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CW OPTICAL BISTABILITY IN NON-ABSORBING LIQUIDS AND LIQUID CRYSTALS USING HeNe AND DIODE LASERS

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We report the first demonstrations of cw submilliwatt optical bistability in metallic mirror cavities containing water, alcohol and other solvents. Such thermal bistability is also reported for a hybrid dielectric/metallic cavity containing the nematic liquid crystal 4-cyano-4′-pentylbiphenyl (also known as PCB, 5CB or K15), illuminated by a low power diode laser.

1. Introduction

Thermal, dispersive optical bistability has been observed in a number of semiconductor materials, e.g. bulk ZnSe [1], InSb [2], HgCdTe [3], ZnS and ZnSe interference filters [4,5] and GaAlAs waveguides [6]. In all of these cases, absorption in the material produces a temperature rise, and in turn a refractive index change. In addition to this effective irradiance-dependent, thermo-optic nonlinearity, the plane parallel surfaces of the sample, or the multilayer dielectric stacks in the filter case, provide reflective feedback. The combination of nonlinearity and feedback produces the observed optical bistability.

For many applications of bistability to optical information processing (logic gate arrays, displays, spatial light modulators) it is important that the critical power level, below which bistability cannot be achieved, be significantly less than 1 mW. Otherwise, for example, the number of gates simultaneously operable using cw laser sources of typically 10 W total power, is too limited. Further, when considering integration with communications devices, and miniaturisation of digital optical systems, it is important that such logic gates are addressable by semiconductor lasers, and laser arrays.

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An optimisation study of the interference filter bistability [7] led to a number of significant conclusions:

(i) In existing filters, where absorption takes place in the spacer region of the Fabry-Perot etalon, an attempt to increase the effective nonlinearity by using more strongly absorbing materials will eventually destroy the cavity finesse, conversely, cavities with very high finesse will have too little absorption. The optimum cavity is one in which the absorption and finesse are balanced by the condition [7],

$$\alpha D \simeq 2 - R_F - R_B, \qquad (1)$$

where α is the absorption coefficient in a cavity of length D and surface reflectivities R_F and R_B. Because thin cavities (filters) are necessary for the degree of plane-parallelism demanded of a large area device, one deduces typically 10 mW bistability for an optical beam spot-size of 50 μm. To reduce this level it is essential to approach the diffraction limit for spot-sizes, and simultaneously to pixellate the sample to prevent transverse heat loss.

(ii) The source of cavity heating need not, however, be absorption in the spacer region itself, even though irradiance levels are highest there. Equally the nonlinear dispersion may, in principle, be either in the spacer or in the reflective stacks.

One alternative cavity design is therefore a non-absorbing spacer material with a temperature-dependent refractive index, in thermal contact with an irradiance dependent heat source. It is necessary

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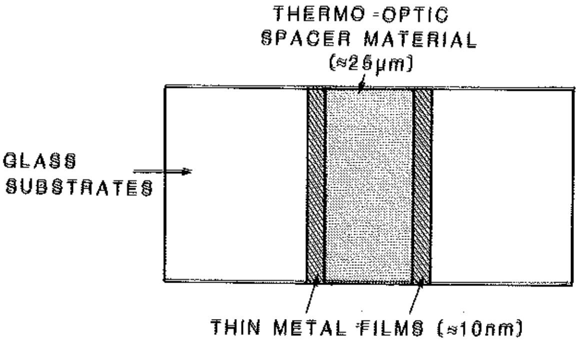

Fig. 1. Schematic of the metal/metal cavities and with liquid spacer materials.

then, only that the heat source experiences the optical feedback provided by the overall cavity. The use of metallic reflective mirrors surrounding any thermo-optic material should therefore lead to an optically bistable response. Further, providing the heat conduction into the spacer region is efficient, a very high finesse cavity can be employed, leading to reduced power requirement.

(iii) The operational wavelength for thermal bistability, as opposed to electronic, or self-electro-optic bistability, is determined by the cavity wavelengths and not by the precise absorption spectrum of the material. For example, ZnSe filters have been operated at 514 nm through to 677 nm, and at 850 nm [8,9].

