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Self-focusing of Laser Beams in Cadmium Manganese Telluride $Cd_{0\cdot4}Mn_{0\cdot6}Te$

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Abstract

Laser beam induced self-focusing in a relatively new diluted magnetic semiconductor cadmium manganese telluride ($Cd_{0\cdot4}Mn_{0\cdot6}Te$) has been observed. We found that a thermally-induced change in nonlinear refractive index is the main mechanism responsible for the self-focusing effect. The nonlinear refractive index has been determined using experimental results.

1. Introduction

In recent years mercury cadmium telluride (MCT) and closely related compounds, the diluted magnetic semiconductors (DMS), have stimulated research interest because the bandgap of these materials can be tuned to a wide operational range of wavelengths. In addition, the large Faraday rotation obtainable in DMS can be applied to the design of optical isolators.

We have explored the possibility of nonlinear optical signal processing using DMS and have confirmed the existence of the laser beam induced self-focusing effect (without damage) in one particular DMS crystal, cadmium manganese telluride ($Cd_{0\cdot4}Mn_{0\cdot6}Te$) at 295 K. To our knowledge, this is the first report of self-focusing in crystals of cadmium manganese telluride. An investigation of laser beam induced self-focusing and defocusing in these crystals not only provides useful knowledge on their optical and other physical characteristics, but can also lead to practical applications such as light power limiters (Leite *et al.* 1967) and optical bistable devices (Smith *et al.* 1984).

We found that the self-focusing effect is mainly due to a thermally-induced change in the nonlinear refractive index, although other mechanisms such as electronically-induced optical nonlinearity may also be involved. We have also found that the magnetic field does not affect the self-focusing effect, so that the self-focusing and the Faraday effects coexist independently in the crystal. In addition, important parameters such as the focal length of the laser beam induced thermal lens and the nonlinear refractive index of the cadmium managnese telluride (CMT) crystal have been obtained in our experiment.

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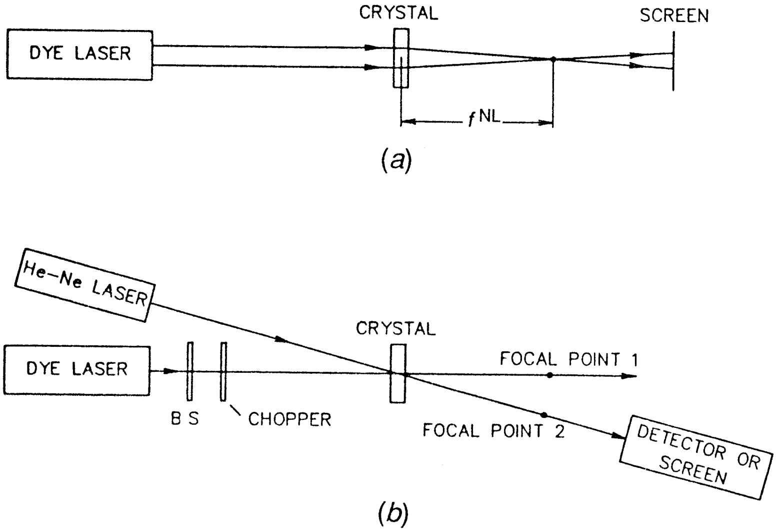


Fig. 1. Experimental set-up for the measurement (*a*) of focal length and (*b*) of the response time, where BS is a beam splitter.

2. Experimental

Fig. 1 shows the experimental set-up. In Fig. 1*a*, a dye laser beam impinges normally on a thin slab of CMT crystal with a thickness $l = 1 \cdot 96$ mm. The far-field pattern of the self-focused laser beam is projected on a screen. This set-up is used to measure the focal length of the self-focused laser beam. In Fig. 1*b*, a He–Ne laser is used to provide a probe beam, and a chopper is used to create light pulses from the CW dye laser, in order to investigate transient phenomena. A dye laser is chosen because its wavelength can be changed to find the focal length of the laser induced lens as a function of operating wavelength.

3. Results and Discussion

Referring to Fig. 1*a*, the focal length was found by measuring image size at two different points. These results were also checked by direct observation of the focal positions. The thermal lens power (the reciprocal of the measured focal length) as a function of input power and absorbed power is shown in Fig. 2, indicating that the focal length decreases with the input and the absorbed power.

Fig. 2*a* shows that at longer wavelengths where the absorption is smaller, less self-focusing is observed. However, as can be seen from Fig. 2*b*, all the points are practically on the same line even if the wavelengths are different. Therefore, the self-focusing effect in this material is much more dependent on the absorbed power than on the incident power. However, the cause of the deviation from a straight line at low powers in both Figs 2*a* and 2*b* is not clear.

