Optical limiters using photorefractive nonlinearities

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We report experimental and theoretical studies of the use of the photorefractive effect in the design of optical limiters. Preliminary results indicate extinction coefficients of at least 98–99% with 1 J/cm^2 transmitted before steady state is reached.

INTRODUCTION

The ability of photorefractive crystals such as barium titanate and strontium barium niobate to record spatially phase shifted real time holograms with high diffraction efficiency is the basis of many new optical devices involving coherent amplification. Some examples are unidirectional ring resonators, passive phase conjugate mirrors and coherent image amplifiers.[1] While in the past, most attention has been paid to gain and beam amplification in these devices, we pay attention here to the beams which are deamplified, as a means of developing optical limiters.

FANNING LIMITER

In many cases photorefractive nonlinearities are so strong that a laser beam passing through a crystal loses much of its power to a broad fan of light resulting from amplification of radiation scattered by imperfections in the crystal.[2,3] A crystal acting in this way can be thought of as an optical limiter which dumps excess power several angular degrees away from the incident direction into the fanning direction (Fig. 1). In preliminary experiments we have shown that as much as 98–99% of the incident light can be diverted in this manner. Some of the features associated with this fanning limiter are as follows.

(a) The limited radiation is mostly deflected, not absorbed in the crystal, thus minimizing possible damage to the limiter caused by overheating. Damage thresholds for the crystals are quite high. We have done experiments in barium titanate that involve cw intensities of more than 100 W/cm^2. The main potential for damage lies in the possibility of the crystal temperature rising above its Curie point ($\sim 120\,^\circ$C in barium titanate) where it becomes cubic and loses its linear electro-optic coefficient.

(b) The crystals are effective over the entire visible spectrum.

(c) Since fanning is produced only by coherent light, natural incoherent light is not discriminated against. On the other hand, the coherence lengths required for fanning are not large; the effect is operative even for picosecond pulses from mode-locked lasers.

(d) The response of the crystal is low at low intensities, saturating at about 1 W/cm^2 so that low-power laser beams are not limited. Increasing the intensity above this level increases the speed of response proportionally. About 1 J/cm^2 will be allowed to pass through a barium titanate crystal undeflected before the fanning reaches steady state.

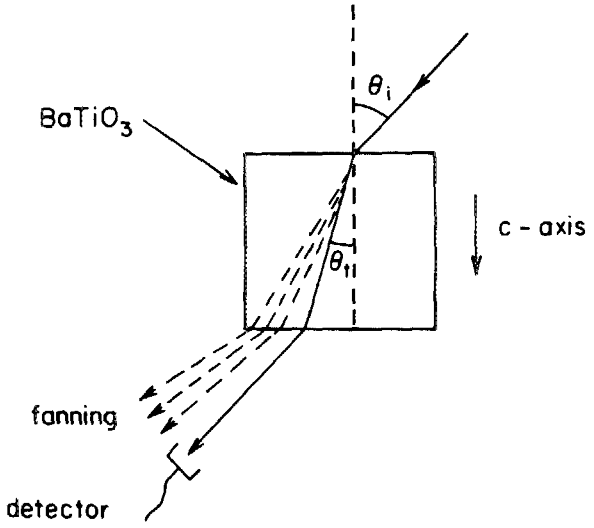

FIG. 1. Fanning limiter crystal showing direction of *c* axis (defined here as pointing towards the electrode which had been positive when the crystal was poled) and the internal and external angles of incidence.

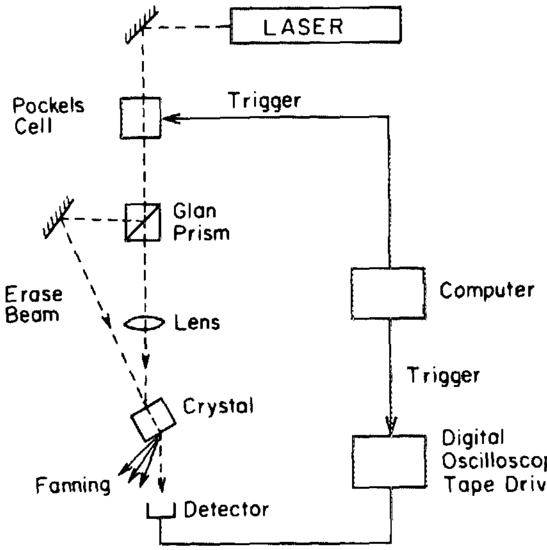

FIG. 2. (a) Apparatus used to investigate fanning limiter. An argon-ion laser generates light at 488 nm polarized perpendicularly to the plane of the figure. A Pockels cell and Glan prism are used to form an electro-optic shutter and source of an ordinary polarization erase beam. When the incident light reaches the barium titanate crystal, it has been converted by the Pockels cell to extraordinary polarization. The crystal response is recorded by a digital oscilloscope and magnetic tape drive. The crystal measured 5×5×4 mm with the *c* axis parallel to the 4-mm side.

