PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Giant Nonlinearities and Low Power Optical Bistability in Cadmium Sulphide Platelets

M. Dagenais

Phil. Trans. R. Soc. Lond. A 1984 **313**, 265-268
doi: 10.1098/rsta.1984.0105

Phil. Trans. R. Soc. Lond. A **313**, 265–268 (1984)
Printed in Great Britain

Giant nonlinearities and low power optical bistability in cadmium sulphide platelets

By M. Dagenais

GTE Laboratories Incorporated, 40 *Sylvan Road*, *Waltham*, *Massachusetts* 02254, *U.S.A.*

Both whole-beam and transverse continuous wave optical bistability are observed at milliwatt power levels near the band gap in thin uncoated cadmium sulphide platelets. The whole-beam bistability is free from cavities and requires an absorption coefficient that increases with intensity.

INTRODUCTION

This paper reports the observation of both whole-beam and transverse optical bistability in thin uncoated cadmium sulphide (CdS) platelets at milliwatt power levels when a continuous wave laser is tuned near the band gap. The observed whole-beam bistability is thermally induced and can be relatively fast due to the high thermal conductivity of CdS at low temperatures. It is free from cavities, does not require external feedback and exhibits a very large contrast ratio (over 10) between the 'on' and 'off' states. In samples of small surface area, whole-beam bistability is observed for temperatures varying between 5 and 50 K. The transverse bistability measurements were made with larger samples immersed in superfluid helium. A large induced absorption of thermal origin is detected and is believed to be responsible for our transverse bistability results. Very large transverse effects are observed in the far field. As the input intensity is varied, we observe large hysteresis loops in the centre part of the beam. When the whole beam is monitored, no switching is observed. At high intensities, very regular self-pulsations with a 10 μs period appear. The pulsations are attributed to thermal effects. To better understand the origin of the large observed nonlinear behaviour, the intensity and the time dependence of the total beam absorption was studied. Sharp induced absorption lines appearing in less than 10 ns are detected near the band gap. The optical saturation of the I_2 bound exciton is also observed.

WHOLE-BEAM BISTABILITY

For the whole-beam bistability measurements, a good optical quality CdS sample, 10 μm thick with a surface area of less than 0.01 cm^2, is held electrostatically to a glass slide and then mounted in a cryogenic dewar. The laser is detuned a few wavenumbers below the I_2 bound exciton resonance, an exciton bound to a neutral donor. We observe large steady-state inverted hysteresis loops in the whole-beam transmission with contrast ratios between the on and off states greater than 10. Only a few milliwats of input power are required to observe this bistability. As the detuning below the bound exciton resonance is increased, larger hysteresis loops are observed and higher input intensities are required to observe optical bistability. Bistability is seen for detunings as large as 20–30 cm^{-1} below the resonance and at input intensities up to about 20 mW. For very small detunings below the resonance, and for detunings above the resonance, we do not observe any hysteresis (except at high intensities). Whole-beam bistability is observed for sample temperatures (with the laser off) as low as 5 K and as high as 50 K. For samples of larger surface areas, we are not always able to observe whole-beam bistability. These results can be explained in the following way. When the sample is illuminated with light whose frequency is less than the bound exciton resonance, the sample heats up locally as the intensity increases. This causes the resonance to shift to lower energies (closer to the laser frequency). As it shifts toward lower energies, more heat is generated in the sample owing to the increased absorption and the exciton resonance frequency continues to shift until it slightly overshoots the frequency of the laser. The transmission suddenly switches from a high state to a low state due to this rapid shift in the excitonic frequency. The laser light is then on the high-energy side of the resonance and is substantially absorbed. This point is a stable point since, if the resonance was to continue to move away from the laser, the absorption would decrease, the sample would cool, and the resonance would move back toward the laser (negative feedback). When the intensity is reduced, switching back to a high state is obtained at a much reduced intensity because heat is stored in the sample.

We have recently developed the theory of this effect (Dagenais & Sharfin 1984) and have obtained good qualitative agreement (see figure 1). Transient measurements with a mechanical chopper indicate switch-on and off times faster than 20 μs, our actual time resolution; switch-off times (high to low transmission) can be much faster. Switch-on times are expected to be slower and depend on the rate at which the heat is taken away from the sample. It can be improved by immersing the sample in liquid helium and by optimizing the size of the sample. This type of optical bistability is particularly suited for XOR, AND and inverted logic gate operations. It combines ease of sample preparation, low power operation and high reproducibility.

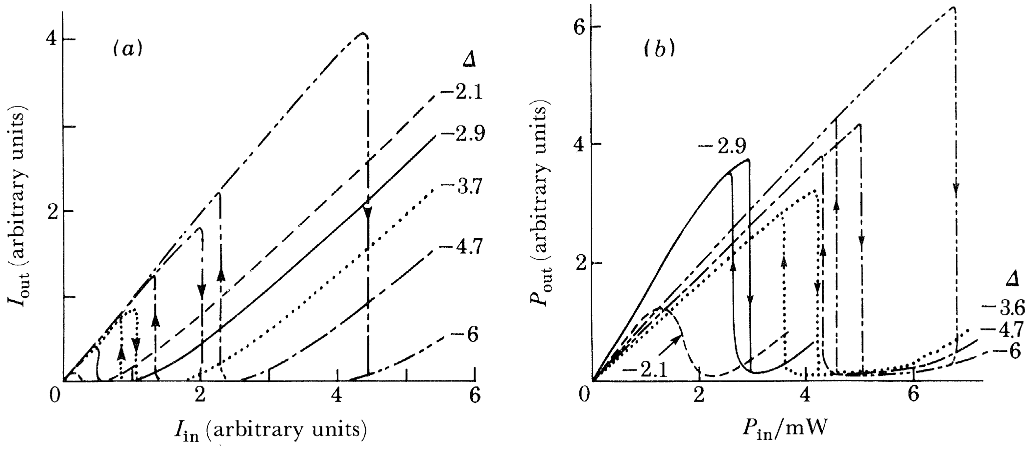

FIGURE 1. Whole-beam bistability. (*a*) Theoretical predictions; (*b*) experimental observations; $T = 7$ K.