2. Butterfly-bistability using metal/metal cavities

To emphasise the above predictions we have constructed a number of cavities to the design shown in fig. 1. Metal films (aluminium, gold or chromium) typically 100 Å thick are deposited on glass slides. A cavity is formed between two such metal surfaces, using mirror separations of order 25 μm. We have used both conventional liquids within the cells, and liquid crystals. In the former case we have thereby demonstrated that there is nothing remarkable about the use of semiconductors for thermal dispersive bistability, let alone the use of ZnSe. We also verify that the power level required for bistability is inversely proportional to the spacer thermo-optic coefficient.

Fig. 2 shows the transmission response for an aluminium mirrored cavity containing water, for three different cavity detunings (obtained by sample translation or rotation) from the operational (633 nm) HeNe wavelength. For large enough detunings we observe a butterfly-bistability that is a characteristic of metal/metal cavities [10]. As the incident power level is increased there is a switch-point (P_2) at which the transmitted power drops sharply. On reducing the incident power the transmission rises until a second switch point (P_1) where it again drops sharply, to the original level for input P_1. Between P_1

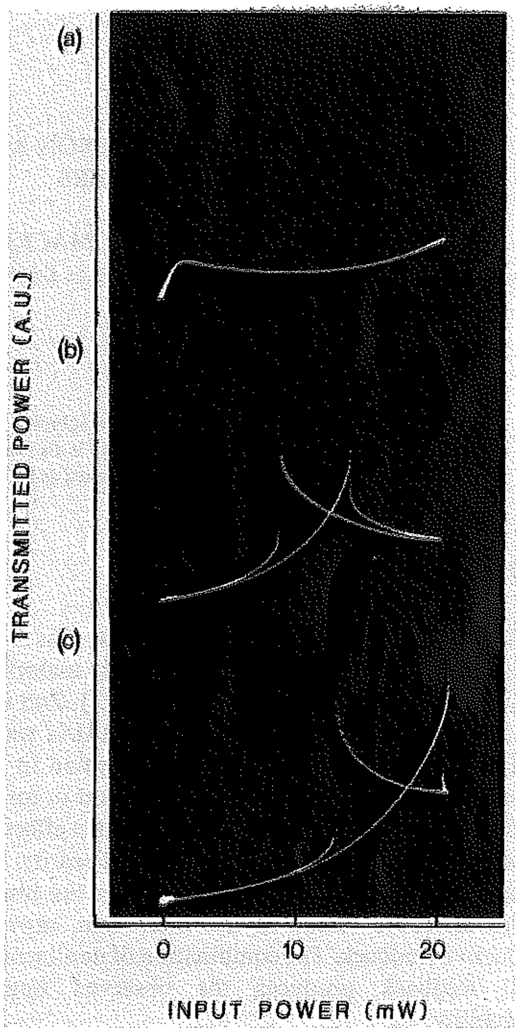

Fig. 2. Optical bistability in water, for initial conditions (a) close to cavity resonance, showing strong power limiting, (b) above-critical detuning, showing butterfly-bistability.

and P_2 there are two stable output levels for each input, except at one power level (P_d) where the two output levels are degenerate. In table 1 we give the observed critical switching powers. These levels are obtained for a detuning such that butterfly-bistability is just able to unfold; and are the incident powers at the point of unfolding. Tabulated room temperature thermo-optic coefficients [11] are also presented in table 1, and the inverse proportionality of the critical switching levels to the thermo-optic coefficients is brought out. In all cases the laser spot size ($1/e^2$ diameter) was 25 μm. A second example of butterfly-bistability is given in fig. 3(a), this being for an aluminium cell containing an alcohol (Glenfiddich malt whisky).

In the accompanying theoretical paper it is shown that the metallic front mirror of the Fabry-Perot is responsible for the unusual shape of the bistable responses above [10]. Fig. 3(b) shows the theoretical fit to the whisky bistability results. We show also in fig. 4 that higher orders of switching are achievable at relatively low power levels, two orders being observed for the whisky cell illuminated with cw HeNe radiation and four orders in a dielectric/metal cell containing ethanol, illuminated at 514 nm with a cw argon ion laser.