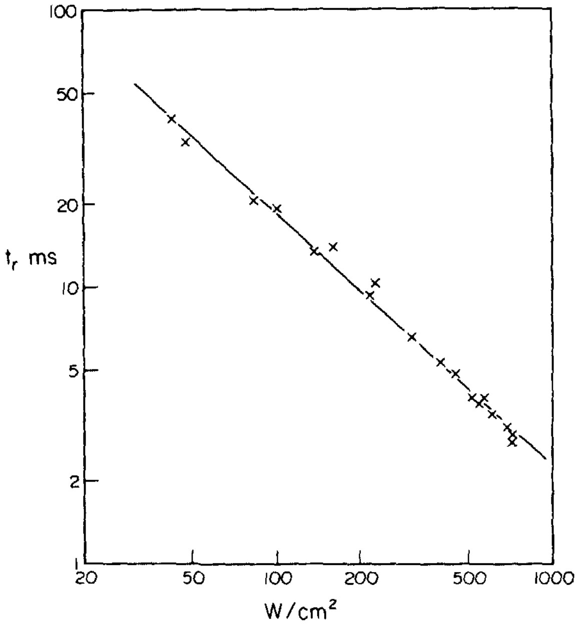

FIG. 3. Response time t_r as a function of incident intensity. Data is corrected for Fresnel reflections. Angle of incidence is 71°.

(e) The limiter uses volume holography so that a crystal which is limiting light from a particular direction and at a particular wavelength will not limit light of different frequency and/or direction. If light of different frequency and/or direction becomes sufficiently intense to warrant limiting, then separate fanning gratings will be set up to limit that light.

(f) The crystal may be refreshed as often as needed by erasing the fanning grating with a bright (even incoherent) light, or by simply waiting for the natural decay of the gratings by dark current conduction (seconds to minutes in our samples of barium titanate).

EXPERIMENT

We have performed experiments in a single-poled crystal of barium titanate to investigate the intensity dependence of the effect, as well as the variation of efficiency and speed of response with the angular orientation of the crystal with respect to the incoming beam. Figure 2 shows the experimental configuration in which an electrooptic shutter was opened to allow 488 nm light from an argon-ion laser to be focused onto a single-poled crystal of barium titanate. At the same time, a digital oscilloscope was triggered and the temporal evolution of the intensity of light allowed to pass directly through the crystal was recorded and transferred to magnetic tape. To take advantage of the large electro-optic coefficient r_{42}, the light was arranged to be of extraordinary polarization with respect to the crystal axes. One of the components of the shutter was a polarizing beamsplitter which reflected light of ordinary polarization onto the crystal when the shutter was closed. This beam served to erase the index gratings in the crystal which were responsible for the fanning, so that the crystal was returned to its original state, in preparation for taking new data.

The response time t_r as a function of incident intensity for a particular angle of incidence is shown in Fig. 3. This time is defined here as the time taken for the transmissivity $T(t)$ to fall from $T(0)$ to $T(\infty) + [T(0) - T(\infty)]/10$, viz., 90% of steady-state response. A best fit analysis of this data shows a relationship of the form

$$t_r = 1.1\, I^{-0.91} \text{ sec},$$

where I is the intensity in W/cm^2 corrected for Fresnel losses. In each case, the steady-state normalized transmittance defined as $T(\infty)/T(0)$ was about 2.5%. Figures 4 and 5 show the steady-state normalized transmittance and response time versus external angle of incidence with respect to the c axis of the crystal at 30 W/cm^2 incident intensity. Also shown is the total energy per unit area allowed to pass through the crystal [assuming $T(\infty) \sim 0$; valid for external angles of incidence greater than 40°]. Both response time and efficiency are seen to improve at higher angles. The refractive index of barium titanate is about 2.5 so that after refraction at the crystal surface the angles of propagation with respect to the c axis become considerably smaller. These are also plotted on the abscissae of the graphs.

