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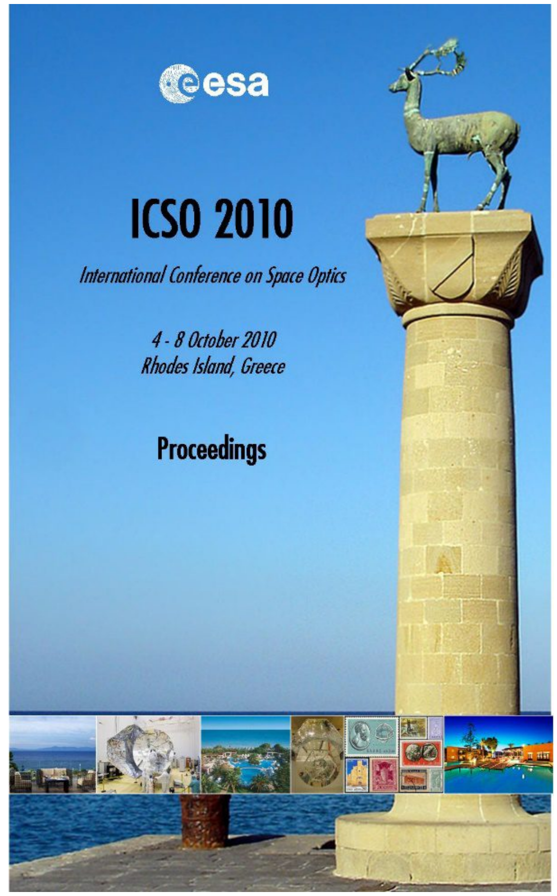

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DEVELOPMENT OF LIQUID CRYSTAL BASED ADAPTIVE OPTICAL ELEMENTS FOR SPACE APPLICATIONS

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I. ABSTRACT:

In this paper we present the results obtained within the context of the ESA-funded project Programmable Optoelectronic Adaptive Element (AO/1-5476/07/NL/EM). The objective of this project is the development of adaptive (reconfigurable) optical elements for use in space applications and the execution of preliminary qualification tests in the relevant environment.

The different designs and materials that have been considered and manufactured for a 2D beam steerer based on passive matrix liquid crystal programmable blaze grating will described and discussed.

II. INTRODUCTION

Over the last decade photonics has been playing an ever increasing role in space applications, in contexts as diverse as in inter and intra satellite communications, remote sensing (*e.g* LIDAR), lunar descent and landing and rendezvous and docking. Photonic devices have the big advantage over the conventional technologies that they are intrinsically free of moving parts, which are prone to fail as a result of the harsh launch and space conditions. Furthermore, photonic devices are, as a rule, characterised by a much reduced pay load, a small footprint and are, in the case of liquid crystals(LC), working with very low electrical fields and currents, which result in a low power consumption, and thus a minor need for heat dissipation.

The UPM laboratory has developed very low power consumption retro-moduladores for wireless optical communications [1], been involved in the manufacturing of reconfigurable optical retarders for the Solar Orbiter and has developed beam-steerers, and configurable lenses within the framework of the above mentioned ITT. All of these devices have been based on liquid crystal technology. Furthermore the consortium as a whole or in parts has been involved in numerous certification studies of photonic devices funded by ESA.

III. BEAM STEERING

Three generic 3-D optical technologies for beam steering are commercially available today: micro electro mechanical systems (MEMS, or "micro mirrors") [www.dlp.com], deformable mirrors [www.OkoTech.com] and miniature silicon back-plane liquid crystal spatial light modulators (SLMs) [www.Holoeye.com], often referred to as LCoS (liquid crystal on silicon) SLMs. All are well suited to the design and fabrication of large-capacity 3-D optical space switches in optical communications, requiring 2-D high-resolution beam-steering matrices. However, they are based on two different principles to route the light paths: beam steering by a micromirror and beam diffraction by a pixelated LC SLM. Either technique has its own advantages: Micro mirror arrays have low loss and are intrinsically polarization and wavelength insensitive. In contrast, LC SLMs (or LC digital hologram, LCDH) operate with no moving part and can be configured for a wide range of switching topologies. This property is due to the large available spatial bandwidth (in two dimensions) of digital holograms, which can be used not only to steer or route the optical signals, but also to provide additional functions, such as focusing or adaptive wavefront correction. [2].

