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Resolution in Optically Addressed Spatial Light Modulators based on dye-doped liquid crystals

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Dye-doped nematic liquid crystals (LC) are studied as materials for single layer Optically Addressed Spatial Light Modulators (OASLMs). The dopant is 2,5 azo-substituted anthraquinone (ASAQ) dye. The resolution in the ASAQ doped LC systems does not depend on the device thickness (in 5μm to 125μm range). The efficiency increases with the increase of the thickness and begins to saturate in devices thicker than 40μm. The limiting resolution in the thick devices is 400 line pairs per mm (lp/mm). The limitations of performance (efficiency and resolution) in the studied systems are discussed.

OCIS codes 230.1150, 230.4320, 230.6120.

Introduction

Optically addressed SLMs (OASLMs) are becoming increasingly important in many applications including projection displays, optical correlation and real-time holography. Dye-doped LC systems are highly promising materials for novel OASLMs based on photorefractive orientational effects. [1,2,3,4,5,6] Such devices would transfer images onto high power beams without the need for special layers or circuitry. They could be used in transmission and we shall show that the resolution of 1-layer dye-doped-LC device competes with that of currently available 2-layer amorphous silicon OASLMs. [7]

Resolution is one of the critical parameters for many applications of OASLMs. ***Resolution*** is defined as the spatial frequency (lp/mm) at which the modulation transfer function (MTF) of the device is 50% (efficiency decreases by the factor of two). The ***limiting resolution*** is the spatial frequency at which the signal from the device is still detectable.

Resolution can be limited by many physical phenomena. In two-layer optically addressed spatial light modulators the three main limiting factors of the resolution are the fringing field effect, the diffusion of charges in the photoconductor bulk, and the charge spreading at the interface of the photoconductor and the liquid crystal layer. [8] The resolution of two-layer devices has been reported to be usually around 50 line pairs per millimetre (lp/mm). [9, 10, 11, 12] In special cases when using carbon doped silicon layer, a *limiting resolution* of up to 360 lp/mm is possible [13] (from graphical data in reference 13, the *resolution* is 200 lp/mm). Achievable phase retardation in these devices is 2π. This corresponds to maximum possible diffraction efficiency of 34% when recording sinusoidal grating in Raman-Nath regime.

The studies of single layer dye-doped liquid crystal films suggest that very high resolution may be achieved. For example, in C_{60} doped nematic devices the limiting resolution of 100-200 lp/mm has been reported. [14] In these films resolution depends on the sample thickness, and efficiency peaks when the spatial frequency is double the sample thickness [15] (henceforth called optimal spatial frequency). The reported efficiency in these devices is up to 5% at optimal spatial frequency (phase retardation is $\pi/7$). Permanent effects in MR doped systems have been shown to possess very high limiting resolution, up to 500 line pairs/mm.[16] Up to 20% efficiency had been reported in these devices at 125 lp/mm (phase retardation up to $\pi/3$). Also, limiting resolution of up to 1000 lp/mm has been reported for photorefractive effects involving space charge build up in NLCs doped with anthraquinone dyes.[17] Resolution in systems involving space-charge depends on spatial frequency. The efficiency for such anthraquinone dye-doped devices had been reported to be about 20% (phase retardation $\pi/3$) at optimal spatial frequency of 50 lp/mm, and efficiency drops to 5% at 100 lp/mm.

In this paper we shall concentrate on the resolution of the 2,5 azo-substituted anthraquinone (ASAQ) dye-doped nematic liquid crystal (LC) devices. This dopant is an interesting alternative to MR doped systems.[18] The 2,5 azo-substituted anthraquinone (ASAQ) dye DC161 is dichroic and has maximum absorption at 527 nm. The dye structure is shown on Fig.1. The dye had been synthesised at Standard Telecommunications Labs, Harlow, UK by Dr. Coates.

The mechanism of the optical nonlinearity has been shown to be due to the trans-cis transition in dye molecules in the bulk.[19] We have reported efficiency for these devices to be up to 1.5% (phase retardation $\pi/12$) at 80 lp/mm.[20] Based on the trans-cis model, the only limiting resolution factor is diffusion of cis dye species from illuminated regions into dark regions and a corresponding diffusion of trans species from dark into illuminated regions.

Devices and measurement techniques

Samples

For the described studies we have chosen planar aligned devices filled with cyano-biphenyl nematic liquid crystals doped with 0.5% and 1% wt of dichroic ASAQ dye DC161. One set of devices had thickness 5, 9 and 15 microns and used 5CB nematic liquid crystal from Merck as host material and SiOx as alignment layer. Similar planar aligned devices with E7 host from Merck (a mixture of cyano-biphenyls) and polyimide as alignment layer have been built to study the resolution and efficiency behaviour in thick devices. The thicknesses of those are 10 μm, 14 μm, 20 μm, 40 μm, 60 μm and 125 μm. Although higher dye concentrations yield higher efficiency, [5] we have chosen dye concentration of 0.5% wt in order to decrease absorption and thus ensure better distribution of writing beam intensity in the highly absorbing media.

