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OPTICAL BISTABILITY IN MOLECULAR BEAM DEPOSITED ZnSe/BaF₂ MULTILAYER INTERFERENCE FILTERS

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Abstract - Complete interference filters have been fabricated using ultrahigh vacuum molecular beam techniques and optically assessed. The wavelength dependence of optical bistability is compared with theory between 676 and 521nm for a 6 μ m thick filter with ZnSe/BaF₂ multilayer reflectors. Both dispersive bistability and bistability due to increasing absorption were observed at 514nm.

1 - INTRODUCTION

Thermo-optic interference filters based on II-VI semiconductors are attractive as test-beds for all-optical computing schemes. They can be uniformly fabricated in large areas, and therefore offer the potential for large arrays of optically bistable devices with the convenience of room temperature, visible light operation /1/. The nonlinear mechanism has now been well characterized as a thermally induced, dispersive optical nonlinearity /2,3/. Most effort has involved evaporated ZnSe since this is a well established thin film coating material and provides a band gap energy which is resonant with the 514nm output of the argon laser. However, standard thermal evaporation techniques are limited in what can be achieved in terms of material quality and complexity of structure. This paper reports on the application of a new optical coating technology, molecular beam deposition (MBD), for the fabrication of complete Fabry-Perot etalons. The MBD technique is capable of producing dense films, free of porosity and with low contamination levels which should improve the stability of thermo-optic devices. An immediate advantage of the MBD technique for optical bistability is the ability it provides to produce much thicker, mechanically stable layers. This is significant in terms of optimising the structure for lower switching powers, reducing the required temperature rise, controlling heat flow and the ability to achieve optical bistability due to increasing absorption.

Interference filter etalons have the general structure, HLHL... (mHH)...LHLH where H indicates a quarter wavelength optical thickness ($\lambda/4$) layer of high index material (ZnSe, $n \sim 2.7$ at 514nm) where λ is the vacuum wavelength, and L is a $\lambda/4$ layer of low index (e.g ThF₄, $n = 1.55$). The integer, m, (typically 8 for thermally evaporated layers) gives the etalon spacer thickness. These etalons can be self-tuned with a laser because of band edge absorption in the ZnSe causing a rise in lattice temperature; the absorption edge shift to longer wavelengths at higher temperatures results in an increase in the refractive index and therefore also in the round trip etalon phase change. The MBD filters fabricated for these studies have 6 μ m thick ZnSe spacers (m = 120). Earlier work on ultrahigh vacuum (UHV) film fabrication has produced ZnSe films with high laser damage thresholds /4/. The low index material chosen was BaF₂ ($n = 1.45$). Recent work on fluoride deposition has highlighted the potential of barium and lead fluorides as low index materials for use over a wide range of wavelengths /5/. Techniques have been developed for the control of the microstructure of the films offering the potential for controlling the properties of different materials within novel structures. A previous paper has reported results on optical bistability in filters constructed with thick MBD ZnSe spacers with conventional, thermally evaporated ZnSe/ThF₄ mirrors /6/.

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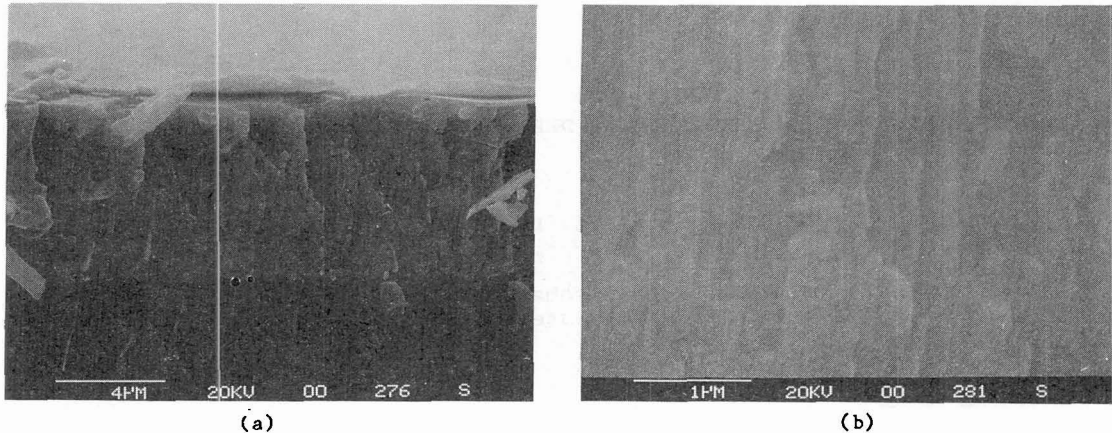


Fig. 1 - Scanning electron micrographs of cleaved cross-sections of MBD filter structure, sample AP245. The outer reflector layers are just discernible in (a).

