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LCoS SPATIAL LIGHT MODULATORS AS ACTIVE PHASE ELEMENTS OF FULL-FIELD MEASUREMENT SYSTEMS AND SENSORS

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Abstract

Spatial light modulators (SLM) are devices used to modulate amplitude, phase or polarization of a light wave in space and time. Current SLMs are based either on MEMS (micro-electro-mechanical system) or LCD (liquid crystal display) technology. Here we report on the parameters, trends in development and applications of phase SLMs based on liquid crystal on silicon (LCoS) technology.

LCoS technology was developed for front and rear projection systems competing with AMLCD (active matrix LCD) and DMD (Digital Mirror Device) SLM. The reflective arrangement due to silicon backplane allows to put a high number of pixels in a small panel, keeping the fill-factor ratio high even for micron-sized pixels.

For coherent photonics applications the most important type of LCoS SLM is a phase modulator. In the paper at first we describe the typical parameters of this device and the methods for its calibration. Later we present a review of applications of phase LCoS SLMs in imaging, metrology and beam manipulation, developed by the authors as well as known from the literature. These include active and adaptive interferometers, a smart holographic camera and holographic display, microscopy modified in illuminating and imaging paths and active sensors.

Keywords: spatial light modulators, liquid crystals on silicon, phase modulation, optical metrology, active interferometry, active microscopy, digital holography.

1. Introduction

The advent of spatial light modulators (SLMs) has contributed enormously to various applications in photonics during the last years. SLMs became increasingly popular in optics due to technological improvements such as reduction in the physical dimensions, improvement in the resolution, large fill factor, fast time response, whilst being economically accessible. In particular the versatility of SLMs based on liquid crystal (LC) and silicon materials made these devices applicable to biology and industrial inspection.

Liquid crystals are outstanding materials for SLMs because of their inherent property of very large birefringence and their facility to control the alignment of the molecules using an electric field [1].

SLMs exploit these features by fabricating matrices of micrometer LC containers (pixel size is typically as small as 8-32μm [2]) called liquid crystals on silicon (LCoS) devices [3]. Each pixel has a thin polymer layer to set boundary conditions by inducing an initial alignment to the rod-like shape liquid crystal molecules. The refractive index is controlled by applying different voltage levels to reorient the molecules resulting in a variable phase modulation [4].

In LCoS SLMs it is possible to modulate amplitude, phase and/or polarization by using different configurations in the initial LC alignment in addition to polarization elements. The three most known LCs configurations are homeotropical (perpendicular to the substrate),

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parallel to the substrate and twisted (helix-like structure) [5]. In the paper we focus on phase only modulators with fast response and high spatial resolution. The most suitable and common LC alignment configuration for phase only modulation in LCoS SLMs is the parallel one, as LC cells with this configuration can be understood as voltage-controlled waveplates. Actually, SLMs based on LC technology offer the option to modulate phase in a range of 0-2π (or more, depending on the wavelength) having a millisecond response [6]. These capabilities make LCoS an appropriate solution for multiple applications in optics.

In adaptive optics LCoS SLMs are configured as deformable mirrors and made possible the compensation of aberrations in astronomical images [7]. Similarly, LCoS modulators are used nowadays to estimate aberrations in human eyeswith high accuracy and fast time response [8]. They are also crucial in active phase contrast microscopy, where phase filtering is induced to visualize transparent biological specimens and to actively enhance the contrast in the images. A remarkable contribution is observed for the case of digital holography, where LCoS enables accurate quantitative phase measurements in microscopy [9] and futuristic applications in 3D real-time display and video [10]. Optical tweezers and particle manipulation techniques have also been benefited from the advent of LCoS SLMs [11] by producing structured beams [12] for e.g. the study of biological samples or 'lab-on-a-chip' applications [13]. In metrology, SLMs have contributed to improve phase measurements by utilizing an active reference beam which can perform accurate phase shifts and remove deformations in the wavefront.

For their high performance and versatility, LCoS SLMs have gained interest within the scientific community and became popular for technological applications. However, a profound knowledge of the performance of this device is crucial to achieve the precision and efficiency expected. The liquid crystal's nature itself and the fabrication process introduce an uncertainty in the phase modulation. However, these imperfections are not the only inconvenience. The illumination angle, wavelength and polarization are restricted to certain range of values [14], otherwise it is possible to observe wavefront aberrations, depolarization of the illumination beam, etc. Consequently, an individual characterization and calibration are mandatory for each LCoS system. The performance of the optical system strongly depends on the careful calibration of the LCoS that is used for any particular application.