Experimental techniques

A holographic grating is recorded on the sample using two Ar+ laser beams (λ=514 nm). No external electric field is applied. The beam from the laser is collimated and expanded to obtain a uniform intensity profile. Then it is split by a non-polarising beam splitter. In order to make measurements at high spatial resolution, a Michelson interferometer setup is used (Fig.2).

The beams are directed to overlap on the sample. The interference pattern that is formed is a sinusoidal grating. This setup allows large angles between the interfering beams without increasing the path difference between them. Therefore the path difference stays within the coherence length of the laser. The recorded spatial frequency in this setup can be varied from 2.5 μm to 33.3 μm (400 lp/mm to 30 lp/mm).

A weak He-Ne laser beam (λ=633 nm, 1 mW) is used to read the recorded grating. The diffracted orders are symmetrical. The first diffracted order is measured using a photo-multiplier and oscilloscope during switch “on” and switch “off” of the writing beams. All the beams are polarised along the director of the LC, i.e. along the alignment direction of the device. In order to minimize the error due to fluctuations, the measurement was done by collecting and averaging a set of experimental data points during the illumination period.

Experimental results

Resolution

From the resolution studies in DC161 (Fig.3) we find that the efficiency remains the same when a larger spatial frequency (10-33 μm) is used, and starts to decrease when the spacing becomes smaller than 8-10 μm. It almost vanishes for grating periods smaller than 2.5 μm (400 lp/mm).

Such uniform behavior of the efficiency for grating periods larger than 8-10 μm is very important for device applications. An arbitrary image will contain a range of spatial frequencies, and the efficiency should remain the same for all these spatial frequencies in order to ensure a faithful image transfer. Moreover, the limiting resolution is virtually independent of the dye concentration and the sample thickness.

Thick devices

From previous research, we know that efficiency strongly increases with an increase in the sample thickness. [20] Therefore, a simple way of improving efficiency of DC161 doped devices could be to build thick devices. This should not lead to a loss in resolution. To test this hypothesis experiments in thick 0.5% DC161 doped E7 devices (40, 60 and 125 μm) have been conducted in the Raman-Nath regime. In the following experiment low efficiency is due to the fact that we are using low doping level, different host material and alignment agent; also, as confirmed by microscope studies, the dispersion of the dye is not homogenous.

Measurements in thick devices show that:

⇒ the resolution limit remains the same as for thin devices (***down to 3 μm);***

- ⇒ the efficiency grows with device thickness but, due to the strong absorption making only the front part of the device active, it starts to saturate if the thickness is increased above 40 μm. (Fig. 4.);
- ⇒ diffraction efficiency in a 0.1% doped 125 μm thick device showed low diffraction efficiency, about 4 times lower than in 0.5% doped device of the same thickness and material (the efficiency scales with the dye concentration at low doping levels).

Equally high resolution and almost unchanged temporal switching characteristics [21] compared with thin (≤ 25μm) devices make thick devices based on DC161 doped liquid crystals a good option for improving the efficiency.

The diffraction regime defines the maximum possible diffraction efficiency obtained from the grating. At small induced retardation (<1 rad) and consequently low diffraction efficiency (<20%) Bragg matched and Raman-Nath diffraction regimes do not differ significantly (Fig. 5.). Only when the induced retardation approaches at least π/2, the difference in these two regimes becomes significant. In order to achieve a uniform light intensity distribution throughout the whole thickness of the device, low dye concentrations (0.1% wt) should also be used.

Conclusions

Diffraction efficiency is approximately independent of line spacing in all devices doped with an azo-substituted anthraquinone dye for gratings with a period larger than 8-10 μm. This resolution threshold is independent of the device thickness, and dye concentration within the 0.5% wt - 1% wt range.

The diffraction efficiencies observed in 0.5% doped E7 devices are low, of the order of 0.02% - 0.03% and correspond to optical phase excursion of about π/30. In 1% doped 5CB devices diffraction efficiency reaches 1.5% (optical phase excursion π/12). [20]

Experiments on thick devices have confirmed that the resolution is independent of the sample thickness. The dynamics in 125 μm thick devices is almost the same as in thin ones (≤ 25 μm). The efficiency of the thin devices increases when the thickness is increased. At a given optical intensity of writing beams, in samples thicker than 40 μm diffraction efficiency saturates, probably due to the high absorption in the devices.

We had shown earlier [20], that diffraction efficiency of the discussed system is proportional to dye concentration and increases quadratically with device thickness. Therefore for device optimisation it is better to increase thickness and choose dye concentration accordingly.