2 - ETALON FABRICATION AND ASSESSMENT

The MBD layers were deposited in a Vacuum Generators load-locked UHV system fitted with 3 Knudsen sources and in-situ surface diagnostics. The source materials were contained within high purity graphite crucibles which were carefully outgassed following baking of the entire deposition chamber at 180°. The ZnSe source was ultra-high purity polycrystalline ZnSe which had previously been prepared by chemical vapour deposition from a mixture of zinc vapour and hydrogen selenide. The barium fluoride source was high purity crystalline optical grade material. Source temperatures were adjusted to give deposition rates of 0.9 $\mu\text{m}/\text{h}$ for ZnSe (896°C) and 0.7 $\mu\text{m}/\text{h}$ for BaF₂ (1185°C) at pressures of 10⁻⁸mbar. The glass substrate temperature during growth for the entire MBD deposited layer was 300°C. Filters were built up by first depositing a two-period stack comprising $\lambda/4$ thick layers of ZnSe and BaF₂ centred at 633nm, followed by the ZnSe spacer and finally a matching two period mirror to complete the etalon. The multilayers were exceptionally smooth with no evidence of surface texture visible by Nomarski interference microscopy. A small built-in wedge allowed tuning of the etalon.

Transmission spectra were recorded at a number of sample temperatures in one sample, in order to determine the dispersion in both the refractive index and the index change with temperature $\delta n/\delta T$. The results are shown in figure 2. Transmission measurements were also carried out at five wavelengths using low power, focused krypton laser radiation in order to determine precise maximum and minimum values by fully resolving the fringes /7/, table 1. From these results peak mirror reflectivities of about 70% were deduced assuming equal values of reflectivity for front (R_F) and back (R_B) mirrors. These reflectivities may be compared with the theoretically predicted values of $R_F = 81\%$ and $R_B = 74\%$ assuming no absorption in the stacks. Values of αd were also estimated where α is the absorption coefficient and d is the etalon spacer layer thickness. The ZnSe absorption coefficient varies from about 100 to 1000 cm^{-1} between 676 and 521 nm. The absorption edge is less abrupt than for bulk polycrystalline ZnSe, as found for conventional, thermally evaporated thin films /2/.

Table 1: Parameters for sample AP245

$\lambda(\text{nm})$	$T_{\text{max}}(\%)$	$T_{\text{min}}(\%)$	αd	$R(\%)$	f	$P_c(\text{mW})$
521	23	8	0.63	52	2.39	14
531	28	7	0.47	57	1.93	11
568	38	3.5	0.24	69	1.22	9.5
647	62	3	0.09	70	1.34	19
676	73	4	0.07	67	1.77	25

3 - OPTICAL BISTABILITY

Spacer layers 6 μm thick produce etalon fringes with spacing at less than 10nm in the visible. This allowed optical bistability to be observed at five krypton laser wavelengths between 676 and

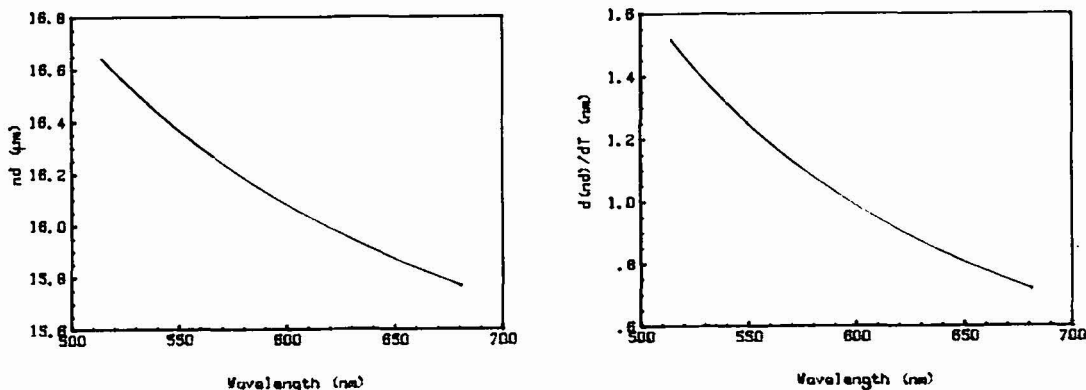


Fig.2 - Measured dispersion in optical thickness, nd and its temperature dependence, $d(nd)/dT$ (sample AP244)

521nm implying a spot size, $\omega_0 = 12\mu\text{m}$ ($1/e^2$ intensity radius). Input-output characteristics measured at 531nm are shown in figure 3a, with critical switching recorded at 11mW. Measurements of critical switching power at the five wavelengths are plotted in figure 3b; the minimum critical power observed was 9.5mW at 568nm. The optimum wavelength is a trade-off between the larger nonlinearity at shorter wavelengths due to higher absorption plus slightly larger dn/dT , against the higher absorption causing a reduction in the finesse of the etalon.