In this paper we describe the typical parameters of a phase LCoS SLM and the methodology for its calibration in relation to our experience, as shown in Section 2. Section 3 presents a review of applications of phase LCoS SLMs in microscopy, metrology, imaging, beam manipulating and digital holography that have been developed by the authors as well as are known from the literature. Finally, in Section 4 the conclusions and final remarks of this work are presented.

2. Properties and calibration methods

As mentioned above, the electrically controllable LC birefringence enables the possibility to modulate amplitude, phase and/or polarization of the incident beam [4]. Actually, the ultimate goal of SLMs is to achieve precise and fast control of all three variables. Nevertheless, the current technology still suffers the lack of such capabilities and most of the devices accurately modulate one of these attributes. In this Section the parameters of transmissive and reflective SLMs based on LCs are contrasted. The LC parameters used in LCoS SLMs are described and the reasons to perform a careful calibration for each LCoS modulator are presented.

The parameters of transmissive and reflective modulators differ between each other due to different manufacturing technology. SLMs based on LC materials consist of an array of pixels that contains a LC layer sandwiched between two flat electrodes to control its alignment by a potential difference. The plates are transparent (glass plus a transparent conductive layer) or reflecting (silicon) and initial alignment of the nematic molecules are set due to a thin polished polymer layer. A single SLM's pixel is built by placing LC material between two transparent electrodes for the transmissive modulator. For a reflective one (LCoS SLM) the combination of a transparent and a reflecting plate is utilized.

An advantage is observed for the case of reflective SLMs because light passes twice through the LC layer. This fact increases the modulation range and makes them suitable to be used as phase modulators for the visible and near IR range [15]. The diffraction efficiency is higher for the phase mode than for the amplitude one, and for bigger values of fill-factor [16]. LCoS SLM technology delivers a high fill-factor with small pixel pitch and high resolution.

Both transmissive and reflective SLMs have the same modulation bit depth, image frame rate and signal format as in conventional LC displays. Thanks to that, LC SLMs offer an easy way to address and modify its parameters just by the use of a conventional PC. The choice of LC SLMs modality depends on the application, however due to its large modulation range and geometrical parameters LCoS SLMs offer more possibilities.

Table 1 shows a comparison of an exemplary transmissive and a reflective LCoS SLM. The comparison is performed for the most common used devices (at least in Europe) provided by Holoeye Photonics AG [17].

Table 1. Comparison between transmission and reflective liquid crystals SLMs (Holoeye Photonics AG).

	Transmissive liquid crystal microdisplay	Reflective liquid crystal microdisplay (LCoS SLM)
Modulation	Amplitude or Phase	Amplitude or Phase
Modulation Range	2π Phase Shift @ 532 nm	2π Phase Shift up to1064 nm
Panel size	21 mm x 26 mm	15.36 mm x 8.64 mm
Resolution	832 x 624	1920 x 1080
Pixel Pitch	32 μm	8 - 32 μm
Fill Factor	55%	87%
Optical Flatness	Not specified	3-4 lambda 633 nm (after correction lambda/2)
Image Frame Rate	60 Hz	60 - 180 Hz
Depolarization	Not specified	<1% (for nearly normal illumination)
Addressing	8-bit	8-bit
LC Type	Twisted Nematic	Twisted and Parallel Nematic
Voltage	0-5V	0-5V
	Transmissivity: 27%	Reflectivity: 59-63% @ λ= 405-1064 nm
Driver Software	Geometry / Gamma Control	Geometry / Gamma Control
Special Optical Features	Intensity Ratio of 1000:1 @ 633 nm Coherent Light Source	Extended Wavelength Range up to 1550 nm 1000:1 @ 633 nm Coherent Light Source

Some of these parameters may vary and/or depend on the control parameters, so the calibration of LCoS SLMs is crucial in order to obtain high performance in optical systems where phase only modulators are required. It is worth to mention that the accuracy of the phase modulation is closely related to the applied voltage, the wavelength, polarization and incident angle illumination. Additionally, during the manufacturing process it is essential to obtain a uniform LC alignment.

Let us consider the most convenient LC molecular alignment for phase modulation i.e. the parallel configuration. As shown in Fig. 1 the LC molecular alignment tends to go from parallel to perpendicular with respect to the substrate by applying voltage. It is clear that upon transmission through this cell, linearly polarized light is retarded as a function of the voltage-controlled birefringence. However, the direction of polarization needs also to be considered.

