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Program

Abstracts

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UNIVERSITAT_{DE}
BARCELONA

Co-chairs:

Bahram Javidi, University of Connecticut

Santiago Vallmitjana, Universitat de Barcelona

Artur Carnicer, Universitat de Barcelona

Invited speakers

Justo Arines	Is wavefront coding an alternative to adaptive optics for retinal imaging?
Yasuhiro Awatsuji	3D image reconstruction of transparent gas flow by parallel phase-shifting digital holography
Karl-Heinz Brenner	Verification of Near-field Calculations by Conservation Laws
Juan Campos	Beam amplitude and polarization control by liquid crystal cells
Yeshaiahu Fainman	Nanoscale Engineering Optical Nonlinearities and Nanoemitters
Thierry Fournel	Towards weak optical PUFs by random spectral mixing
Jesper Glückstad	Light Robotics: bridging optics with the nano-world
Hans Peter Herzig	Optics in 2D, Bloch surface wave phenomena and applications
Takashi Inoue	Applications of spatial light modulators in biomedical imaging
Toru Iwane	Light-field displays and Light-field Optics
Bahram Javidi	Multidimensional Optical Sensing and Imaging for Displays, Computational Imaging, Optical Security, and Healthcare
Rainer Leitgeb	Digital aberration correction for in-vivo retinal OCT imaging
Abhijit Mahalanobis	Pixel Resolution Improvement using a Sliding Mask
Pierre Marquet	Quantitative phase-digital holographic microscopy: a new imaging modality to identify original cellular biomarkers of diseases
Andres Marquez	Effective modeling of Pa-LCoS devices and application in data storage in photopolymers
Estela Martín-Badosa	Force measurement in the manipulation of complex samples with holographic optical tweezers
Manuel Martínez-Corral	Full-parallax immersive 3D display from depth-map cameras
David Maluenda	Non-Uniform Polarized Beams: Applications to Optical Encryption
Osamu Matoba	Multi-modal Digital Holography for Live Cell Imaging
Maria S. Millan	Image quality and security through nonlinear joint transform encryption
Dongkyung Nam	Analysis of Blur Characteristics on 3D Displays
Jean-Christophe Olivo-Marin	Mathematical Microscopy
Pepijn Pinkse	Pushing the limits of single-photon information encoding
Filiberto Pla	Range estimation techniques from Integral Imaging
Demetri Psaltis	Learning from examples in optical imaging
Jose A. Rodrigo	Freestyle laser traps: applications and future outlook
José Manuel Rodríguez-Ramos	Real time phase compensation using a Tomographical Pupil Image Wavefront Sensor (TPI-WFS)
Sergio Saez	SECPhO: connecting light, with industry
Toralf Scharf	Lightfields behind amplitude masks
Jung-Young Son	Light fields from digital hologram displays
Adrian Stern	A decade of implementation of compressive sensing concepts to optical and imaging systems
Enrique Tajahuerce	Imaging through scattering media by microstructured illumination
Simon Thibault	Non paraxial light propagation for high resolution imaging
Zeev Zalevsky	Super-resolved imager with nanometric resolution based on silicon coated gold nanoparticles

Invited talk

Effective modeling of PA-LCoS devices and application in data storage in photopolymers

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Abstract—Parallel aligned liquid crystal on silicon (PA-LCoS) devices are widely used in many optics and photonics applications to control the amplitude, phase and/or state of polarization (SOP) of light beams. We present a novel model enabling to calculate the voltage dependent retardance provided by PA-LCoS devices for a very wide range of incidence angles and any wavelength in the visible. To our knowledge it represents the most simplified approach still showing predictive capability. We are particularly interested in the application of PA-LCoS microdisplays as the data pager in holographic data storage systems (HDSS). In this work we show both theoretical and experimental results addressing hybrid-ternary modulated (HTM) data pages and using our in-house produced PVA/AA photopolymer as the storage material. We demonstrate that PALCoS devices cannot implement pure HTM but a rather close approximation. Experimental results with PVA/AA show biterror rates (BER) in the range of the threshold for potential application in HDSS (about 10^{-3}).