In the following we use the model of a laser beam induced thermal lens to explain the observed experimental results. The focal length of such a lens is expressed by the aberration-less approximation (Altshuler *et al.* 1986):

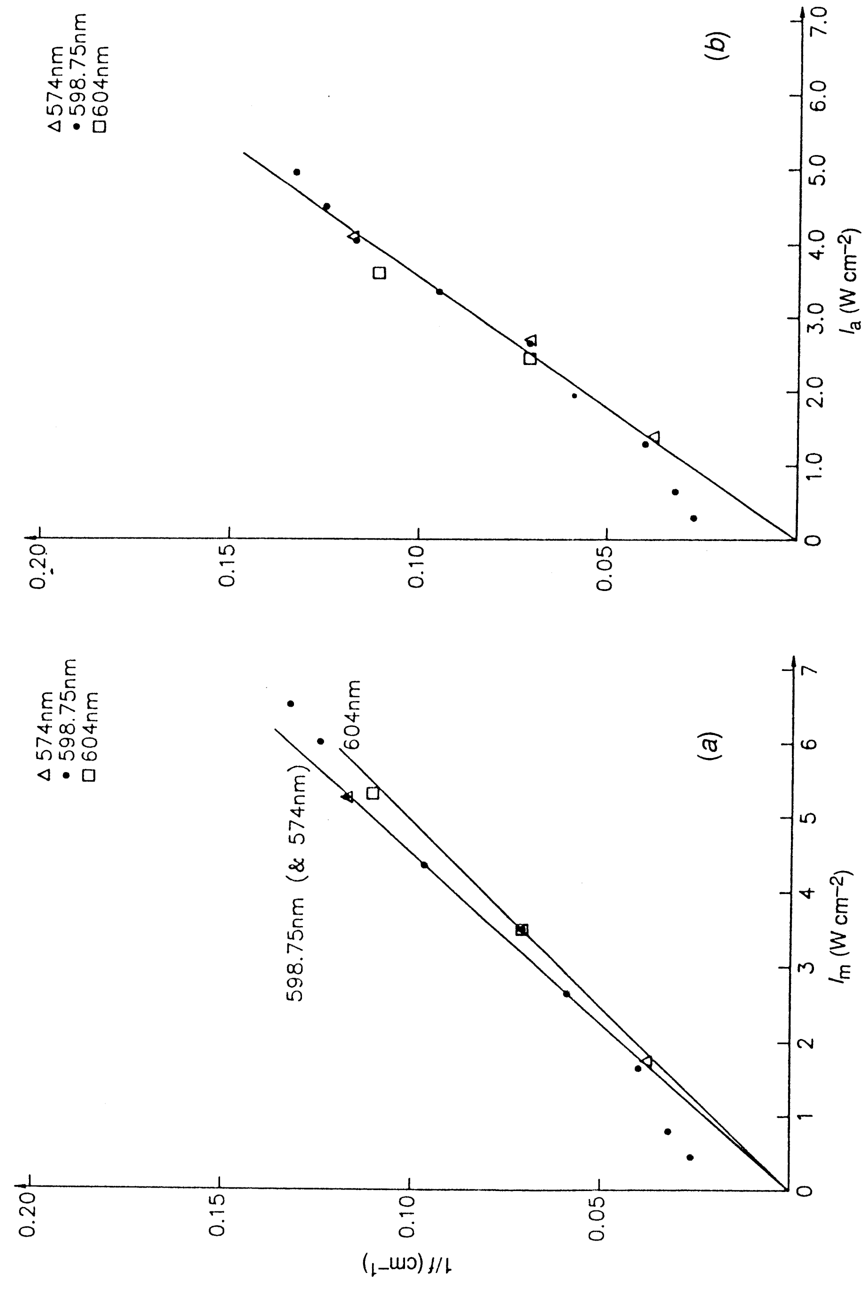


Fig. 2. Thermal lens power (the reciprocal of the measured focal length) as a function of *(a)* input power and *(b)* absorbed power.