Unfortunately, the molecular reorientation in the LC layer does not follow a linear behavior in relation to the voltage. This results in a nonlinear control of the phase retardance.

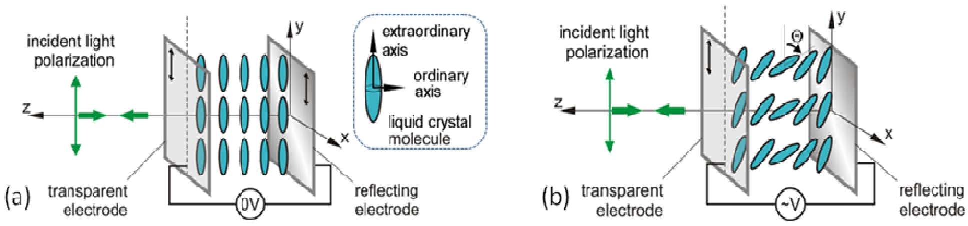

Fig. 1. Parallel configuration with (a) OFF voltage and (b) ON voltage states.

Actually, because the voltage levels are mapped in greyscale (between 0 and 255) by means of a computer, an accurate relation between the voltage and greyscale levels may be established through software along the whole SLM's aperture [17]. This can be done by means of calibration of the so-called LCoS SLM gamma curve.

Experimental LC phase response can be evaluated using a single point fringe position tracing like double slit interferometer [18] or performing intensity measurements over the aperture [19]. As mentioned before, the illumination itself is an important factor for the calibration process [20]. Clearly, the phase modulation range depends on the illumination wavelength [15] and the incident beam angle α [14]. Fig. 2 presents our experimental results of the phase shift measurements as a function of voltage (0-2.6 V) for the HoloEye HE1080P when illuminated with a wavelength of λ=532 nm, for incident angles between 0 and 45º. These results are in agreement with Ref. [14] and point out that for α<10° a modulation depth reduction is negligible. For the cases of larger illumination angles (even up to 45°) a 2π phase delay may be achieved using a compensation technique that is essential for accuracy.

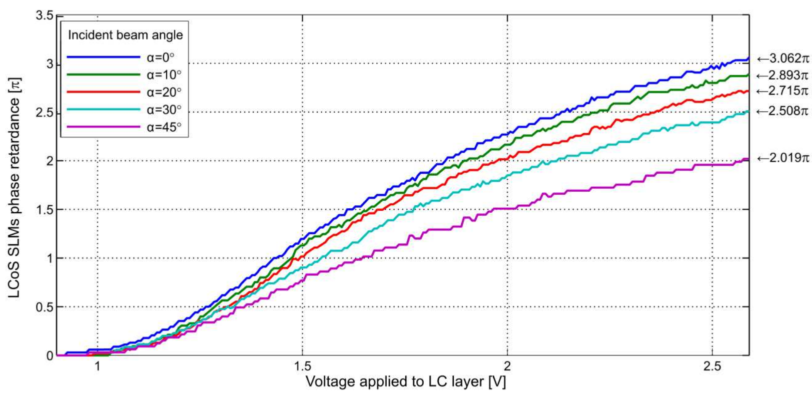

Fig. 2. Tilt depended phase-shift characteristics for a wide range of voltage and wavelength λ=532 nm.

Another fact that needs to be taken into consideration is the shape of the cover glass that may induce aberrations to the wavefront. The nonflatness of the cover glass appear as an additional spatial variation of the phase shift and voltage along the pixels and represents the case of an aberrated wavefront. According to technical specifications and experimental results [17, 21], these aberrations can be considered to be almost spherical and do not exceed 10 radians within the visible range of illumination. Therefore, the effect observed can be understood as the superposition of a very weak lens to the addressed optical function. For some applications, this effect may be neglected or compensated whilst in other applications it gives significant effects. Unfortunately, this compensation needs to be applied for each individual pixel, so that these aberrations cannot be compensated using the gamma curve or potentiometer settings. In order to determine the correction, the wavefront aberrations need to be measured correctly.

With this aim, one may determine the wavefront aberration by inserting an LCoS in one of the arms of a Twyman-Green interferometer [19] and compare it with a flat reference mirror (Fig. 3a). Addressing the LCoS SLM with the phase values compensating its systematic error (Fig. 3b) it is possible to achieve a plane wavefront with an accuracy of λ/2. In this way SLM's non-uniformities may be corrected alone or together with other wavefront deviations occurring in the system [21].