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Abstract—Parallel aligned liquid crystal on silicon (PA-LCoS) devices are widely used in many optics and photonics applications to control the amplitude, phase and/or state of polarization (SOP) of light beams. We present a novel model enabling to calculate the voltage dependent retardance provided by PA-LCoS devices for a very wide range of incidence angles and any wavelength in the visible. To our knowledge it represents the most simplified approach still showing predictive capability. We are particularly interested in the application of PA-LCoS microdisplays as the data pager in holographic data storage systems (HDSS). In this work we show both theoretical and experimental results addressing hybrid-ternary modulated (HTM) data pages and using our in-house produced PVA/AA photopolymer as the storage material. We demonstrate that PA-LCoS devices cannot implement pure HTM but a rather close approximation. Experimental results with PVA/AA show bit-error rates (BER) in the range of the threshold for potential application in HDSS (about 10^{-3}).

Keywords—LCoS; parallel-aligned; holographic data storage; photopolymer; birefringence, spatial light modulators.

I. INTRODUCTION

Parallel-aligned liquid crystal on silicon (PA-LCoS) microdisplays are used as spatial light modulators (SLM) in many optics and photonics applications since they enable the more energetic efficient phase-only operation without amplitude coupling [1]. They can be assimilated to linear variable retarders, and as such are characterized by their linear retardance. Recently, we demonstrated a novel characterization method based on time-average Stokes polarimetry [2], able to provide robust and precise measurement of the linear retardance value even in the presence of flicker, exhibited by electrooptic devices such as LCoS displays.

Accurate calculation of the performance of liquid-crystal cells is possible when the different physical parameters characterizing the LC material and the LC cell are known [3]. However, most of the time users of LC devices have not access to this detailed information. Then more simplified models and/or reverse-engineering approaches, enabling analytical expressions, are then highly desirable. In this sense recently we demonstrated a novel model [4] which, through a reverse-

engineering approach, is able to provide with a good accuracy the linear retardance value versus applied voltage as a function of both the incidence angle and the illuminating wavelength for PA-LC devices. The model is based on only three physical parameters whose values are obtained without ambiguities by fitting a limited amount of calibration measurements.

A very exciting field of application of SLMs is holographic data storage systems (HDSS), which enables true 3-D storage of information and also associative memory retrieval. Many scientific and engineering aspects need to be addressed for HDSS to be viable in the commercial arena as reported recently by Anderson et al. [5], with long time archival storage as the main application in focus nowadays. Impact of ongoing advances in SLM technology, and specifically in PA-LCoS microdisplays needs to be explored.

Since PA-LCoS enable phase-only operation, they are ideal for binary or multinary phase-only data pages which leads to DC term cancellation when recording the Fourier transform of the data page. Recently we showed [6] that more conventional binary intensity modulated (BIM) data pages provide a viable performance with PA-LCoS devices in HDSS. Hybrid-ternary modulation (HTM) [7] is another scheme which combines the ease of detection of BIM pages together with DC term cancellation of phase-only modulation. In [6] we studied the challenges, both theoretical and experimental to be faced.

One of the most demanding components in HDSS is the recording material. Among photopolymers, polyvinil alcohol/acrylamide (PVA/AA) materials combine good optical properties, ease of fabrication, self-development capability and they offer the capability to establish thick recording layers. Efforts have been done in order to optimize this material for holographic memories [7]. Some promising results were shown in [6], where a PVA/AA photopolymer compound in combination with BIM and the HTM data pages was analyzed in our holographic memory testing platform.

In this work we present some of the latest results obtained by the Holography and Optical Processing group in the interrelated research lines dealing with the modeling of PA-LCoS devices, in Section II, and its application, together with photopolymers, to HDSS, in Section III.

II. PA-LCoS MODEL

A. Theory

Figure 1. Diagram for the PA-LC cell considered in the model proposed.

Next we introduce our simplified model for PA-LC devices. Its general diagram is presented in Fig. 1, where we explicitly consider a reflective cell with a cell gap d . Incidence plane and LC director are along the XZ plane. LC molecules have their director axis (optical axis) aligned at an angle φ with respect to the traversing light beam direction. θ_{LC} is the refraction angle in the LC medium. When a voltage V is applied the director axis tilts an angle α with respect to the entrance face. This is the only voltage dependent magnitude, i.e. $\alpha(V)$. At the backplane the light beam is reflected and a second passage is produced across the LC layer whose effect is equivalent to a forward propagation at an angle $-\theta_{inc}$. In the model we define two off-state parameters, combination of the LC indexes ordinary and extraordinary, n_o and n_e , together with the cell gap d . They are $OPL = dn_o$ and $OPD = d\Delta n$, which correspond respectively to the magnitudes of the optical path length for the ordinary component and the optical path difference between extraordinary and ordinary components. Proper derivation in [4] leads to the following analytical expression for the retardance,

$$\Gamma = \frac{2\pi}{\lambda} \frac{OPL}{\cos \theta_{LC}} \left[\frac{1 + (OPD/OPL)}{1 + (OPD/OPL) \cos^2 \varphi} - 1 \right] \quad (1)$$