$$f^{NL} = \frac{r_0^2}{\Delta n^{NL}} \frac{1}{d}, \tag{1}$$

where f^{NL} is the focal length of the nonlinear lens, r_0 is the half-width of the laser beam, Δn^{NL} is the refractive index change at the centre of the gaussian beam, and d is the effective thickness of the crystal. The change Δn^{NL} is also expressed as (Altshuler *et al.* 1986)

$$\Delta n^{NL} = n_2 \langle E^2 \rangle = n_2 I_m, \tag{2}$$

where n_2 is the nonlinear refractive index, $\langle E^2 \rangle$ is the time average of the electric field of the beam and I_m is the laser power density. The effective thickness of the crystal is defined as

$$d = \{1 - \exp(-\alpha_\lambda l)\}/\alpha_\lambda, \tag{3}$$

where α_λ is the absorption coefficient of the sample at the wavelength λ and l is the thickness of the sample. Substituting (2) and (3) into equation (1), the relationship between the focal length f^{NL} and the input power is obtained as

$$f^{NL} = \frac{r_0^2}{n_2 I_m} \frac{\alpha_\lambda}{1 - \exp(-\alpha_\lambda l)}. \tag{4}$$

With the measured values of f^{NL}, I_m, r_0, l and α_λ, the nonlinear refractive index n_2 can be obtained from equation (4) as

$$n_2(574\ \text{nm}) = (2\cdot9 \pm 0\cdot2) \times 10^{-3}\ \text{cm}^2\ \text{W}^{-1}, \quad \text{for } \alpha_\lambda = 38\cdot5\ \text{cm}^{-1},$$

$$n_2(598\cdot75\ \text{nm}) = (1\cdot4 \pm 0\cdot1) \times 10^{-3}\ \text{cm}^2\ \text{W}^{-1}, \quad \text{for } \alpha_\lambda = 18\cdot3\ \text{cm}^{-1},$$

$$n_2(604\ \text{nm}) = (0\cdot9 \pm 0\cdot1) \times 10^{-3}\ \text{cm}^2\ \text{W}^{-1}, \quad \text{for } \alpha_\lambda = 11\cdot2\ \text{cm}^{-1}.$$

The calculated values of n_2 are of the same order of magnitude as that of a $Cd_{0\cdot185}Hg_{0\cdot815}Te$ crystal at a laser wavelength $\lambda = 10\cdot6\ \mu m$, i.e. $1\cdot8 \times 10^{-3}\ \text{cm}^2\ \text{W}^{-1}$, where n_2 is caused by the thermal effect (Craig *et al.* 1985). Equation (2) used here is valid for Kerr type media (the CMT crystal is basically a Kerr type). A better explanation may be obtained by using the more complete theory proposed by Akhmonov *et al.* (1972).

The relationship between the measured absorption coefficient α_λ and the operating wavelength λ is plotted in Fig. 3. We can see that when λ increases, α_λ decreases. From the results obtained from equation (4), obviously the nonlinear refractive index n_2 also decreases with increasing λ. If $\exp(-\alpha_\lambda l) \ll 1$, then $f^{NL} = r_0^2 \alpha_\lambda / n_2 I_m$ should be comparatively independent of wavelength (see Fig. 2). The experimental results are in agreement with this theoretical model.

To investigate further the mechanism for the formation of the nonlinear lens, we kept the average power constant by increasing the peak power (using a variable beam splitter) and decreasing the repetition rate of the laser pulse

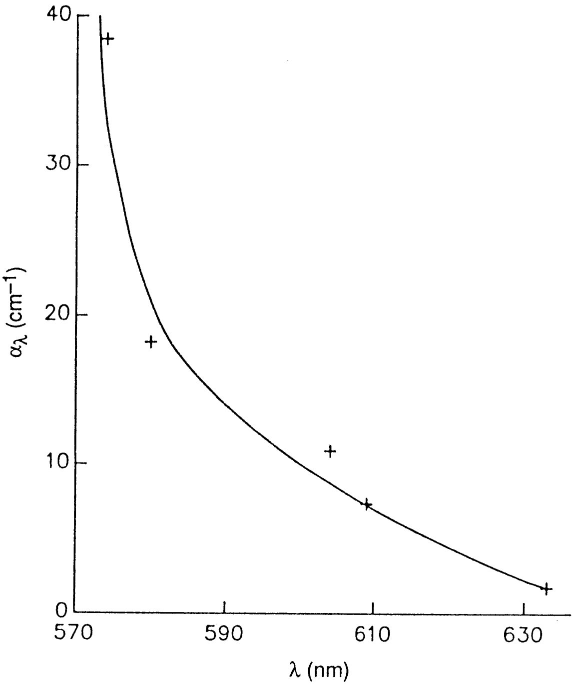


Fig. 3. Relationship between the measured absorption coefficient α_λ and the operating wavelength λ.