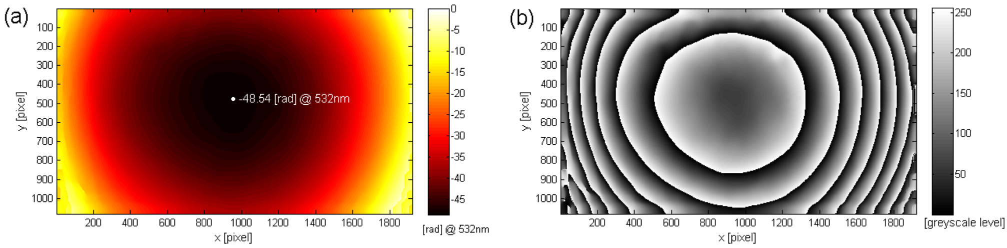

Fig. 3. Experimental results of a wavefront aberration induced by LCoS SLM (a) and the correction phase map (b).

A common and widely studied concern in LCoS SLMs is the depolarization induced to the modulated beam. Depolarization can be observed for the case of not normal illumination due to the LC birefringence. Furthermore, for any illumination case this undesired effect can be also observed due to temporal fluctuations in the LC molecules [22]. Actually, it has been reported that depolarization can exceed 10% depending on the addressed gray level on the incident state of polarization [23]. However, both the incident beam angle [14] and wavelength need to be taken into consideration for the presence of depolarization effects in local (single pixel) and global regions (wavefront aberrations) [15].

3. Applications

As mentioned in Section 1, the versatility of LCoS SLMs enables their extensive use in optics in particular for the use as phase only modulators. This section lists some applications where LCoS are used in the reference arm of an interferometer and discusses the use of LCoS in holographic cameras. This section also describes the case where LCoS are placed in the illumination path of an optical set-up as e.g. structured illumination required for applications in micro-object manipulation. In addition, the extensive application of LCoS in microscopy is summarized for i.e., point spread function engineering for the creation of phase masks, phase contrast as an active phase filter, and digital holography for capture and reconstruction of 3D objects. The final application discussed in this paper is the use of LCoS as a sensor, more specifically as optical extensometers.

For simplicity in the illustrations, the illumination angle in the SLM for all optical schemes is 45º.

3.1. LCoS in the reference arm of an interferometer

In interferometry, LCoS spatial light modulators can be used to replace the reference mirror in a classical Twyman-Green (T-G) configuration. The presence of an active element in the reference beam enables the use of arbitrary phase distributions that correct and/or compensate errors in the measurements or extend the range of measurements. This is achieved, as reported in Ref. [21], by introducing a particular reference wavefront to introduce linear or circular spatial carrier frequency in an interferogram or by compensating some deformations of an object wavefront. A basic scheme of an active interferometer is shown in Fig. 4a. The beam splitter divides the beam into two wavefronts. The first beam illuminates the specimen and the second beam acts as a reference that is modified by the LCoS. Introducing sufficient tilt into a plane reference beam allows the application of Fourier transform or spatial carrier phase shifting method for automatic interferogram analysis. For particular cases the reference beams with conical or helicoidal wavefronts has to be matched to an object shape, which can be easily introduced by LCoS SLMs.