According to Fig. 1, angle φ is given by,

$$\varphi(\theta_{inc}, V) = \frac{\pi}{2} + \alpha(V) \mp \theta_{LC}(\theta_{inc}) \quad (2)$$

, where the minus (plus) sign applies for the forward (backward) passage. The total retardance in the PA-LCoS is given the addition of the forward and backward retardances. In the case of normal incidence and LC director axis parallel to the entrance face, then Eq. (1) simplifies into the well-known expression $\Gamma = 2\pi d\Delta n/\lambda$.

B. Results

The specific PA-LCoS device considered in this work is a commercially available PA-LCoS microdisplay, model PLUTO distributed by the company HOLOEYE. It is filled with a nematic liquid crystal, with 1920x1080 pixels and 0.7" diagonal. The retardance measurements are obtained applying the time-average Stokes polarimetric technique [2]. Both off and on-state retardance measurements have been taken at various angles of incidence (3°, 23°, 35° and 45°) and for three wavelengths (473, 532 and 633 nm) sampling the visible spectrum. We used the measurements taken at 3° and 35° for calibration of the model parameters through an optimization procedure. Measurements at 23° and 45° validated the predictive capability of the proposed model as shown in [4].

Figure 2. Theoretical results for the retardance dynamic range: (a) Vs. wavelength, for three incidences; (b) Vs. incidence, for the three wavelengths.

Once verified the predictive capability of the model, we investigate some of the possibilities it offers. We fit the extended Cauchy relation $A + B/\lambda^2 + C/\lambda^4$ to the *OPD* values obtained for the three wavelengths. In the case of the *OPL* values simply a linear interpolation is applied. In this way we are able to obtain the retardance not only for a wide range of incidences (till 45°) but also for the wavelengths in the visible region of the spectrum and for each of the voltages (gray levels) applied. The retardance dynamic range, difference between the maximum and minimum retardance for a specific wavelength at a specific incidence angle, is usually the magnitude of interest in spatial light modulation applications, e.g. to display phase-only blazed gratings or diffractive lenses a 360° retardance dynamic range is needed. In Fig. 2 we plot the retardance dynamic range for 3 specific incidence angles and as a function of the visible spectrum wavelengths.

III. APPLICATION TO HOLOGRAPHIC DATA STORAGE

A. Data page modulation with the PA-LCoS

PA-LCoS as the data pager in HDSS can be applied to produce different modulation regimes. Next we focus on HTM, which is very much demanding on the phase and amplitude modulation properties of an SLM and which to our knowledge was first studied in [6] with PA-LCoS devices. First, we calibrate the linear retardance with the time-average Stokes polarimetric technique [2], and then we use these values to calculate the complex amplitude modulation of the PA-LCoS device inserted between linear polarizers. We use the Jones formalism for polarization, since it enables calculation of both the amplitude and phase-shift. Specific retardance measurements have been taken at an angle of incidence of

11.5° and for the wavelength 532 nm, to which the PVA/AA photopolymer is sensitized. These are the working conditions of the PA-LCoS device in the HDSS setup. The PA-LCoS device is addressed with electrical configurations minimizing the possibility of flicker. Further details in [6].

HTM requires three gray level values, two of them with a high and equal intensity transmission and with a 180° relative phase-shift (ON levels), and a third gray level with a low intensity transmission (OFF level). After performing a series of optimizations and simulations we have found that the PA-LCoS device cannot fully meet these requirements. We have found that the trajectory in the complex plane is always a circle (Fig. 3). This means that if the OFF level is close to the origin, two equidistant points in the circle with a 180° phase-shift difference and with some intensity transmission are not possible. A compromise can be found if the circular trajectory is slightly shifted at the cost of producing some leakage of light in the OFF value. Therefore, PA-LCoS devices do not produce a pure HTM modulation, but they enable an approximate trade-off, which we call pseudo-HTM modulation (pHTM). In Fig. 3 we show the complex amplitude modulation for one of the possible pHTM configurations obtained in our simulations. It corresponds to input and output polarizers at 55° and -45° with respect to lab vertical. We plot the phasor evolution in the complex plane where we see that the circular trajectory is not traversing the origin. Phase-shift difference between the ON values is 206° and intensity contrast is 1:10.