OSCILLATOR LIMITERS

The photorefractive gain mechanism responsible for fanning has also been the basis for many novel optical de-

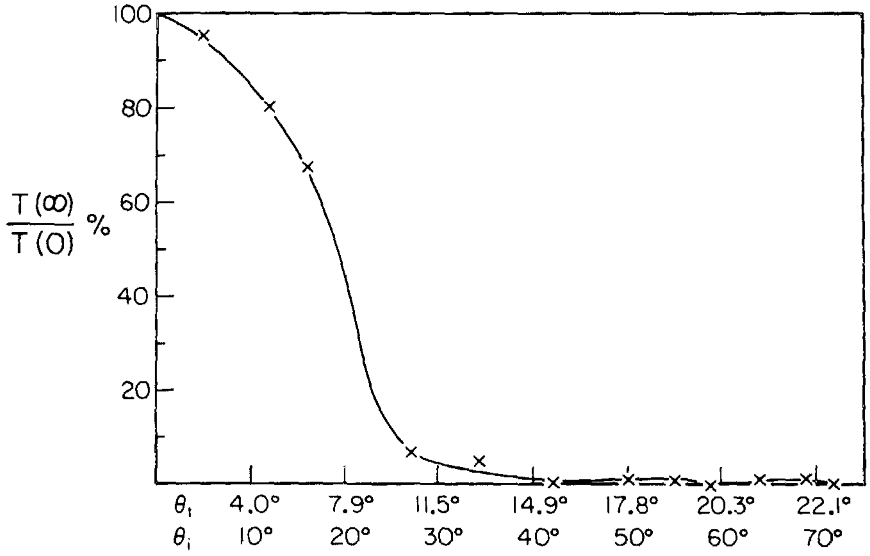

FIG. 4. Steady-state normalized transmissivity as a function of external (and internal) angle of incidence at 30 W/cm^2. Data is corrected for Fresnel reflections.

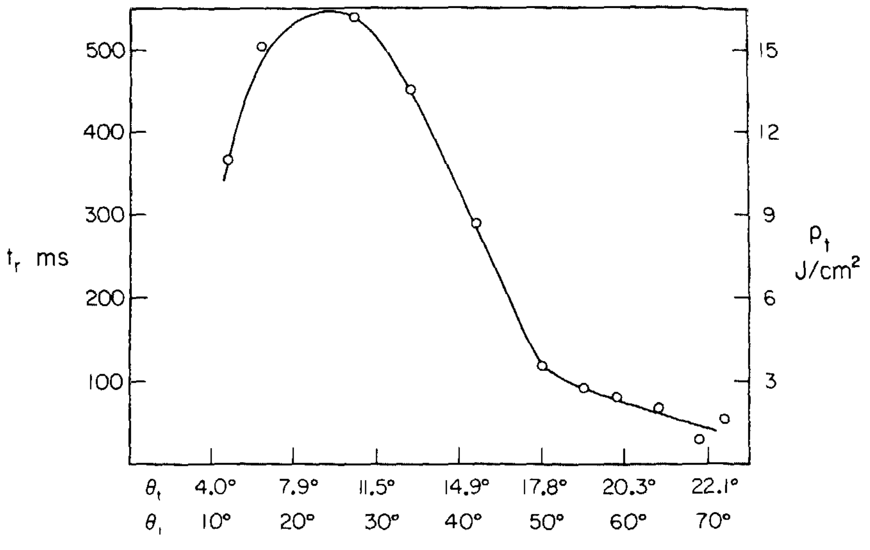

FIG. 5. Response time t_r vs angle of incidence at 30 W/cm^2. Also shown is the total energy allowed to pass through the crystal [approximating $T(\infty)$ as zero; valid for external angles of incidence greater than 40°].

vices including unidirectional ring resonators and passive phase conjugate mirrors (PPCM's). In each of these devices a pumping beam is deflected by self-induced phase gratings into oscillation beams. The transfer of pumping beam into oscillation beam can be considered as a limiting mechanism for the pumping beam. In the following paragraphs we describe each of these devices and the manner in which it can be used as an optical limiter. One of the potential advantages of these oscillation devices over fanning limiters is that the off-axis oscillation is typically confined to a smaller solid angle than that associated with fanning and may be more easily isolated from other parts of the optical system containing the limiter.