In contrast to the deformable mirrors (DMs), an SLM is highly pixelated and thus capable of introducing changes in phase with a high spatial resolution. Although the phase range of any individual pixel is approximately 2π, using phase-wrapping techniques the overall phase-change to a wavefront of many times 2π is possible, limited only by the number of pixels in the SLM. An SLM used in this way acts as a diffractive optical element where the desired phase change occurs mainly in the first diffraction order. Consequently, an SLM with the potential for phase discontinuities has an effective stroke of many tens of wavelengths. However, the SLM is slower to update than a DMs (standard twisted SLMs have a refresh rate of approximately 30Hz).

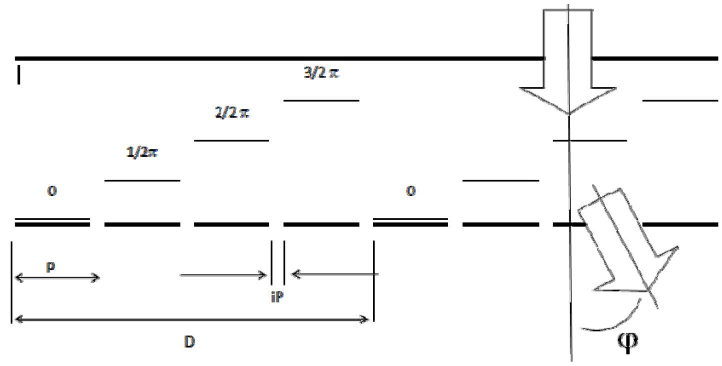

Fig. 1. A 4 step Blazed Grating. P :Pixel Pitch, iP:InterPixel, D:"Prism Pitch" φ : Steering angle

Being a diffractive element the efficiency of guidance depends on the applied pattern. The worst case scenario corresponds to a simple binary phase grating where only 40% of the energy is guided towards the first (positive) order of diffraction. Changing the pattern to a 4 step sawtooth pattern – *a blazed grating* – increases this number in theory to 81%. In this number (derived from the efficiency equation $\eta = \left(\frac{\sin(\pi/q)}{\pi/q}\right)^2$, where a 2π retardation device is assumed and q represents the number of steps in the pattern) ignoring any loss originating in the interpixel space [3]. Assuming a reflective device capable of introducing a phase difference of minimum 1064nm per path, a deviation of ±2º at 1064nm can be achieved with pixel pitch sizes in the order of 7.5μm, using a 4 step sawtooth pattern.

Existing commercial implementation of the LCOS SLMs uses a LCOS backplane taken directly from the display manufacturing. The pitch of high end devices is in the order of 8μm with fill factors of approximately 97% (www.holoeye.com). This configuration with a 4-step sawtooth (η–theoretical = 81%) pattern gives a deviation angle of roughly 1.8º for a device capable of introducing 2π phase difference @ 1064nm. This deviation can be increased using various techniques externally such as bend mirrors and prisms, which will affect the quality of exiting light beam.

Boulder Nonlinear Systems (BNS), Colorado USA, has for a long time been leading the commercial development of LC based SLM systems, and has contributed significantly to the scientific progress in the area *e.g.* [4, 5]. One product of special interest to this project is their high resolution 1D (Liquid Crystal on Silicon) LCoS based SLM (1.6μm pitch with 1μm electrodes and 0.6μm inter electrode gap). A dielectric mirror coating has been applied on top of the electrodes in order to increase the reflectivity of the device and to mask the diffraction pattern otherwise caused by the electrodes.

Like in other LCoS, the photonic device is a compact package in which the LC is situated directly on top of a very-large-scale integration) silicon chip. Although having an enviable small footprint, this design has one basic feature disqualifying it for space applications: The silicon chip is place right in the active area of the device, and hence it will be subjected to radiation which will jeopardise the longevity of the device. This apart from the elevated costs in producing a fully integrated chip made us look towards alternative solutions.

