

# Increasing Absorption Optical Bistability Operating in the Front Surface Layer of High Absorption Samples

Changde Xie, Jiangrui Gao, Yimin Lian, Xiaoping Yang, and Kunchi Peng

Institute of Opto-Electronic Researches, Shanxi University, Taiyuan, Shanxi, Peoples Republic of China

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**Abstract.** The increasing absorption optical bistability in a bulk ZnSe sample with quite high absorption has been observed. Our experiments show that the bistability operates only in the front surface layer of sample and that the back layer of sample can be regarded as a linear absorber and heat sink.

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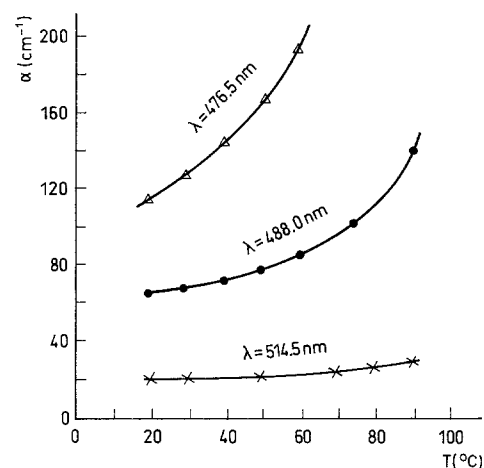
Several previous papers [1–3] have discussed the optical bistability in ZnSe material. The condition for increasing absorption optical bistability derived by Wherrett et al. [4] is  $\alpha_0 l \leq 0.18$ , where  $\alpha_0$  is the absorption coefficient and  $l$  is the sample thickness. Ref. [3] shows that when  $\alpha_0 l \approx 4$  exceeds the value for bistability, there is no bistable loop and only thermal runaway is observed. However, our experiments on different thickness samples of bulk ZnSe with quite high absorption ( $\alpha_0 l$  in the range 1.12–13.2) have demonstrated that the mirrorless intrinsic optical bistability can be obtained in thick high absorption samples. It is important that the experimental results show the bistability in this kind of sample operating only in the front surface layer of the samples where the absorption is less than 0.18. There is therefore no contradiction with previous theoretical conclusions.

## 1. Experimental Results

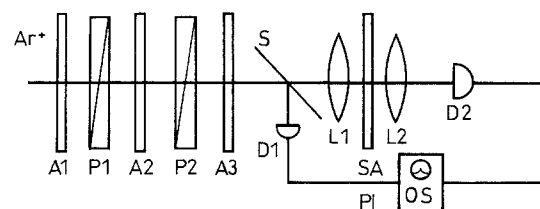
The polycrystalline ZnSe used in our experiments is PVD-grown. It must be borne in mind that the optical properties of PVD-grown ZnSe differ from batch to batch. We have three kinds of ZnSe samples bought from different crystal factories; their absorption coefficients and temperature dependence measured experimentally are very different. The kind of samples with the highest absorption coefficient were selected for our experiments. The temperature dependences of the absorption coefficient of our samples for 514.5 nm, 488.0 nm, and 476.5 nm laser wavelengths are shown in Fig. 1.

Figure 2 shows the experimental layout. A linearly polarized TEM<sub>00</sub> cw argon laser was used as the light source. At first, the input power was controlled by the

rotatable half-wave plate A1 and the plane polarizer P1 to protect the sample against damage. The laser beam was then scanned at about 70 Hz by the second rotatable quarter-wave plate A2 and plane polarizer P2. The quarter-wave plate A3 is an optical isolator used to