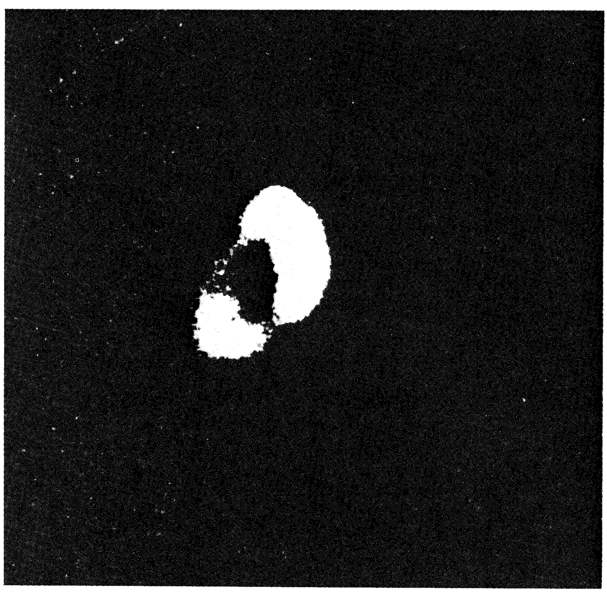
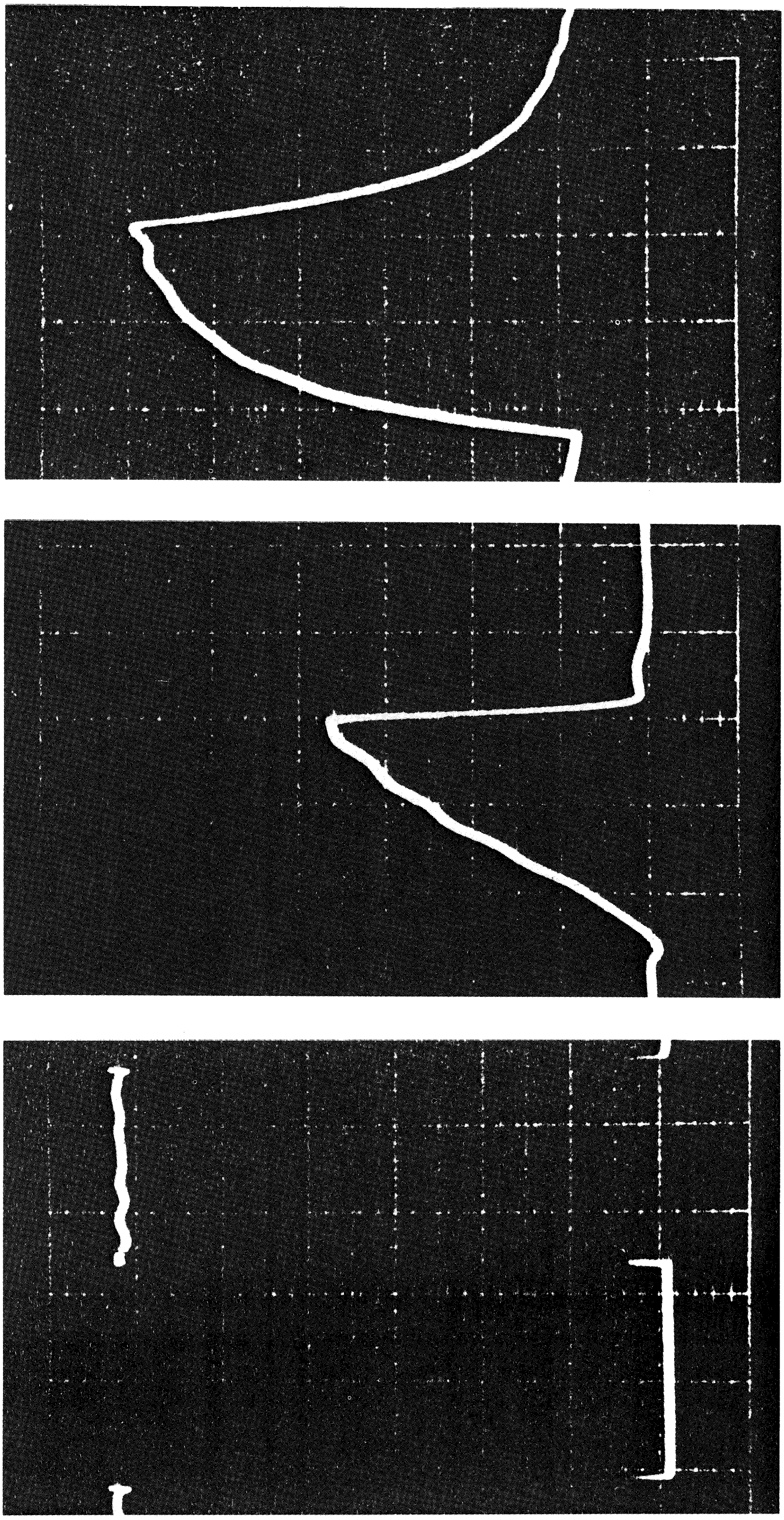


Fig. 4. The far-field pattern of the He–Ne laser beam after passing through the CMT crystal.