TRANSVERSE BISTABILITY

For the transverse bistability measurements, a 20 μm thick CdS sample is immersed in superfluid helium. Optical bistability can be seen for detunings below and above the bound exciton resonance. Here, we present our results for detunings of about 2 cm^{-1} below the resonance (Dagenais & Winful 1984*a*). At very low intensities, the far-field profile of the output beam from the sample is observed to be Gaussian. As the intensity is increased, the beam diameter increases and a circular fringe pattern develops. By increasing the input intensity further, the number of rings increases at the same time as the fringe diameter decreases continuously. This continues with increasing intensity until a sudden discontinuity in the position of the rings in the far field occurs. No simultaneous change of the total transmitted power through the sample is observed (see figure 2). From this we deduce that the laser beam profile within the sample must change discontinuously without a concomitant change of the total transmitted power. Such an effect has recently been predicted by Firth & Wright (1982) in connection with optical bistability in a low-finesse cavity. By monitoring the intensity of the central spot only, using an aperture and a detector in the far field, it is found that the transmitted intensity through the aperture increases monotonically with the input intensity to a point where it suddenly drops. As the input intensity is reduced, the transmitted light decreases and remains below the previous transmission until it switches back to its initial value at a lower input intensity than when it switched previously. Large hysteresis loops are observed and more than one hysteresis loop can be recorded as the intensity is varied (see figure 2). Optically induced refractive index changes as large as 0.15 are deduced from measurements of the transverse ring profile. As the incident intensity is increased, the transmitted intensity can exhibit highly regular pulsations (Dagenais & Winful 1984*b*) with a period of the order of 10 μs. If the whole transmitted beam is collected with a large aperture lens, the pulsation is rather washed out. The pulsations are believed to be due to an interplay between thermal effects and the intrinsic nonlinear effects. Detailed absorption measurements were made and the intensity dependence of the absorption was studied. The saturation of the bound exciton is observed (Dagenais 1983). Sharp induced absorption lines are also seen near both the bound and the free exciton. The transmission through the crystal can be changed by a factor of three when the laser intensity is increased from a low value to a high one (*ca.* 10 kW cm^{-2}). Gated absorption measurements reveal that an important fraction of the induced absorption can appear in 10 ns or less. This demonstrates that this is a highly nonlinear system with a potentially fast response time.

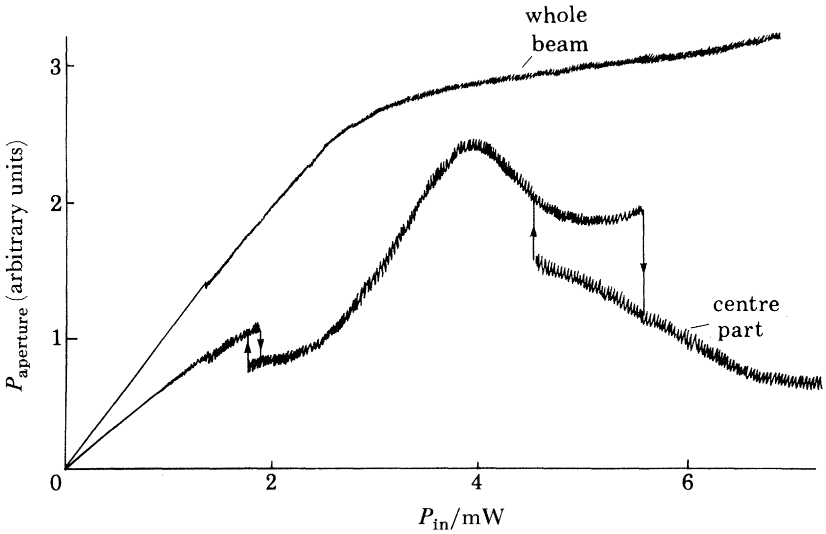

FIGURE 2. Observation of transverse optical bistability; $\nu = 20529.5\ \text{cm}^{-1}$, $T = 2$ K.

CONCLUSION

In conclusion, large nonlinear effects at low incident power are seen near the band gap of CdS. The observed whole-beam bistability does not require a cavity or external feedback and combines ease of sample preparation, low power operation and high reproducibility. Clear evidence for spatial bistability without whole-beam bistability is also reported.

The author acknowledges W. F. Sharfin and H. G. Winful for informative, stimulating discussions. The author is indebted to Dr D. C. Reynolds of Wright Patterson Air Force Base for his generosity in providing very high quality cadmium sulphide platelets.

REFERENCES

Dagenais, M. 1983 *Appl. Phys. Lett.* **43**, 742–744.
Dagenais, M. & Sharfin, W. F. 1984 *Appl. Phys. Lett.* (In the press.)
Dagenais, M. & Winful, H. G. 1984*a* *Appl. Phys. Lett.* **44**, 574–576.
Dagenais, M. & Winful, H. G. 1984*b* In *Optical Bistability*, vol. 2 (ed. C. M. Bowden, H. M. Gibbs & S. L. McCall), pp. 267–272. New York: Plenum Press.
Firth, W. J. & Wright, E. 1982 *Optics Commun.* **40**, 233–238.