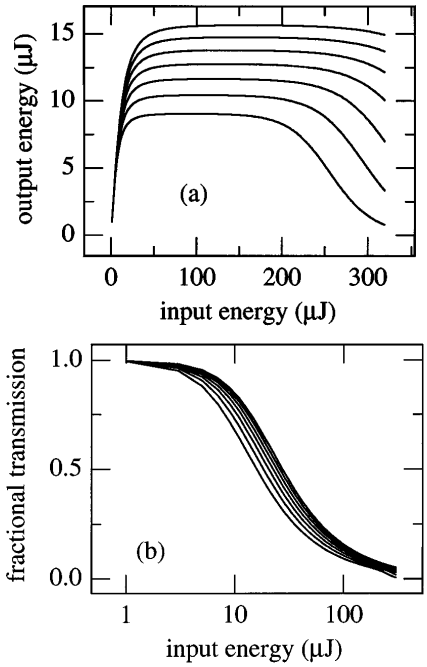

Fig. 5. Modeling of the nonlinear Christiansen filter assuming 1-ns pulses and the beam diameter optimized for each filter thickness, which ranges from 0.9 mm (top curve) to 0.3 mm (bottom curve). Shown are (a) output energy versus input energy and (b) fractional transmission versus input energy.

typical of conditions relevant to intended uses of the power limiter. We also assumed as above that $n_2 = 1.5 \times 10^{-14}$ esu.

We performed these calculations under three different sets of assumptions and present the results in Figs. 3–5. Figures 3 and 4 are intended to convey a feeling for how the transmission characteristics of the nonlinear Christiansen filter depend on physical characteristics such as the cell length and the laser beam diameter. In contrast, Fig. 5 shows the characteristics of an optimized filter design. For Fig. 3 we assumed that the diameter of the incident beam is kept fixed at 30 μm and studied the influence of varying the thickness of the scattering filter. For Fig. 4 we kept the cell thickness fixed at 3 mm and studied the influence of varying the beam diameter. Finally, Fig. 5 shows the predictions for a series of filters that have been optimized in the sense that, for each cell length L, the laser beam diameter d is selected so that the Rayleigh range of the laser beam is equal to the cell length, that is,

$$L = 2\pi(d^2/\lambda). \tag{4}$$

Note that, as a result of this scaling law, a shorter scattering cell leads to better power limiting than does a longer cell. Note also that limiting at a level of 10 μJ or lower is possible for an optimally designed scattering filter. This value is close to the design goal of 3 μJ for certain classes of optical limiters, because pulses containing less than 3 μJ of energy cannot cause damage to the retina of the human eye.[20]

In summary, we have constructed an optical power limiter based on the concept of nonlinear induced scattering and have found that the device operates in a manner consistent with the predictions of a simple theoretical model. This device is in many ways similar to that proposed by Yoo and Alfano,[21] who considered a multilayered system of alternating high and low nonlinear materials for use in laser protection system. Our device differs from theirs in that it is randomly inhomogeneous in the transverse directions as well as in the longitudinal direction. Our device also bears some similarity to that reported by Justus *et al.*,[3] which operates by means of the combined action of thermal defocusing in an absorbing liquid and nonlinear induced scattering. Our device should be contrasted with that reported by Al'tshuler *et al.*,[22] who demonstrated self-transparency through use of a nonlinear change in refractive index to equalize the indices of the two materials contained in a scattering cell.

The device that we have demonstrated is useful only for essentially monochromatic radiation at the design wavelength. One could overcome this limitation by achromatizing the device by matching both linear refractive index and the dispersion of the liquid component with those of the glass particles. A liquid solution consisting of three or more components could be used for this purpose.

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