(*a*) (*b*) (*c*)

Fig. 5. The input dye laser pulses (*a*) and the traversing probe He–Ne laser pulses: Input dye laser power (*b*) $I = 60$ mW and (*c*) 20 mW. The units on the abscissa are 50 ms/div.

simultaneously (or the opposite way). We observed that the focal length of the nonlinear lens was unchanged. Therefore, the focal length is dependent on the average power of the pulsed beam rather than the pulse peak power itself. This observation indicates that this self-focusing effect may be mainly due to the thermal effect. An intense laser beam with a transverse gaussian distribution of intensity causes a radial gradient of temperature in the material and hence the change in the refractive index. In the case of $Cd_{0\cdot4}Mn_{0\cdot6}Te$, as $dE_g/dT < 0$ (Khoi and Gaj 1977), then we have $dn_2/dT > 0$ (Craig *et al.* 1986) (where E_g is the energy gap and T the temperature). Therefore, a positive thermal lens is formed in the crystal and the effect is self-focusing rather than self-defocusing, which is in agreement with the experimental results.

If the thermal effect is mainly responsible for the formation of the nonlinear lens, a relatively slow response of the lens formation and deformation is expected. The time response of the lens formation was measured by the experimental set-up shown in Fig. 1*b*. Instead of directly observing the image intensity change of the transmitted dye laser beam, a low power He–Ne laser beam which did not cause a self-focussing effect was introduced as a probing beam. The He–Ne laser beam was also focused by the nonlinear lens. Similar to the far-field pattern of the dye laser beam, the far-field pattern of the He–Ne laser beam has a dark central spot surrounded by a bright halo (Fig. 4). A photodiode (with a small aperture) was placed at the dark central spot, and the time dependence of the intensity stored on an oscilloscope. Fig. 5 shows photographs of the input dye laser and the traversing He–Ne laser pulses, taken from the storage oscilloscope.

Since the absorption in our CMT crystal is large ($\alpha l \approx 3\cdot5$ at $\lambda = 598\cdot75$ nm), the method and formula for obtaining the value of the thermal diffusion coefficient D by measuring the thermal relaxation time (Fuh and Code 1985) cannot be directly used. Instead D can be estimated to be $1\cdot1\times10^{-2}\ \mathrm{cm\,s^{-1}}$, using the relationship $D = r_0^2/4t_r$ where t_r ($= t_{r2}$) is the thermal response time (Sheldon *et al.* 1982) which can be obtained from experiment (Fig. 5*c*).

Let us consider the response for the formation of the thermal lens in the CMT crystal. With the onset of a laser pulse (see the rising edge of the pulse in Fig. 5*a*), a thermal lens is gradually formed. This corresponds to the falling tails shown in Figs 5*b* and 5*c*, because the central spot changes from being a bright spot (no lens yet) to a dark one (the lens forms). With this experimental set-up, the photodiode placed at the centre of the diffraction pattern caused by the nonlinear medium, only registers near-zero intensity before the medium has completely formed the nonlinear lens at higher powers. Therefore, it does not record the complete nonlinear lens forming process. Hence, especially at the higher powers, the measured result is far shorter than the material response time (Fig. 5*b*). Therefore, we take the values from the low power experiment which have less error than the high power experiment (Fig. 5*c*).

The $Cd_{0\cdot4}Mn_{0\cdot6}Te$ crystal we used is not of high optical quality and is somewhat inhomogeneous. There were visible defects inside the crystal which result in dark clouds and mask over the far-field pattern of the traversing laser beam. This may adversely affect the accuracy of our experimental results, and prevent the illumination of very high laser power, which can cause damage to the crystal due to excess absorption.

4. Conclusions

We have observed a strong laser induced self-focusing effect in the relatively new DMS crystal $Cd_{0 \cdot 4}Mn_{0 \cdot 6}Te$. Similar results have been obtained with $Cd_{0 \cdot 5}Mn_{0 \cdot 5}Te$, and therefore the ratio of Cd and Mn content is not too critical to the self-focusing effect. Self-focusing can occur at millwatt levels of average incident power, whereas for other materials the power required is usually of the order of a watt. Although there may be several causes of the self-focusing effect, we found that a thermally-induced change in the refractive index is usually the chief cause in this crystal.

Acknowledgments

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