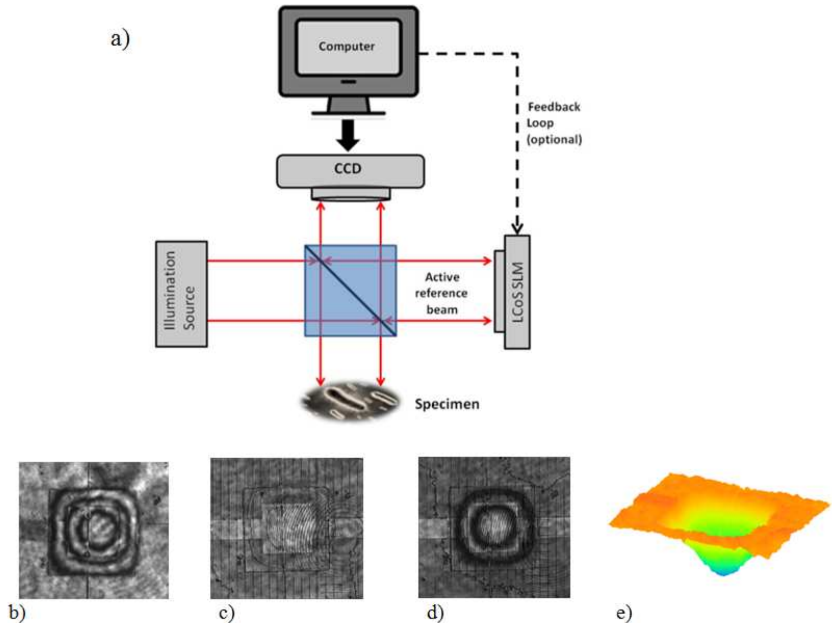

Fig. 4. Active Twyman-Green interferometer with an LCoS SLM in the reference beam: a) its scheme and the interferograms and results obtained during micromembrane out-of-plane deformation measurement: b) initial interferogram, c) corrected interferogram of unloaded and d) loaded membrane and e) its calculated out-of-plane deformation.

The same configuration can be used in Phase-shifting Interferometry, where the phase of the reference beam is shifted by chosen values of phase steps in order to obtain a series of interferograms used for accurate determination of the phase of an object wave. With this purpose the LCoS enables the generation of phase shifts at a temporal bandwidth within the msec range. Notably, in contrary to conventionally phase shifting techniques, this is achieved without the use of any mechanical moving components. The exemplary results obtained during measurement of a silicon micromembrane with an initial shape in an active T-G interferometer are presented in Fig. 4b-e. After phase correction performed by LCoS (the feedback loop from computer) in order to remove interference fringes from the interferogram of a specimen in initial state (Fig. 4b), the null interferogram field was obtained (Fig. 4c) and out-of-plane deformation of this specimen was directly measured on the basis of interference fringes that appear in the interferogram (Fig. 4c). The phase calculation (Fig. 4e) was performed by means of five frame phase shifting algorithm with the phase shifts introduced by LCoS SLM.

Having an active reference beam does not only simplify the measurement process, but also predicts the advent of its automation. This makes active interferometry suitable for more applications in the industry and bioengineering.

3.2. LCoS in microscopy

The field of microscopy has benefited strongly from the advent of LCoS SLMs. An example is given by the Structure Illumination Microscopy, which solves some limitations of conventional microscopes regarding the transmitted spatial frequencies in both the transverse and the axial directions. The limitations are given by the optical transfer function (OTF) of the system, which determines the resolution [12]. Because structured light is a field that presents a certain structure in amplitude and phase for each transversal section [24], it is possible to achieve either a super resolution in the transversal direction or an optical sectioning capability.

LCoS are commonly used to modulate the incoming light in order to obtain structured illumination for microscopy as is shown in Fig. 5.

Notably, Structured Illumination is particularly useful for such applications as particle manipulations and optical tweezers [25]. The use of LCoS provides a very high degree of freedom, as the Structured Light patterns can be programmed freely and applied for a given biological application, as e.g. cell sorting, DNA unwrapping, etc. These capabilities make LCoS a suitable component in the development of ‘lab-on-a-chip’ technologies.

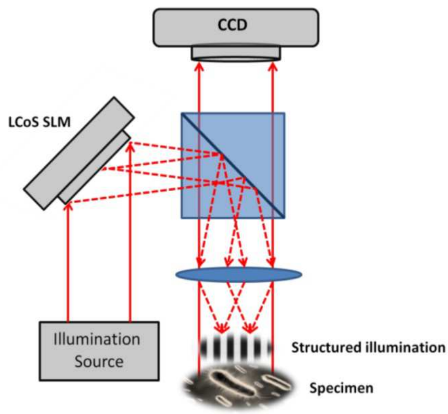

Fig. 5. Schematic of a Structured Illumination Microscope using LCoS SLM.

Another area of research where LCoS have been proved useful is the so-called optical Point Spread Function (PSF) engineering. The aim in PSF engineering is to overcome a detector-limited resolution by adding an appropriate phase mask to the conventional image system and obtain the final image by digital post-processing [26, 27]. In other words, imaging systems limited by the detector size can have an improved performance in terms of resolution by modulating the PSF with the adequate phase mask.