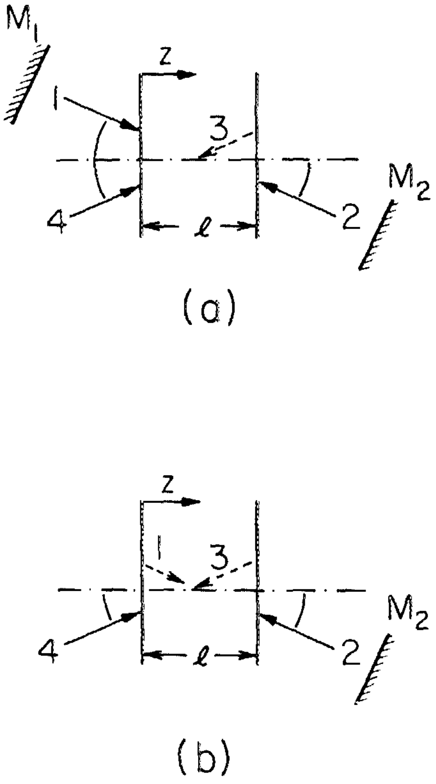

FIG. 6. (a) Linear passive phase conjugate mirror. (b) Semilinear passive phase conjugate mirror.

Linear and semilinear passive phase conjugate mirrors[4] (Fig. 6)

When a laser beam passes through the photorefractive crystal which is the effective four-wave mixing nonlinear medium of the system, light traveling in the M_1-M_2 crystal cavity is amplified into an oscillation beam which then pumps the crystal as a phase conjugate mirror (linear mirror). The coupling can be strong enough to enable oscillation even in the absence of mirror M_1. In this mode of operation. (semilinear mirror) the orientation of the remaining mirror M_2 need not be maintained very carefully in contrast to the case of the linear mirror where alignment of the cavity between the two external mirrors important. While the theory of the semilinear mirror indicates that it should not be self-starting we have found that sufficient seeding can be provided by making mirror M_2 curved to refocus the fanning light into the crystal. The application of the phase conjugate mirrors in optical limiters involves the arrangement of Fig. 7. When laser radiation passes through the crystal oscillation is quickly established in the off-axis cavity. Instead of being transmitted through the crystal the beam is almost entirely diffracted into this cavity. The energy of the oscilla-

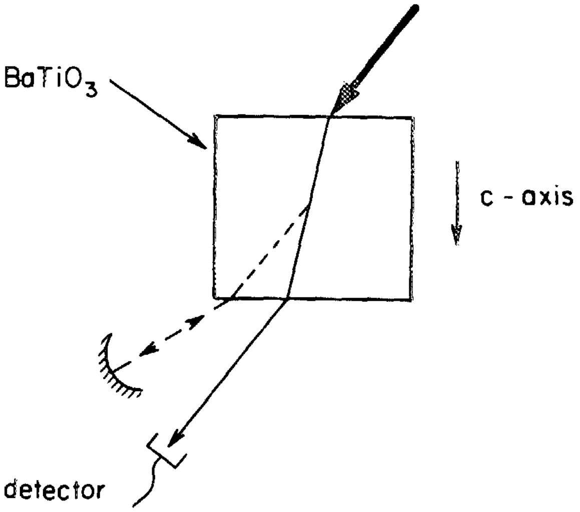

FIG. 7. Semilinear mirror as protective limiter.