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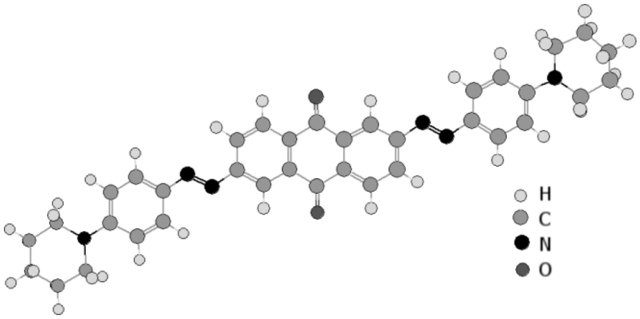

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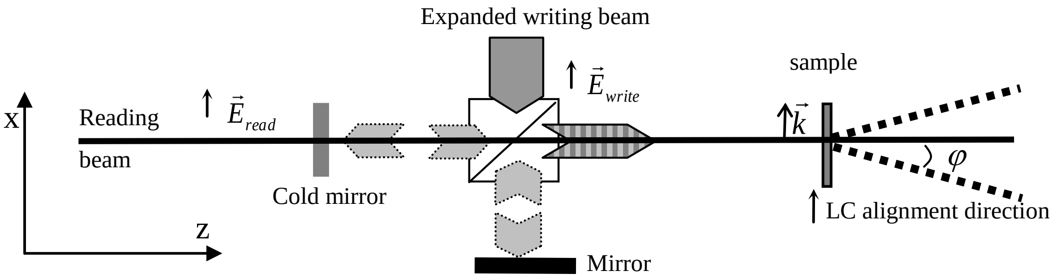
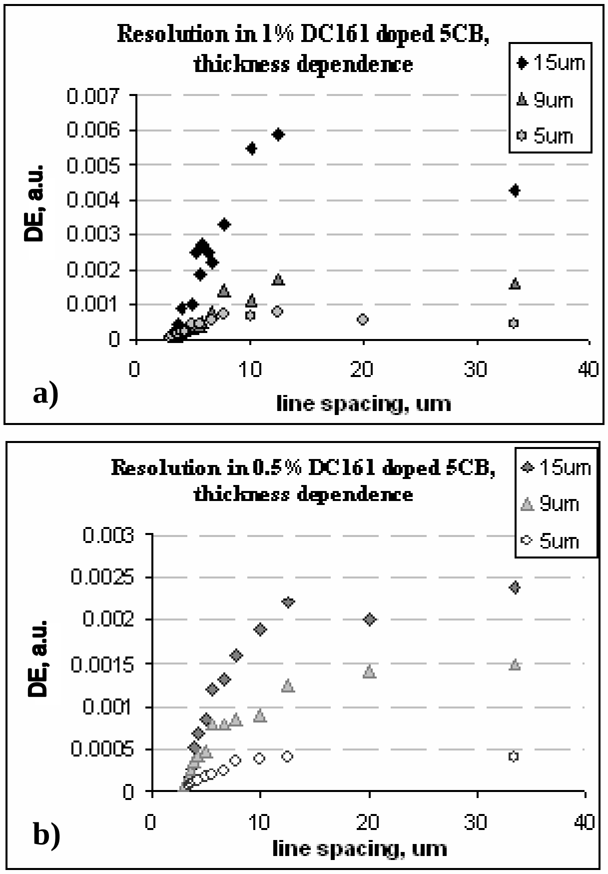


$$\vec{E}_{read} \parallel \vec{E}_{write} \parallel \textit{LC director } \vec{n} \parallel \textit{grating vector } \vec{k} \parallel x$$

Fig. 2. Experimental setup for holographic grating formation experiment. Diffraction is in xz plane.



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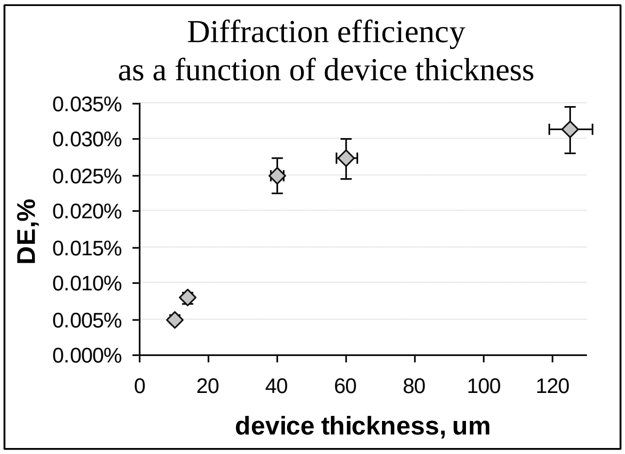

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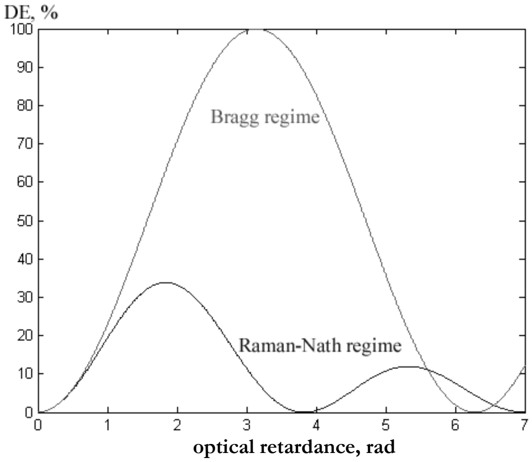

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