3. Submilliwatt bistability using nematic liquid crystals

Nematic liquid crystal materials, suitably oriented, have extremely high thermo-optic coefficients [12]. Fig. 5(a) shows the transmission of an aluminium/aluminium cell containing the nematic liquid crystal K15 (5CB or 4-cyano-4′-pentylbiphenyl). This material was chosen because it has a nematic–isotropic transition temperature of 308.5 K just 22 K above the ambient temperature. We are therefore able to take advantage of the enhancement of the thermo-optic coefficient at temperatures closely below the phase transition [12]. Butterfly-bistability is observed for HeNe laser power levels above 0.38 mW.

One can regain the conventional hysteresis loops for dispersive bistability by replacing the front metallic mirror by an effectively non-absorbing dielectric reflective stack. Additionally this configuration allows greater flexibility in optimisation design.

Table 1
Critical switching powers for a number of liquids and other materials. All experiments refer to optical spot-sizes ($1/e^2$ radii) of 25 μm. There are small variations of cavity reflectivities and cell thicknesses.

	Material	Critical switching power P_c (mW)	Thermo-optic coefficient $\partial n/\partial T$ (K^{-1})	$P_c\, \partial n/\partial T$
(a) Aluminium/aluminium cells				
	Water	6	-1.5×10^{-4}	0.9×10^{-3}
	Isopropanol	2.5	-4×10^{-4}	10^{-3}
	Ethanol	1.7		0.7×10^{-3}
	Champagne	4		
	Glenfiddich	2.2		
	Carbon disulphide	1.2	-8×10^{-4}	10^{-3}
	K15 (o ray)	2.6	4×10^{-4}	10^{-3}
	K15 (e ray)	0.38	-2×10^{-3}	0.8×10^{-3}
(b) Dielectric/gold cell				
	K15 (o ray)	0.98	4×10^{-4}	4×10^{-4}
	K15 (e ray)	0.19	-2×10^{-3}	4×10^{-4}
(c) Typical ZnSe interference filters [8]				
	ZnSe	10	2.5×10^{-4}	2×10^{-3}

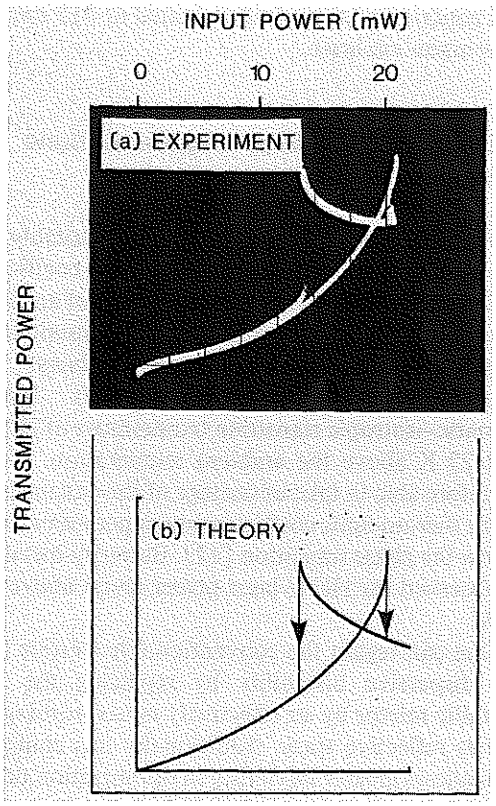

Fig. 3. Butterfly-bistability in a metal/metal cell containing Glenfiddich malt whisky. (a) Experiment. (b) Theory.