Figure 3. Simulation for pHTM. Phasor evolution in the complex plane. Input and output polarizers at +55° and -45° with respect to the vertical of the lab.

B. Holographic memory results with PVA/AA photopolymer

The PVA/AA photopolymer composition we use in the HDSS is similar to the one used in previous works [8]. This photo-chemical composition is characterized by the presence of yellowish eosin (YE) as dye and N,N'-methylene-bis-acrylamide (BMA) as crosslinking monomer. It also contains a co-sensitizer which is triethanolamine (TEA), the acrylamide (AA) monomer and the PVA as a binder. The thickness of the samples is around $90 \pm 2 \mu\text{m}$ and the refractive index modulation achieved for a single holographic grating with a spatial frequency of 1150 lines/mm is 0.005. Thicker samples can be prepared with PVA/AA photopolymer, which is necessary when multiplexing many data pages. We concentrate on the results obtained when the pseudo-HTM data page is addressed. In Fig. 4 we show the retrieved results when no photopolymer is in the system, i.e. only the effect of the setup and implementation on the PA-LCoS is considered, achieving a BER of $2.0 \cdot 10^{-3}$. When the photopolymer is used to record the pHTM data page, then a BER of $5.6 \cdot 10^{-2}$ is obtained.

Fig. 4. Experimental results pHTM data page and no material. (a) Data page; (b) Histogram.

IV. CONCLUSIONS

We presented a novel model enabling to calculate the voltage dependent retardance provided by PA-LCoS devices for a very wide range of incidence angles and any wavelength in the visible. Then, we have also shown that pure HTM data pages cannot be obtained with PA-LCoS devices, however, a rather close performance is obtained when implementing the pseudo-HTM data pages. Experimental results with PVA/AA show bit-error rates (BER) in the range of the threshold for potential application in HDSS (about 10^{-3}).

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REFERENCES

- [1] Z. Zhang, Z. You, D. Chu, "Fundamentals of phase-only liquid crystal on silicon (LCOS) devices", *Light: Science & Applications*, vol. 3, pp. 1-10, 2014.
- [2] F. J. Martínez, A. Márquez, S. Gallego, M. Ortuño, J. Francés, A. Beléndez, and I. Pascual, "Averaged Stokes polarimetry applied to evaluate retardance and flicker in PA-LCoS devices," *Opt. Express*, vol. 22, pp. 15064-15074, 2014.
- [3] P. Yeh, C. Gu, *Optics of Liquid Crystal Displays*. New York: John Wiley & Sons Inc, 1999.
- [4] F. J. Martínez, A. Márquez, S. Gallego, J. Francés, I. Pascual, A. Beléndez, "Effective angular and wavelength modelling of parallel aligned liquid crystal devices," *Opt. Lasers Eng.*, vol. 74, pp. 114-121, 2015.
- [5] K. Curtis, L. Dhar, A. Hill, W. Wilson and M. Ayres, Eds., *Holographic Data Storage: From Theory to Practical Systems*. Chichester: John Wiley & Sons, Ltd, 2010.
- [6] F.J. Martínez, R. Fernández, A. Márquez, S. Gallego, M. L. Álvarez, I. Pascual, and A. Beléndez. "Exploring binary and ternary modulations on a PA-LCoS device for holographic data storage in a PVA/AA photopolymer," *Opt. Express*, vol. 23, pp. 20459-20479, 2015.
- [7] E. Fernandez, A. Márquez, S. Gallego, R. Fuentes, C. García, and I. Pascual, "Hybrid ternary modulation applied to multiplexing holograms in photopolymers for data page storage," *J. Lightwave Technol.*, vol. 28, pp. 776-783, 2010.
- [8] S. Gallego, A. Márquez, S. Marini, E. Fernández, M. Ortuño, and I. Pascual, "In dark analysis of PVA/AA materials at very low spatial frequencies: phase modulation evolution and diffusion estimation," *Opt. Express*, vol. 17, pp. 18279-18291, 2009.