An expression giving the wavelength dependence of the critical switching irradiance, I_c , for optothermal devices has been derived by Wherrett et al /8/. Two regimes may be considered. For large spot sizes, such that longitudinal heat dissipation into the substrate dominates cooling,

$$I_c = \frac{\lambda \alpha \kappa_s}{2\pi(\partial n/\partial T)\omega_0} \frac{f(R_F, R_B, \alpha d)}{\alpha d} \quad (1)$$

This is the product of material parameters, (κ_s is the substrate thermal conductivity) and an expression comprising a complicated function of etalon parameters (reflectivities, absorption coefficient and thickness). In the limit of small spot sizes and thick films, cooling is expected to be transverse with heat loss along the layers, in which case, /8/,

$$I_c = \frac{\lambda \kappa_f}{(\partial n/\partial T)\omega_0^2} f(R_F, R_B, \alpha d) \quad (2)$$

where κ_f is the film conductivity. In either case, for a given laser spot size, the wavelength

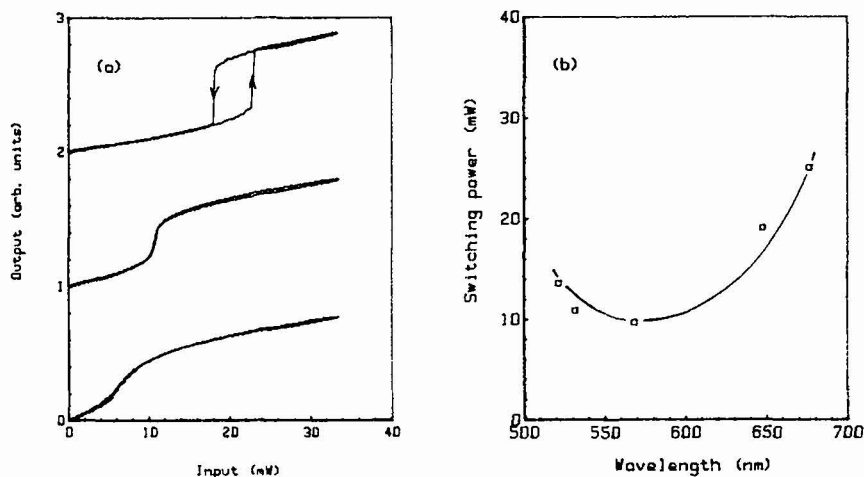


Fig.3 - (a) Input-output characteristics for AP245 at 531nm. (b) Measured critical switching powers for optical bistability compared to theory (line).

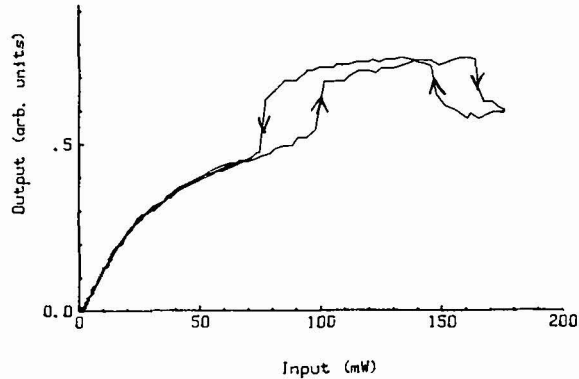


Fig. 4 - Dispersive and absorptive bistability in sample AP245 at 514nm.

dependence of the critical switching power is given by, $P_c \sim \lambda f / (\delta n / \delta T)$. This function is plotted in figure 3(b) for the etalon parameters extracted from the transmission measurements. The line shown has been scaled vertically to overlap the 568nm result. Although the dispersion in $\delta n / \delta T$ is small (about a factor of two between 521 and 676nm from figure 2) inclusion results in an excellent fit to the data.

The size of the illuminated area and how it is heatsunk will effect both the switching power and the switching speed /9/. Although the spot diameter is four times the film thickness in these measurements, the ratio of the thermal conductivity of ZnSe to that of glass is twenty. For the measurements at 568nm, equation 1 predicts a critical switching power of 1.5mW, while equation 2 gives 110mW for ZnSe on glass. Thus, significant transverse cooling is implied by theory under the conditions used here, and the higher value of critical switching power should apply. The measured value of 9.5mW would indicate however that cooling is significant both along the layers and into the substrate. Although some drift of the bistability with time was still apparent in these initial MBD structures, essentially stable operation was maintained for several hours at 568nm /7/. Further studies on the stability of these structures are in progress.

Optical bistability was observed in the same filter with an argon laser operating at 514nm, figure 4. Dispersive bistability is shown here at much higher powers, partly because the filter design is far from optimised at 514nm, but also because a much larger spot size (approx. 100 μ m) was employed in this case. At higher powers a clockwise loop occurs due to absorptive bistability. This effect, due to the inherent feedback between the absorption edge shift and the incident intensity, has been reported previously in thick polycrystalline ZnSe samples at 476nm /10,11/, but not in evaporated layers. The present samples satisfy the requirement, $\alpha d > 0.18$ at 514nm /11/ for this form of bistability to occur.

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