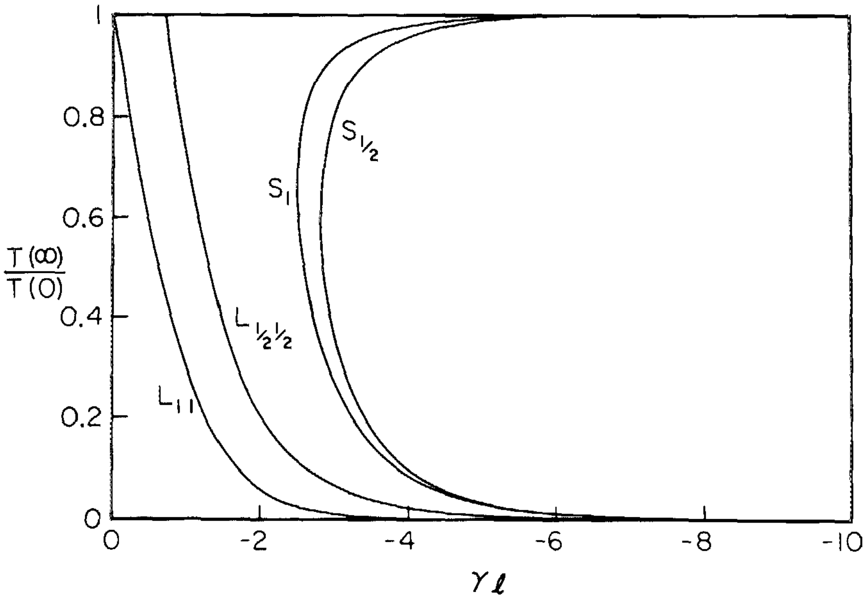

FIG. 8. Theoretical normalized transmissivity of linear and semilinear passive phase conjugate mirrors as protective limiters L_{11}: linear mirror with both cavity mirror reflectivities 100%. $L_{1/2\ 1/2}$: linear mirror with both cavity mirror reflectivities 50%. S_1: semilinear mirror with cavity mirror reflectivity 100%. $S_{1/2}$: semilinear mirror with cavity mirror reflectivity 50%.

tion is then mostly channeled into a phase conjugate reflection of the incident beam.

At the current state of the art of photorefractive crystals, they are capable of very high coupling strengths, so that phase conjugate reflectivities approaching unity would be possible if it were not for reflection and absorption losses. Since these losses are not channeled into the transmitted beam, they fortunately do not impede the effectiveness of the device. As with the fanning effect, the devices only work for coherent radiation and incoherent radiation is allowed to pass through. On the other hand, by placing the external mirrors close enough to the crystal, even to the extent of using the crystal surfaces as mirror substrates, the devices will work for laser beams of almost arbitrarily short coherence lengths. Even if the incident beam is composed of many spectral lines such as from the output of an argon ion laser running on all lines the phase conjugate mirror will still work, as has been recently demonstrated in our laboratory.[5]

An estimate of the potential effectiveness of linear and semilinear PPCM limiters may be formed by extending the theory of the linear and semilinear mirrors,[4] whose intensity reflectivity is given by

$$R = \frac{(\Delta + 1)^2 |T|^2}{M_2 |\Delta T + \{\Delta^2 + (\Delta + 1)^2/M_2\}^{1/2}|^2}, \tag{1}$$

where

$$\Delta = I_2(l) - I_2(0) - I_4(0), \tag{2}$$

$$T = \tanh\{(\gamma l/2)[\Delta^2 + (\Delta + 1)^2/M_2]^{1/2}\}, \tag{3}$$

γl is a coupling strength characteristic of the medium, I_j is the intensity of beam j, and M_j is the intensity reflectivity of mirror j. In these equations we have normalized all intensities by the conserved total average intensity $I_0 = I_1(z) + I_2(z) + I_3(z) + I_4(z)$. Δ is given by the solutions of the equation

$$M_1 M_2 = \left| \frac{T + [\Delta^2 + (\Delta + 1)^2/M_2]^{1/2}}{\Delta T + [\Delta^2 + (\Delta + 1)^2/M_2]^{1/2} + (\Delta + 1)T/M_2} \right|^2. \tag{4}$$

The transmittance of the device $I_T = I_4(l)/I_4(0)$ may be found after some further algebra involving the known expression for I_4 as a function of distance in the crystal[1]:

$$I_T = \frac{[(1 - 1/M_2) - \Delta(1 + 1/M_2)](1 - M_1 R)}{(1 - M_1) - \Delta(1 + M_1)}. \tag{5}$$

This expression is plotted in Fig. 8 as a function of the coupling constant γl for both the linear and semilinear mirrors with several different values of the external mirror reflectivities. It is clear that the full linear mirror is more effective,

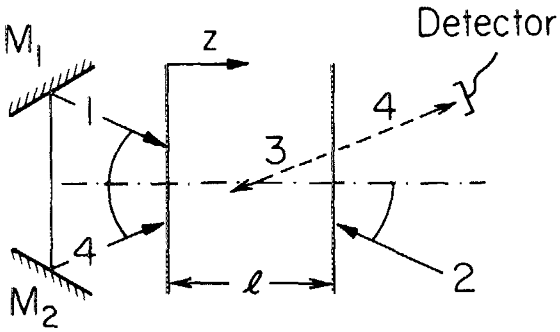

FIG. 9. Ring passive phase conjugate mirror used as an optical limiter. The crystal of length l is depicted between the two vertical lines. The input (limited) beam is labeled 2.