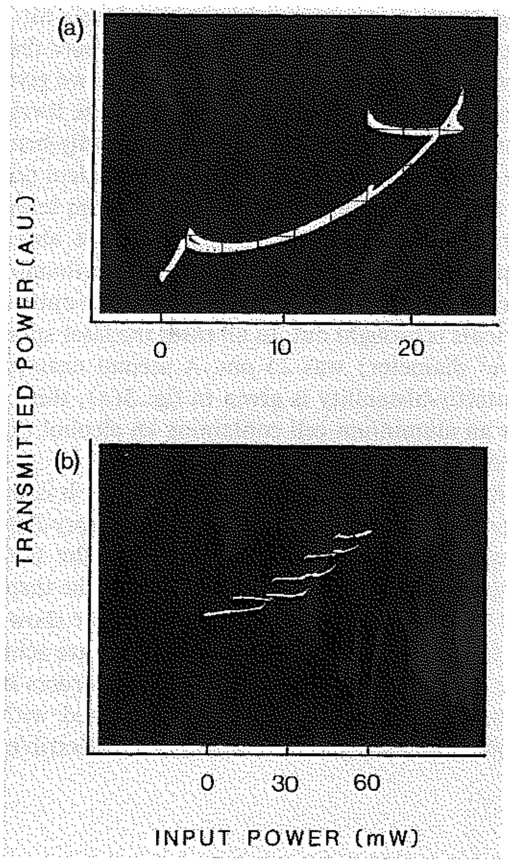

Fig. 4. (a) Two orders of nonlinear Fabry-Perot action observed using a HeNe laser at 633 nm (whisky). (b) Four orders observed at 514 nm (ethanol).

In fig. 5(b) we show a regular, anti-clockwise hysteresis for the transmission response of a non-optimised K15 cell constructed from a 95% reflectivity dielectric stack front mirror and an 85% gold back mirror. The critical switching power is now reduced to 190 μW. Further reduction is expected for a balanced cavity [11].

4. Diode-laser induced bistability

The above power levels for nematic liquid crystal bistability are well within the range of conventional cw diode lasers. As an initial demonstration we have used a 5 mW, 790 nm diode and a non-optimised, 30% reflectivity dielectric front mirror, gold back mirror, K15 cell. With no attempt to achieve tight beam focussing, optical bistability was observed with switch-up at 5 mW, fig. 6.

5. Discussion

There have been a number of studies of optical bistability in nematic liquid crystals [13–17]; here we distinguish the thermal mechanism to which we attribute our present results from those described previously. In the review by Shen [13], and Khoo and Shen [14], results are described for PCB (K15) in which both laser heating effects and molecular reorientation nonlinearities were observed for homeotropically aligned samples. Bistability associated with the nematic–isotropic phase transition [15] and hysteretic effects attributed to the generation of orientational disclination loops [16] have also been reported. Switching in these various cases is characterised by the internal/incident irradiance levels and

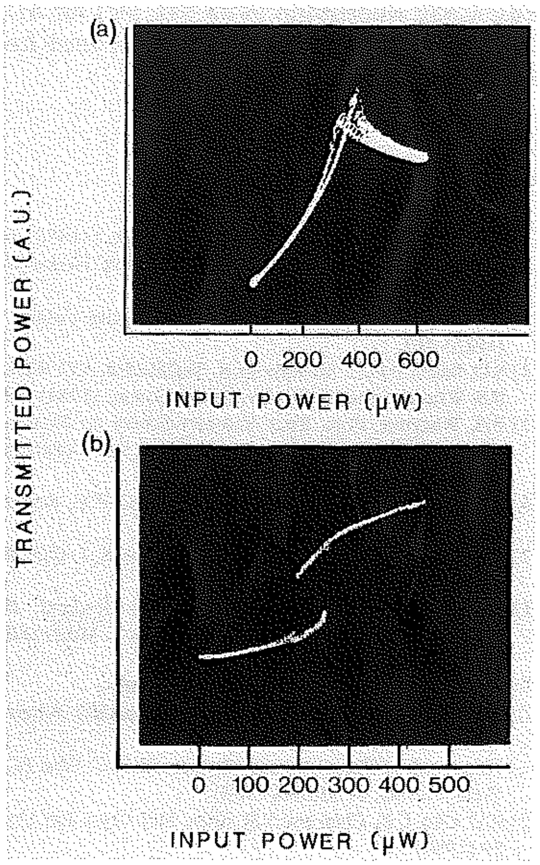

Fig. 5. (a) Critical switching of a metal/metal cell containing K15. (b) 200 μW switching in a dielectric/metal cell containing K15.

