Optical bistability in bulk ZnSe due to increasing absorption and self-focusing

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We report the first observation of cavityless optical bistability in ZnSe. A shift in the band edge and self-focusing occurs due to the temperature rise of the material as the laser irradiance is increased. These two mechanisms are believed to provide the feedback necessary for bistable operation.

Optical bistability in mirrorless systems has been reported for several materials.[1–4] In all of these systems the feedback, necessary for bistability, has been provided by the temperature-dependent absorption coefficient of the material. Such bistable elements may have some interesting device applications, due to the ease of their fabrication and negative logical operation. So far, materials which exhibit this type of bistability have shown several drawbacks: amorphous $GeSe_2$ (Ref. 1) shows photostructural changes, which prevents true steady state operation. CdS (Ref. 2) only operates at cryogenic temperatures, InSb (Ref. 3) and GaAs/GaAlAs heterostructures[4] require infrared wavelength operation which from a device applications point of view (packing density) is not favorable. A practical system, however, should work at room temperature, visible wavelength, and milliwatt power without stability problems.

In a recent publication[5] it has been demonstrated that thermal optical bistability in ZnSe multilayer interference filters satisfies the above requirements and opens up possibilities for device applications. In ZnSe filters the integral cavity plays an important role. Here we report on a complementary investigation on switching phenomena in bulk ZnSe, where reflection at the sample surfaces is found not to be important.

Our investigations were performed on a 2.1-mm-thick sample of polycrystalline ZnSe, supplied by Specac UK Ltd. The light from a Coherent Laser Ar^+ (Innova -10, Model) was focused to a 40-μm diam spot ($1/e^2$). The absorption in the sample became important for laser wavelength shorter than 480 nm. Bistability was observed at the laser line $\lambda = 476.5$ nm, so in the following we shall describe in detail the behavior of the sample at this particular wavelength.

An investigation into the spatial quality of the far-field transmitted beam profile showed strong divergence of the beam occurred as the input power was increased. Figure 1 shows this power dependence of the transmitted beam profile. The appearance of the wings at high powers is characteristic of self-focusing. A divergence of $\sim 7°$ was observed for an input power of ~ 100 mW.

Bistability was observed with switching from high to low transmission occurring at higher power (~ 115 mW). Figure 2 shows the oscilloscope trace of the total transmitted power versus input power. The curves presented in Fig. 2(a) were obtained when both surfaces of the sample were in contact with air. Figure 2(b) shows the trace we obtained when the front surface of the sample was attached to a thick glass, which acts as a heat sink.

Trace 1 of Fig. 2(a) shows the transmitted power as the input power is increased from zero to a power P_1, with few seconds scan time. At P_1 (115 mW) the transmission dropped by more than one order of magnitude. Reducing the power with the same scanning speed resulted in the transmission switching back to a higher transmission state at power P_2 (80 mW). The transmission did not recover fully at this point and further reducing the input power gave trace 2 of Fig. 2(a). It should be noted, however, that on repeating the scan from zero power, the same traces as in Fig. 2(a) could be regenerated.

At very slow scan speeds the transmission curve coincides with the upper branch (trace 1) near zero input power and gradually approaches the lower branch (trace 2) as the power tends to P_2, and a conventional bistable characteristic with a rather narrow, but unambiguous loop is observed. The switching process itself is rather fast; the switching time from high to low transmission state was found to be ~ 100 μs, while switching from low to high transmission state took ~ 500 μs.

As shown in Fig. 2(b) the application of a heat sink eli-

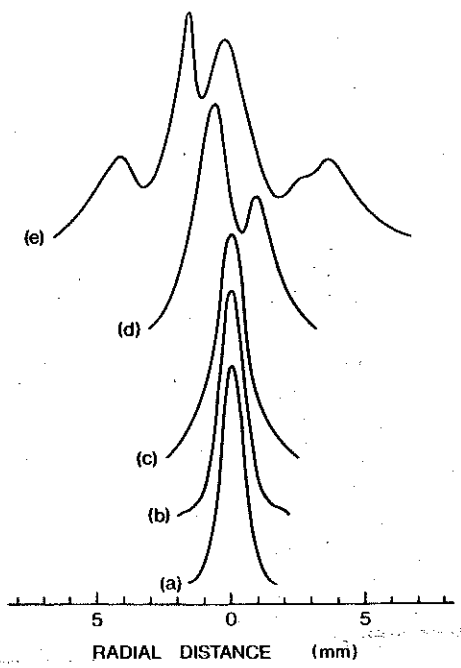

FIG. 1. Spatial profile of the transmitted beam (monitored 10 cm behind the sample) for five different incident powers; (a) 25 mW, (b) 33 mW, (c) 50 mW, (d) 66 mW, and (e) 100 mW.