**Fig. 1.** Absorption coefficient of the ZnSe sample as a function of temperature at different wavelengths



**Fig. 2.** The experimental layout

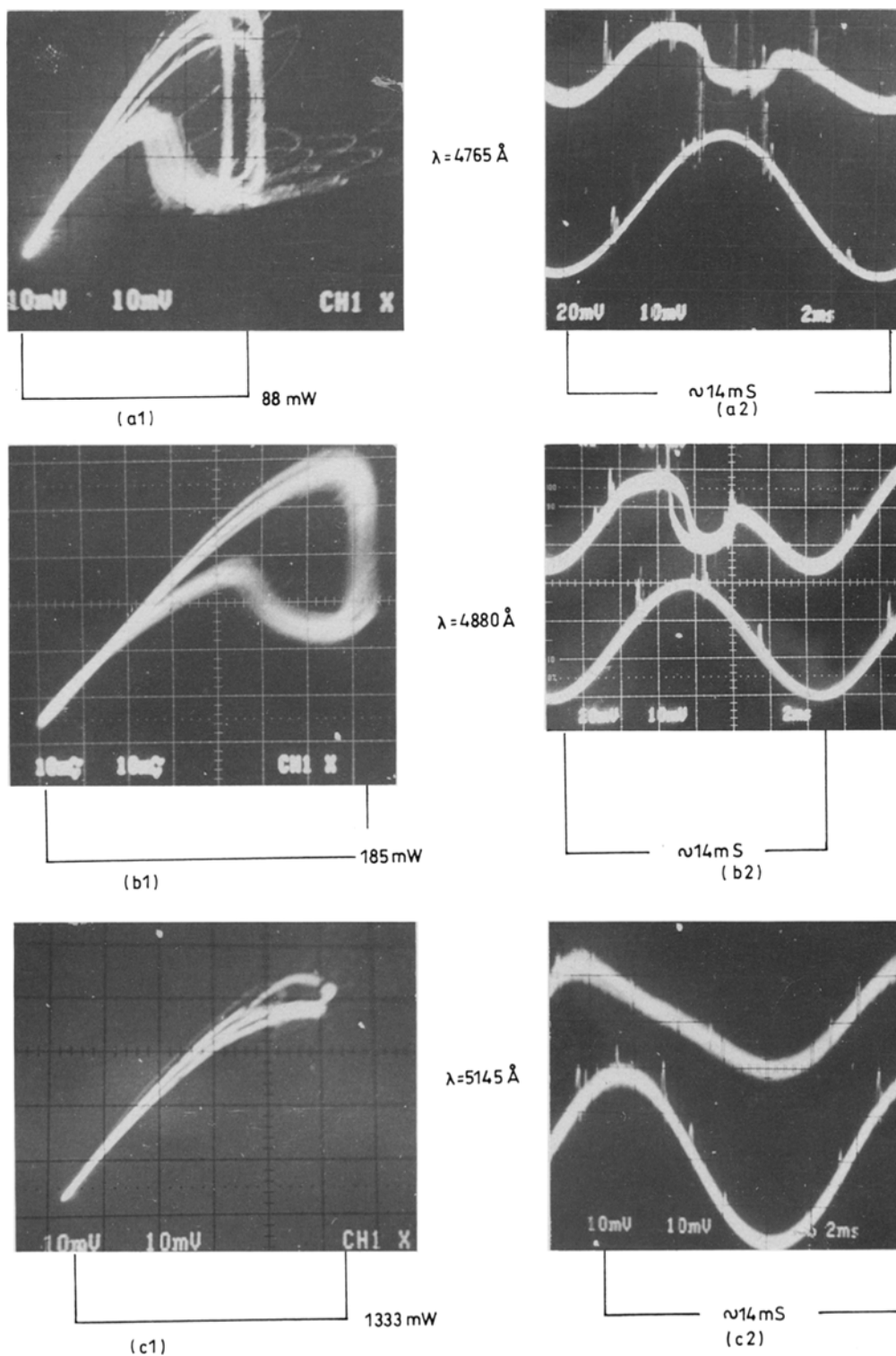


Fig. 3. The absorption bistability curves and input (lower) and output (upper) waveforms

prevent the beam from reflecting back into the laser. The beam splitter S splits the laser beam into two parts, the weaker part goes into the detector D1 as a monitor of the input while most is focused onto the ZnSe sample SA by the lens L1. D1 and D2 are Si photocells and their signals are displayed on an oscilloscope. It must be emphasized that in the experiments the high absorption sample is very

easily damaged when the input power is above the bistability threshold, therefore the input power has to be controlled carefully.

Figure 3 shows the absorption bistability curves and input (lower) and output (upper) waveforms obtained with the 0.56 mm thick ZnSe sample for three laser lines and the same beam spot size of  $w = 25 \text{ \mu m}$ .