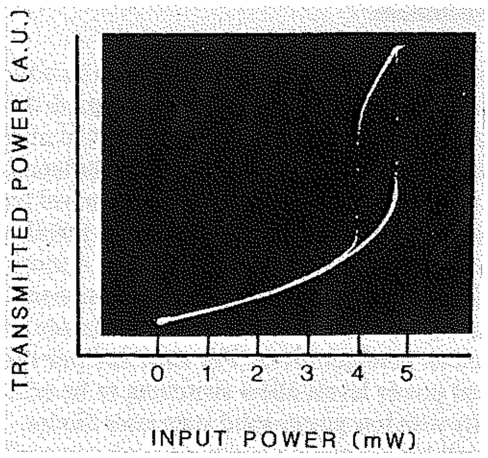

Fig. 6. Diode-laser induced, cw bistability in a K15, dielectric-/metal cell.

the switching speed. Experiments differ with regard to the form of cell (etalon, single-pass, external cavity) and the material conditions (director orientation, doping, bias fields).

In the present case 190 μW power corresponds to an irradiance level of 40 W cm^{-2} incident on the cell; switching times are less than 10 ms. In similar cells, using parallel planar alignment with no biasing electric or magnetic fields, we have also observed bistability of the disclination loop type, typically at 400 W cm^{-2} and 10–100 ms. We do not see the phase, or a Freederickz (molecular reorientation) transition in these cell configurations for incident levels up to 4 kW cm^{-2}. The liquid crystal temperature rise is estimated to be $\Delta T \sim 0.2$ K for the 190 μW switch. From the 296 K thermo-optic coefficient for the extraordinary ray, the implied experimental refractive index change is $\Delta n \sim -4\times10^{-4}$. Critical switching occurs for a relative index change $\Delta n \approx \lambda_v/\mathscr{F}D$, where λ_v is the vacuum wavelength, D the spacer thickness, and $\mathscr{F}$ is the cavity finesse [7]. For our cell $\mathscr{F}\approx 30$, and we estimated a required Δn of -3×10^{-4} at the switch point. Hence the 190 μW switch is quantitatively consistent with a purely thermal mechanism, in agreement with the conclusions from table 1. We note that the use of metallic coatings strongly enhances the laser heating effect, this was previously inferred to occur at $\simeq 350$ mW cm^{-2} as a result of just residual absorption, or absorption induced by dissolving dyes in the liquid crystal [13]. The slow (1s) Freederickz switching has bee seen at very low irradiances, 6 W cm^{-2}, but only by using biasing magnetic fields and homeotropically aligned materials [17]. Even for this alignment some 500 W cm^{-2} are required in the absence of bias [18], and it is not clear that the transition should be seen at all for the planar configuration, which we use.

Bistability in non-absorbing liquids, CS_2 and nitrobenzene, has also been reported previously. This is of quite a different nature to the present work however. The entire cavity was non-absorbing and the relatively very weak optical Kerr reorientational nonlinearity was used to produce nonlinear transient Fabry-Perot action using ruby laser pulses of peak irradiances in the MW cm^{-2} regime [19].

6. Conclusions

Submilliwatt cw optical bistability can be observed in almost any liquid or solid, given a good thermal contact with metallic and absorbing partial mirrors.

Cell configuration has shown to be influential in the type of bistability observed, with a novel type of butterfly-bistability reported here in metal/metal cavities containing a number of liquids. A more conventional hysteresis loop has been obtained using liquid crystal thermo-optical materials inside dielectric/metal configurations. For such cavities the low critical power levels allow switching to be achieved readily with low power solid state laser diodes.

It will be important to determine whether cell fabrication that enables independent switching of arrays of bistable elements can be achieved with 10–100 μW switching power levels. Pixellation of the metallic coatings will be essential to reduce thermal crosstalk, and further improvement is expected from isolation of the active regions of the spacer material.

The very low temperature rises required for switching on all the schemes reported here is low enough that all response branches are stable to drift, in contrast to the ZnSe interference filter case where local temperature rises of 100 K and above occur at switch-ON. In the more sensitive cavities it may become necessary to stabilise the *ambient* temperature to prevent switching due to ambient fluctuations.

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