A good example of PSF engineering is the so-called Wavefront Coding Technology [28]. This technique requires the use of asymmetric phase masks to increase the depth of field in optical systems. It is achieved by using a cubic phase mask which modifies an incoherent optical system in such way that the PSF is insensitive to misfocus, whilst the OTF has no regions of zero values within the passband. The OTF distributions enables the use of digital post-processing to produce a combined optical digital system that has a nearly diffraction limited imaging performance and with extended depth of field. Nowadays, Wavefront Coding has been applied not only to small optical systems as for cameras but also to large astronomical telescopes [29].

Because a conventional cubic phase mask requires a complex fabrication process, LCoS SLMs are a convenient choice. Fig. 6 shows the principle of the PSF engineering using LCoS. The main contribution of LCoS in the modulation of the PSF, is the capability to actively adjust the phase mask profile freely so that the optimal distribution can be obtained in 'real-time'.

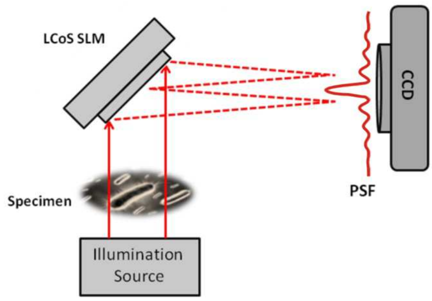

Fig. 6. Point Spread Function Engineering using an LCoS SLM.

The area of Phase Contrast Microscopy (PCM) has also benefited from the use of LCoS SLMs. The aim in phase contrast microscopy is to visualize phase objects in biology and engineering. In conventional PCM the aim is achieved by using a phase filter to modulate the zero frequency of an image. By doing this, the phase information of the object is translated into intensity [30].

However, to obtain optimum results, a specific phase filter is required for each phase object. In fact, the appropriate phase filter distribution depends not only in the phase object features e.g. dimension, phase change induced, but also in the illumination area. Liquid crystals materials can be used as phase contrast filters to overcome this complication due to their tunable refractive index that depends on intensity and electric fields. In Ref. [31] a dye doped LC single cell is used as a phase filter in a phase contrast imaging system. The main advantages of this approach are that the system is self-aligned, and the phase filter is optimum for each phase object because it is self-induced. In addition, due to the presence of a reversible photochromic dye in the LC cell, the phase in the filter can be controlled by rotating the polarization's illumination. Therefore, the contrast in the images can be adjusted from positive to negative in 'real time'. Some examples of the contrasted phase images are shown in Fig. 7.

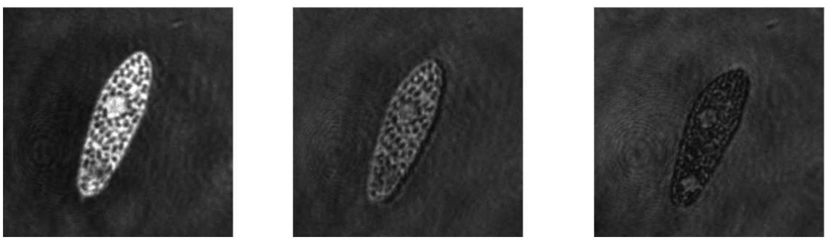

Fig. 7. Real time images of biological specimens (paramecium) obtained by the nonlinear phase contrast microscope based on dye doped LC cell [31].

Another approach to active PCM is found in the use of LCoS SLMs. They offer the capability to not only modulate the zero frequency but higher frequencies as well. In this way, active image processing can be applied to the results by displaying different phase distributions in the filter, e.g. using edge enhancement.

Some good examples of the phase contrast technique that uses LCoS as a phase filter can be found in [32, 33]. The authors programmed various phase profiles into the LCoS SLM to obtain an estimation of the refractive indices changes in the atmosphere and for the visualization of biological specimens. Fig. 8 shows the use of LCoS within a phase contrast setup.

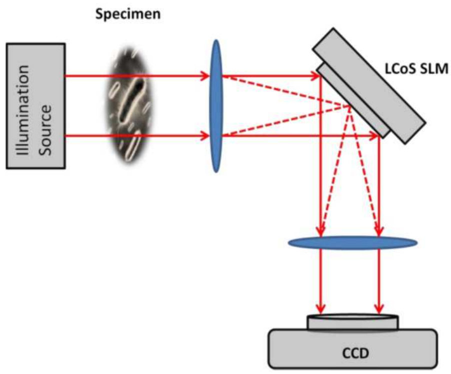

Fig. 8. Schematic of a Phase Contrast Microscope using LCoS SLMs.