**Table 1.** Thicknesses, absorption, and threshold powers for the 488.0 nm laser line with beam spot size  $w=40\ \mu\text{m}$ 

| $l$ [mm] | $d_0 l$ | $P_{th}$ [mW] |
|----------|---------|---------------|
| 0.38     | 2.5     | 280           |
| 0.56     | 3.7     | 300           |
| 1.20     | 7.9     | 350           |
| 2.00     | 13.2    | 590           |

The threshold powers of switching down for the three laser wavelengths are respectively:

$$P_{th}(476.5\ \text{nm}) = 88\ \text{mW}, \quad P_{th}(488.0\ \text{nm}) = 185\ \text{mW},$$

$$P_{th}(514.5\ \text{nm}) = 1333\ \text{mW}.$$

For the 476.5 nm and 488.0 nm laser lines, the switching down time is approximately 0.4 ms. For the 514.5 nm laser line, however, there is no clear switching phenomenon but a small hysteresis loop is clearly recorded. The operating condition of the thermal absorption bistable system depends on the temperature rise and on the temperature dependence of the absorption coefficient of the sample. As shown in Fig. 1, the relations of absorption coefficients and their temperature dependence of our samples for three laser lines are

$$\alpha(476.5\ \text{nm}) > \alpha(488.0\ \text{nm}) > \alpha(514.5\ \text{nm})$$

and

$$\frac{\partial \alpha}{\partial T}(476.6\ \text{nm}) > \frac{\partial \alpha}{\partial T}(488.0\ \text{nm}) \gg \frac{\partial \alpha}{\partial T}(514.5\ \text{nm}),$$

so the experimental results

$$P_{th}(476.6\ \text{nm}) < P_{th}(488.0\ \text{nm}) \ll P_{th}(514.5\ \text{nm})$$

are as expected.

To investigate the dependence of the bistability on the thickness of the samples, four samples with different thicknesses were taken from the same wafer to minimize spurious effects. The results showed that bistability curves similar to Fig. 3 can be obtained with these different samples, and that the switching power increased as the thicknesses of the samples increased; but the switching times were about the same ( $\sim 400\ \mu\text{s}$ ). The thicknesses  $l$  of the samples, the absorption  $\alpha_0 l$ , and the measured switch-

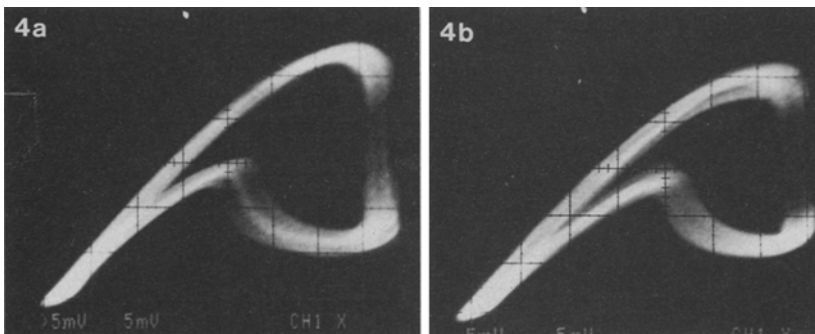
ing down powers for the 488.0 nm laser line and a  $w=40\ \mu\text{m}$  beam spot size are shown in Table 1.

If, after the output powers had switched down, the input powers were continuously increased, the samples were eventually damaged. The damage threshold powers are higher than the switching down powers by about 10–20 mW. Provided the samples were not burnt, the experiments could be repeated very well, but we observed a slow narrowing of the bistable loops. Figure 4a and b are the oscilloscope traces of bistability recorded under the same experimental condition except that (a) was taken about 15 min earlier than (b). Comparing carefully (a) and (b), it is clear that the output power of the high transmission state of (a) is higher by about twenty percent than (b) and that the width of the loop in (b) is narrower by about twenty-five percent than in (a).

## 2. Analysis of Experimental Results

The sensitivity of the bistable threshold powers to the boundary conditions of heat conduction (the thickness of the samples) clearly indicates that thermal effects play an important role in the observed phenomena. The measured bistable critical powers and switching down times are of the same orders of magnitude as the results of other absorptive bistabilities in bulk ZnSe [2, 3], so that the observed bistable characteristics should be a kind of increasing absorption bistability [5]. The absorption significantly increases above a certain temperature due to the thermal shift of the band edge. The laser-induced heating increases the temperature, which, in turn, leads to an increase in absorption coefficient. This results in a positive feedback, which can lead to bistability.