IV. DESIGN CONSIDERATIONS

A. Substrate

In light of the above considerations LCoS devices were discarded a priori. Likewise the radiation stability of thin-film-transistors, commonly employed in liquid crystal displays, is to the knowledge of the authors an unknown, and thus passive matrix consisting of simple ITO tracks with external addressing was decided upon.

It was assumed that the ideal substrate would be ITO covered fused silica. In order to confirm this assumption gamma-radiation testing was done according to ESCC Basic Specification No. 22900 [RD1], at the CIEMAT Náyade Cobalt-60 installation. Both individual substrates –1 mm silica and 1.1 mm ITO covered selected float glass (CEC020-S, Praezisions Glas & Optik GmbH)– and mounted cells with both homogenous and vertically aligned in both substrates were radiated, and subsequently characterised. Surprisingly no significant change in transmission nor in the electrooptical response, was detected even after 80krad. Thus it was decided to employ standard float glass instead of the much more expensive fused silica.

B. Liquid crystal

Nematic liquid crystals are rod-shaped molecules that tend to self assembly so that all the rods are pointing in the same direction, creating a macroscopic uniaxial structure, which generally is highly birefringent. The relaxed state orientation of the molecules in a device is normally governed by the alignment conditions on the two boundary substrates. When subjected to an electrical field the liquid crystals will reorient according to the electric field lines and the dielectric anisotropy of the material.

In conventional homogenous nematic liquid crystals the optical and electrical anisotropy are both positive, and thus the optical axis tends to align itself with the applied field. For that reason the electrode carrying substrates are treated so that the LC molecules are laying parallel to the substrates in absence of an electric field. When a field is applied to the cell, the LC molecules will rise, depending on the field strength and the anchoring force that keeps them parallel to the substrates. The device will have maximum birefringence, and thus maximum refractive index for light polarised along the molecules, when no field is applied.

In some materials the optical anisotropy is positive and electrical anisotropy is negative. One aligns the molecules quasi perpendicular (vertically, hence the name vertically aligned nematics–VANs) to the substrates, and forces the molecules to lay down by applying an electric field. By introducing a slight tilt, one predefines the direction in which the LC will switch, the *switching plane*.

In terrestrial display applications, VAN materials are typically employed since they respond quicker than the conventional homogenously aligned nematics and they suffer less from crosstalk between separate pixels in the display. In phase devices, this advantage is less pronounced since the thickness of the cells is several times that of a display. VAN devices however, have the advantage that in their relaxed vertical state absorb less UV light, and thus their liability towards UV damage is assumed to be reduced [6].

Hence the baseline for the developed device became the VAN materials.

B. Alignment

Conventionally the alignment direction, and thus the switching plane, in LC devices is defined by the rubbing or polarised polymerisation of an organic polymer, typically nylons, imides or azo-compounds. The advantage of these technologies is that a large variation of compounds exists so that any commercial LC may be aligned. However, being “soft” organic materials, the polymer based alignment layers, are susceptible to rupture, or reorientation caused by crystalisation of the LC at low temperature.

For this reason inorganic alignment layers are preferred as alignment layer. Obliquely deposited oxides tend to grow micro crystals generating a regular three dimensional structure which aligns the liquid crystal molecules. In the past we have employed thermally deposited non-stoichiometric silicon-oxide (SiOx) to align a long list of ferroelectrics, antiferroelectrics and moderately low birefringent nematics ($\Delta n<0.1$) both homogeneous (*e.g.* Merck E7) and VANs (*eg.* Merck 6608) [7]. As a result of this study we have discovered that SiOx, does not align higher birefringence materials, and thus it was decided to employ e-gun deposited silica (SiO_2). This material has been employed in high flux LC based projectors, and has been shown to align VAN materials with birefringence as high as 0.17 (Merck 7029) –at least in thin cells [8].