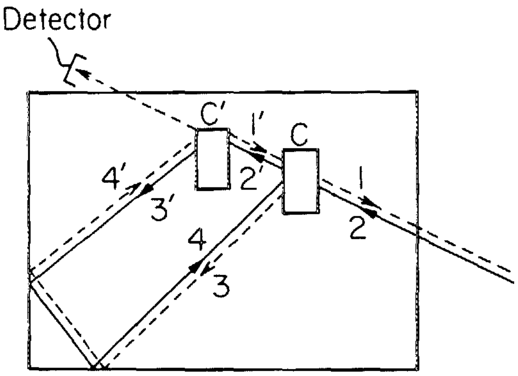

FIG. 10. Two interaction region mirror as an optical limiter. Both interaction regions C and C' are inside a single crystal whose boundaries are indicated by the solid rectangle.

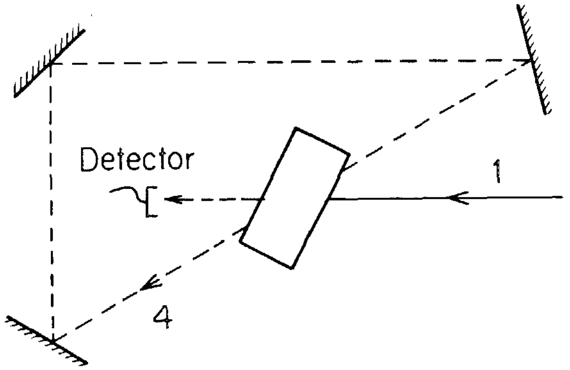

FIG. 11. Unidirectional ring resonator as a limiter.

becoming highly efficient at $\gamma l = -4$, while the semilinear mirror has similar efficiency at $\gamma l = -7$ when both have 100% reflecting feedback mirrors.

In an experimental comparison of the fanning and semilinear limiters a 1.2-mW beam from an argon-ion laser at 488 nm was focused in the fanning limiter configuration onto an appropriately oriented crystal of barium titanate. The steady-state transmissivity was 2.1% and the response time was about 120 ms. By simply adding a 5-cm radius of curvature mirror to the apparatus of Fig. 2 to refocus the fanning light into the crystal and make a semilinear mirror, we were able to examine its effectiveness and compare it with the previous results on the fanning effect device. The response time was the same but the steady-state transmissivity increased to 5%. By using the fanning effect the radiation is scattered into a very large solid angle. This is evidently more effective than confining the radiation to the direction specified by the auxiliary mirror.

Ring passive phase conjugate mirror[6] (Fig. 9)

In the ring PPCM a laser beam is allowed to pass through a photorefractive crystal and is then fed back to it around an optical ring cavity. Phase conjugate oscillation is then set up in the ring cavity and a phase conjugate reflection of the incident beam is formed. This device could be used as a limiter in the manner shown in Fig. 9. The incident light, on its second pass through the crystal is limited by deflection into the phase conjugate direction. Advantages of this device include ease of alignment and a coupling strength threshold lower than that of the semilinear limiter.

Two-interaction-region mirror[7] (Fig. 10)

This device, closely related to the ring mirror, is a single photorefractive crystal operating by itself as a passive phase conjugate mirror. The feedback mirrors of the ring optical cavity are crystal surfaces providing total internal reflection. One of the two interaction regions in the crystal (C) performs the same function as the self-induced gratings of the ring mirror. The other interaction region (C') deflects light away from the original incident direction towards the crystal surfaces at totally internally reflecting angles.

Unidirectional ring resonator[8] (Fig. 11)

In this device the incident beam passes through a photorefractive crystal so that light traveling in a ring cavity set up around the crystal by the three mirrors experiences gain and develops into an oscillation beam. The incident light is thus limited by two-beam coupling deflection into the ring cavity. An advantage of this device is low threshold while a disadvantage is that the alignment is sensitive.

CONCLUSION

In summary, we have proposed and demonstrated a broad new class of optical limiters. These devices, based on photorefractive gain in crystals such as barium titanate and strontium barium niobate, allow limiting over the entire visible spectrum, discriminating only against directions and frequencies where the light is intense, while allowing low intensity light with other directions and frequencies to pass unimpeded.

ACKNOWLEDGMENT

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