The condition for bistability due to increasing absorption has been theoretically derived by Wherrett et al., and is given by  $\alpha_0 l \leq 0.18$  [4]. However, the Wherrett model is based on the assumption that there is no temperature gradient along the longitudinal axis, and that the material is characterized by a single temperature. The criterion  $\alpha_0 l \leq 0.18$  is not straightforwardly applicable to the case of a thick sample with high absorption where there are temperature gradients and thermal conduction along the longitudinal axis. In fact, in our experiments  $\alpha_0 l$  can be anywhere from 1.12 to 13.2. The correct theoretical analysis should include not only thermal conduction in three dimensions, but also the complex temperature



**Fig. 4.** Narrowing down of the bistability curve, (a) was taken 15 min earlier than (b)

gradient resulting from the nonlinear absorption in the samples.

Observing the damaged samples, we found that the damaged regions are always in a thin layer near the front surface of samples under any experimental condition. We measured the depths of the burnt regions by a reading microscope; almost all of them were less than  $0.18/\alpha_0$ . The average depths of the spots burnt by 476.5 nm, 488.0 nm, and 514.5 nm laser lines are respectively 0.013 mm, 0.019 mm, and 0.082 mm while their initial absorption coefficients  $\alpha_0$  are about  $116 \text{ cm}^{-1}$ ,  $66 \text{ cm}^{-1}$ , and  $20 \text{ cm}^{-1}$  (Fig. 1). We moved the focus of the beam into the samples, and repeated the experiments; essentially the same bistable curves were obtained and the damaged portions of the medium were still in a thin surface layer. Only the threshold powers for switch down were increased since the beam spot sizes on the surface of the sample were expanded. This means that the temperatures in the thin front layer of the samples are much higher than in the back layer when bistability is obtained. Therefore, we believe that in the high absorption medium, the increasing absorption bistability may occur only in the surface layer of the sample. We may simply consider the samples as consisting of two imaginary layers; most of laser power is absorbed in the front layer where the nonlinear effects of medium manifest themselves. The back layer simply plays the role of linear absorber and heat sink. The thickness of this front layer (1) may be much less than the sample thickness, so  $\alpha_0 l$  may be  $\leq 0.18$  in accordance with the modes for thin layers. This idea was also supported by the fact that the switching times for different sample thicknesses are of the same order of magnitude as for thin layers [6]. Because the back layer plays the role of a heat sink, there is longitudinal thermal conduction in the thick samples. The thicker the sample is, the larger the longitudinal heat flow; therefore, the higher the critical laser power for the bistability (Table 1). The slow warming up of the back layer of the sample due to longitudinal thermal conduction results in a slow increase in both temperature and absorption of the back layer. Thus the bistable loops slowly narrow down as the illumination time increases, as shown in Fig. 4.

Taghizadeh et al. [2] also observed the bistable operation in a ZnSe sample with absorption  $\alpha_0 l = 1.3$  ( $\alpha_0 = 6 \text{ cm}^{-1}$  and  $l = 2.1 \text{ mm}$ ) for the 476.5 nm Ar laser line. They believe that in the bulk ZnSe bistable system an additional effect, connected with self-focusing, plays an important role. They considered that the role of the front layer of the sample is to focus the beam onto the back layer where thermal runaway takes place. In this case,

using the sample of high absorption coefficient, the laser power is strongly absorbed as the beam propagates through the front layer of the sample, and the effect of self-focusing is relatively small. The light intensity in the front layer of the sample is much higher than in the back layer, and thus the front layer reaches the threshold temperature for switching down before the back part. Once the thin front layer is switched down, the laser intensity downstream becomes very low, so that behind this highly absorbing layer the medium is effectively a linear absorber. This analysis is supported by our experiments. To exclude the possibility of self-focusing, we selected a multiple transverse mode laser to do these experiments. The same results were obtained. When the absorption coefficient of the sample is lower and the effect of self-focusing is stronger, the earlier analysis may be correct. In the case of high absorption, however, our analysis should be adopted.

In conclusion, we have shown that the increasing absorption bistability can operate in bulk nonlinear materials with high absorption. Such systems can be regarded as a superposition of a thin effective nonlinear optically bistable front layer and a linearly absorbing back layer. The absorption  $\alpha_0 l$  in the thin front layer may be  $\leq 0.18$  in accord with theoretical results for thin samples. The back layer plays the role of linear absorber and longitudinal heat sink. The effect of the longitudinal heat sink in increasing the switching power may be significant when the thickness of the sample is large. Therefore, although the increasing absorption bistability can be obtained in thick nonlinear media with high absorption, in optical bistability device applications, we should select thinner samples. Our experiments may complement other experimental results thin-film ZnSe and lower absorption bulk ZnSe.

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