Inorganic alignment layers, in the finished mounted cell, are as inert and solid as the overall construction. But during the assembly of the cell, they are extremely sensitive to the adsorption of organic materials changing the VAN alignment. The outgassing of the gasket material, gluing the cell together, during the curation, is thought to be the main source of the organic contaminants.

Currently significant resources are being invested in solving this problem, and are using a work around employing homogenous LC with a low freezing point (Merck MDA-98 and BL006) with polyimide alignment layer, recognising the limitations caused by employing organic alignment layers, and homogeneous alignment.

C. Driving and interconnection

Using passive ITO tracks means that all addressing of the pixels will be done by an easily shielded external processor. The initial approach was to connect all tracks directly to an external PCB, in which already space certified circuitry would be employed for the addressing. This approach was prevented by the lack of European PCB suppliers willing to provide boards with 50µm pitch. Thus instead the alternatives of mounting an integrated circuit directly on the substrate (Chip-on-glass) or on high resolution flexible circuit substrates (Chip-on-flex) have been employed. In the end, for purely manufacturing reasons, we have opted for the Chip-on-flex solution. After a careful analysis of the available drivers, the Solomon 1783 chip was chosen as a prototype chip. The selection was done on the basis that the chip did not include high resolution circuitry, and that it provided an ample voltage range (19V) sufficiently large for addressing any kind of nematic LC.

The interconnection between the driver circuit and the ITO tracks is done using anisotropic-conducting-adhesive (ANISOLM®, AC-8955YW-23) kindly provided by Hitachi Chemicals Europe, following the recommendations of the manufacturer.

V. MODELLING

In order to design the beam steerer to meet the specifications, a modelling tool has been developed in the Labview environment. Employing the approximation that the LC switching is constant over the electrode, introducing a constant phase retardation, and that the phase transition of the interpixel space is the average of the two electrodes we predict a diffraction efficiency which is slightly superior to the above mentioned sinc formula. In the case of the four step function an efficiency close to 84% is being predicted

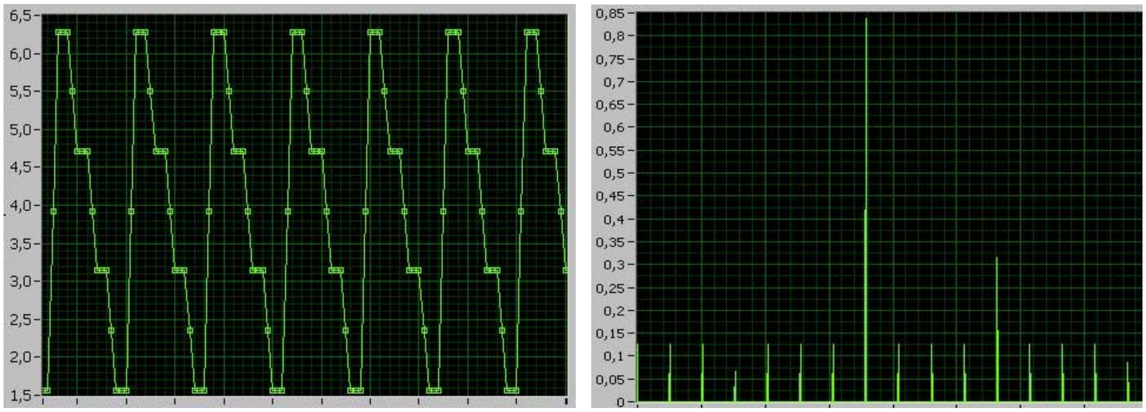

Fig. 2. The four step function simulating the LC behaviour in a device with a 3:1 ration be with the resulting Fourier transform showing a 84% diffraction efficiency.

VI. CONCLUSION

A beam steerer that is foreseen to be able to withstand space radiation has been designed. The predicted behaviour of the device complies with most of the requirements as defined by the ITT which is funding the development, apart from the aspect of transmission where the ITO covered substrates are expected to transmit less than the required 80%. The diffraction efficiency of the 2D beamsteerer, will be reduced by cascading two 1D devices, and is expected to be in the order of 65%.

We have proposed the optimal design of a LC based device, and designed a work around which has been realised, although not characterised at the moment of writing this article.

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