3.3. LCoS in sensors: optical extensometers

Recently a lot of effort is focused on development of new types of sensors which take advantage from the advances in low cost array imaging detectors (CCD/CMOS) [34, 35] and allow to introduce full-field measurement methods in smart, mobile devices with different functionalities (Fig. 9a). One of the very important role of such sensors is measurement and monitoring of in-plane displacement and strains in both: microelements (e.g MEMS/MOEMS fabricated with silicon microtechnologies) as well as directly at engineering structures in specific areas of interest (joints, welds, etc.). This task can be well performed by the grating (moire) interferometry with conjugate wavefronts [36] and specifically with its realization by means of a waveguide interferometric head (IMS). The active version of IMS is shown in Fig. 9b [35]. The illuminating beam is introduced into a glass or PMMA (Poly-methyl methacrylate) plate with parallel plane surfaces, illuminates the beam splitting grating which is realized by LCoS SLM. The +1 diffraction order beam is guided inside the plate and after final reflection illuminates the specimen grating SG. The -1 diffraction order reflected by a side surface is also guided by the plate and illuminates directly SG. The beams modified by the sample grating interfere and provide the information about in-plane displacement of the sample grating perpendicular to its lines e.g. u(x,y). LCoS provide the means of proper automatic interferogram analysis by means of phase shifting or introducing the carrier frequency fringes. It also may facilitate the extension of the measurement range, change of the sensitivity by the controlled modification of the grating period or subtraction of systematic errors in the case of PMMA based IMS.

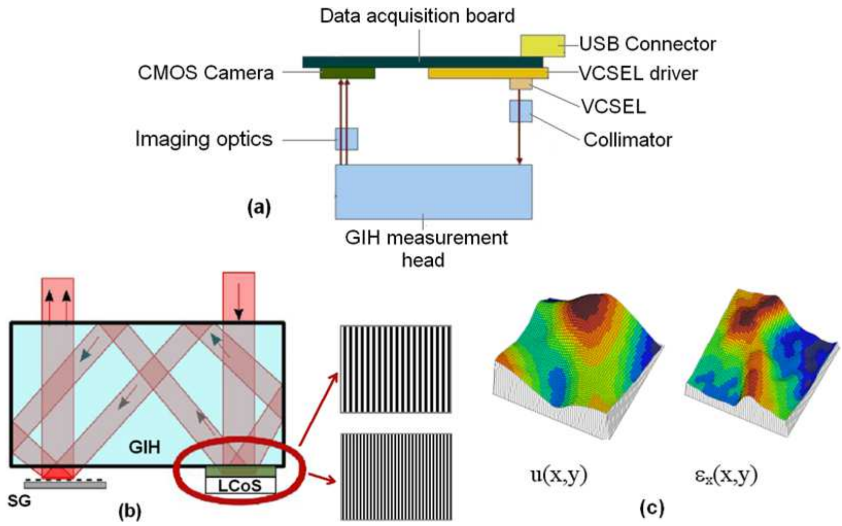

Fig. 9. The full-field in-plane displacement sensor based on grating interferometry: a) the scheme of the sensor and b) the active IMS measurement head with LCoS SLM and indication of the direction of generated beam splitting grating and c) the exemplary u(x,y) and ε_x(x,y) obtained in the investigated microregion.

A similar design (Fig. 9a) and a functional approach can be applied to other sensors based on full-field measurement methods such as two beam or shearing interferometry, digital speckle interferometry or digital holography.

3.4. LCoS in digital holography

Holography is a method where a full object wavefield information can be captured and optically reconstructed giving true 3-D effects. In the last decades, constant development has been made in CCDs and SLMs technologies, giving new possibilities of data recording and displaying. Thanks to its unique properties, digital holography (DH) became a valuable tool not only for 3D display technology [37] but also for optical metrology [38]. So far LCoS SLMs havebeen recognized as the most feasible device for recording and reconstructing processes in DH.