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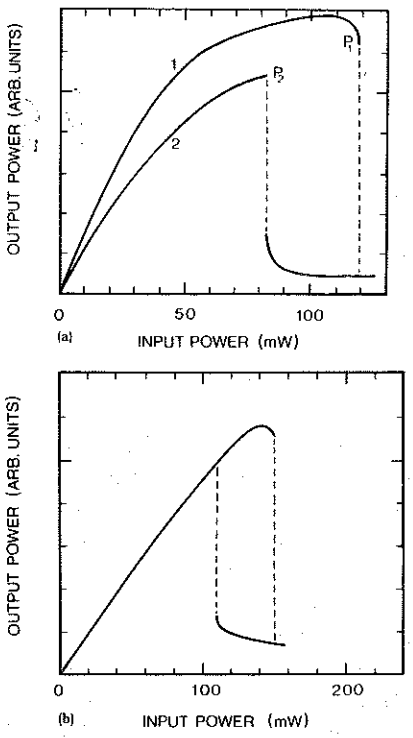

FIG. 2. (a) Oscilloscope trace of bistable operation of bulk ZnSe. Trace (1): increasing input power from zero; trace (2): decreasing input power after switching. (b) Oscilloscope trace of bistability in bulk ZnSe mounted on a glass plate.

minated the two observed traces of Fig. 2(a). This system could be held at any point on the bistability curve for several minutes without the slow drift, or narrowing down of the loop, observed in the previous case. The critical power P_1, however, increased by $\sim 20\%$ (to 135 mW).

The sensitivity of the bistable characteristics of the sample to the boundary conditions of heat conduction clearly indicates that thermal effects play an important role in the observed phenomena. In the case when the sample is surrounded only by air, it can be assumed that the heat flow takes place in the sample itself. Far from the laser beam the heat flow is purely transverse, and the temperature rise θ at a distance r is

$$\theta(r) \sim A \ln R/r, \tag{1}$$

where A is the absorbed energy from the laser beam and it is assumed that the temperature is constant at distance R from the irradiated spot. For a very large sample θ would approach infinity, i.e., an infinitely long time would be required for the temperature to reach its equilibrium value. In reality the sample is of a finite dimension, nevertheless the stationary temperature distribution establishes itself only very slowly, due to the two-dimensional heat flow far from the beam. This effect can explain the observed traces 1 and 2 in Fig. 2(a). When a thick glass plate is attached to the sample, the heat flow becomes three dimensional. Far from the irradiated spot we have $\theta \sim A/r$, so there is no divergence of the temperature rise even for an infinite sample, and the thermal equilibrium is established much faster. In accordance with this consideration in this case only one trace was observed [see Fig. 2(b)].

The observed bistable characteristics strongly resemble

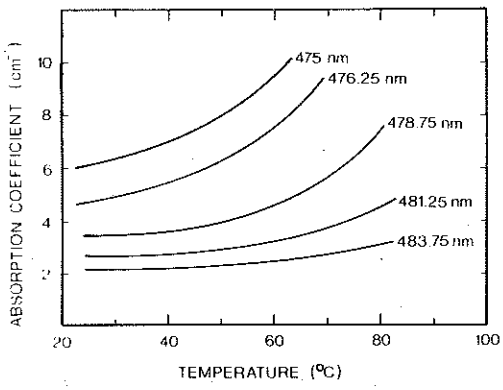

FIG. 3. Absorption coefficient of bulk ZnSe as a function of temperature at different wavelengths.

those found in systems with increasing absorption.[1–4] The absorption coefficient for bulk ZnSe as a function of temperature for different wavelengths is presented in Fig. 3. For $\lambda = 476.5$ nm the absorption significantly increases above room temperature due to the thermal shift of the band edge. The laser induced heating increases the temperature which in turn leads to the increase of the absorption coefficient. This results in a more intensive heating, so there is a positive feedback, which can lead to bistability as shown in Refs. 1–4.

The models presented in Refs. 1–4 refer, however, to thin layers. Applying it straightforwardly to the present case of bulk ZnSe leads to the following difficulty. As shown in Ref. 3, the condition for bistability, due to increasing absorption is $\alpha L \leqslant 0.18$, where L is the sample thickness and α is the absorption coefficient. This relation has been experimentally verified for the case of InSb.[3] In our case, however, $\alpha L = 1.5$, in clear contradiction with the models.

We believe that in the bulk ZnSe bistable system an additional effect, connected with self-focusing, plays an important role. The laser induced heating of the sample results in a temperature variation across the beam. Because the refractive index increases with temperature, the radial temperature gradient acts as a positive lens and focuses the beam. As it can be shown, the critical power for bistability decreases as the spot size is reduced.[1] If the focal length of the laser induced thermal lens is comparable with the sample thickness the reduction of the spot size within the sample becomes significant. This will result in reduction of the threshold power for bistability.

We may consider our sample as consisting of two imaginary layers. The role of the front layer is to focus the beam onto the back layer of the sample where the thermal runaway takes place. The thickness of this latter layer (d) may be much less than the sample thickness, so αd may be $\leqslant 0.18$ in accordance with the models for thin layers.[3]

To make the above considerations more quantitative, we present a crude estimation of the self-focusing effect at the threshold power. The focal length of thermal lenses can be given as in Ref. 6 (neglecting diffraction)

$$Z_f = \frac{r_0}{\sqrt{2\delta n/n}}, \tag{2}$$

where r_0 is the beam radius, n the refractive index, and δn the difference between the refractive index at the center of the beam and just outside the illuminated area. For the thermal

case

$$\delta n/n = \beta\,\delta T\,,$$

with

$$\beta = (1/n)(\partial n/\partial T)\,. \tag{3}$$

δT can be estimated assuming that the temperature variation across the beam is much stronger than along the beam. In this case, using the heat conduction equation $\Delta T = -Q/\kappa$ (Q is dissipation from the laser beam, κ is heat conductivity), the temperature distribution can be estimated as

$$T \approx T_0 - Qr^2/4\kappa\,,$$

from which

$$\delta T \approx \frac{Q}{4\kappa} r_0^2 = \frac{\alpha P}{4\pi\kappa}\,, \tag{4}$$

where P is the power in the front layer of the sample. From Eqs. (2)–(4)

$$Z_f \approx \frac{r_0/\sqrt{\beta\alpha P}}{2\pi\kappa}\,, \tag{5}$$

with $P = P_{\text{in}}\ (1 - R)$ (P_{in} is input power, R is reflectivity of the sample). For ZnSe at $\lambda = 476$ nm, $\beta = 6\times10^{-5}/\text{C}^\circ$,[7] $\kappa = 0.19$ W/cm/C° (Ref. 8), and $R = (1-n)^2/(1+n)^2 = 0.21$. In our experiment we have $r_0 = 20\,\mu$m and $\alpha \approx 6$ cm^{-1}. For the critical power $P_1 \approx 135$ mW [see Fig. 2(b)], Eq. (5) yields $Z_f \approx 3.5$ mm. This length is comparable with the sample thickness (2.1 mm), and implies $\sim 60\%$ reduction of the spot size within the sample.

Although the above consideration is rather crude, it supports the idea that the reduction of the spot size within the sample due to self-focusing play an important role in bistability in bulk ZnSe. The smaller spot size implies faster switching also; this may explain the fact that switching time was found to be in the same order of magnitude as for thin layers.[5]

In conclusion, we have shown that bulk materials can be used in optical bistability device applications. Such systems can be regarded as a superposition of a self-focusing and a thin optically bistable element. The effect of self-focusing in reducing the power and switching times may be significant. Although the slow warming up of the bulk sample at large distances from the illuminated spot can be regarded as a drawback, we have shown that with careful design and engineering, this problem can be overcome.

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