During the recording process, information about amplitude and phase of a scene is captured. The wave field scattered by an object is superimposed with a reference wave of known characteristics and the resulting interference pattern is recorded using a CCD sensor. Thanks to the LCoS SLM it is possible to avoid mechanical reference wave adaptation [39] (Fig. 10a). The modulator is illuminated orthogonally through a polarizing beam so that the reflected light travels straight to the sensor, and the object obtains an external illumination. A polarizer placed in front of the CCD generates interference between these two beams. Phase modulation enables spherical wave adaptation to various object planes, temporal and spatial phase-shifting, optical aberrations correction. This compact setup is presented as Lensless Fourier Digital Holography tool [39], but according to reference and object beams attitude and parameters this holographic camera allow for implementation also a Fresnel hologram capture scheme, phase-shifting [40] method and 'in-line' and 'off-axis' configuration as well [38]. Notably, the 'in-line' arrangement utilizes the field spatial bandwidth product in a more optimum way [41].

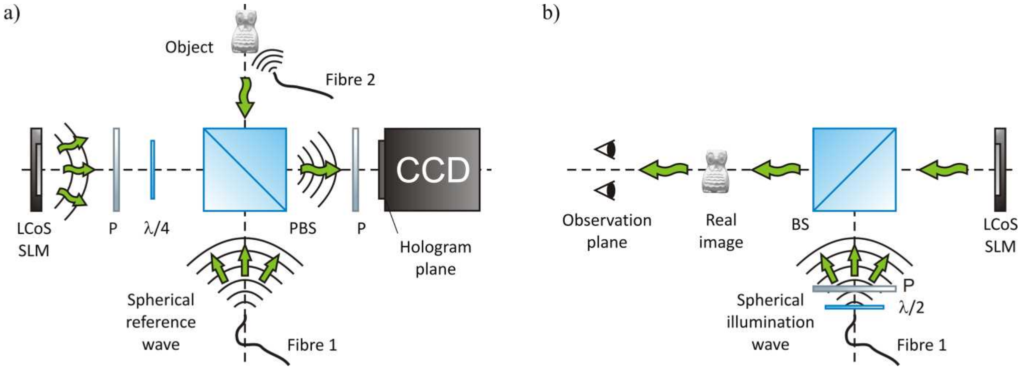

Fig. 10. Digital holography employing LCoS SLM: a) capture, b) reconstruction.

LCoS SLMs are also employed for the reconstruction of digital holograms. The capture setup of a sample reconstruction arrangement is presented in Fig. 10b. SLMs are addressed with the corresponding object phase and are also illuminated by the reference wave. In addition to the techniques mentioned above, a number of hologram reconstruction schemes may be used (including even rainbow holography). LCoS SLM became the most popular commercial device for optoelectronic holograms reconstruction due to relatively good properties as e.g. the high resolution and diffraction efficiency, small pixel size and the ease of use. Many holographic applications that apply zero-order and twin image reduction utilize phase-shifting [38] techniques by the means of phase-only modulation. Remarkably, optoelectronic reconstruction does not exclude computer generated holograms (CGH) [42-44]. This gives great possibilities for 3D-display and metrology.

In comparison to conventional holography, LCoS SLMs reconstruction quality suffers from relatively large pixel size, small apertures and periodic structure. The consequences for these restrictions are limited angular field of view, low image resolution, closeness of aliasing images, high speckle noise, difficult observation conditions and almost impossible binocular viewing, i.e. 3D vision [41]. Recently, some attempts have been made to enhance these features by employing multi-SLMs in a circular configuration to enlarge the aperture and the viewing angle as reported in [42, 44-46].

A common challenge in multi-SLM displays is the discontinuity of the synthetic aperture formed by many SLMs and, in consequence, the angular field of view also suffers discontinuity. This problem may be solved utilizing additional LCoS SLMs for dynamic beam steering [47] at the image plane (Fig. 11a). Two virtual tilted planes are dynamically displayed by the phase modulator and shift the direction of the reflected beams. For the viewer a beam appears to originate from the area within the gap. By synchronizing the tilt values and the displayed information at LCoS SLM1 and LCoS SLM2, it is possible to obtain continuous angular field of view through doubling the number of effective SLMs whilst keeping 30 Hz image frame rate.

In circular holographic display configuration it is common to deal with incident beam angles larger than 10°, due to a simple parallel illumination arrangement. Beside the facts mentioned in Section 2, a mismatch between the orthogonal reference (on-axis configuration) and the inclined illuminating beam is observed. This results in defocusing and image distortion. For tilted planes an algorithm is presented [47], where captured complex wave is processed before loading onto the SLM. As an outcome we obtain a field of the same spatial bandwidth product as the input one, i.e. high quality holographic reconstruction. Experimental results, presented in Fig. 11a-b, prove the method's effectiveness up to α=40°.

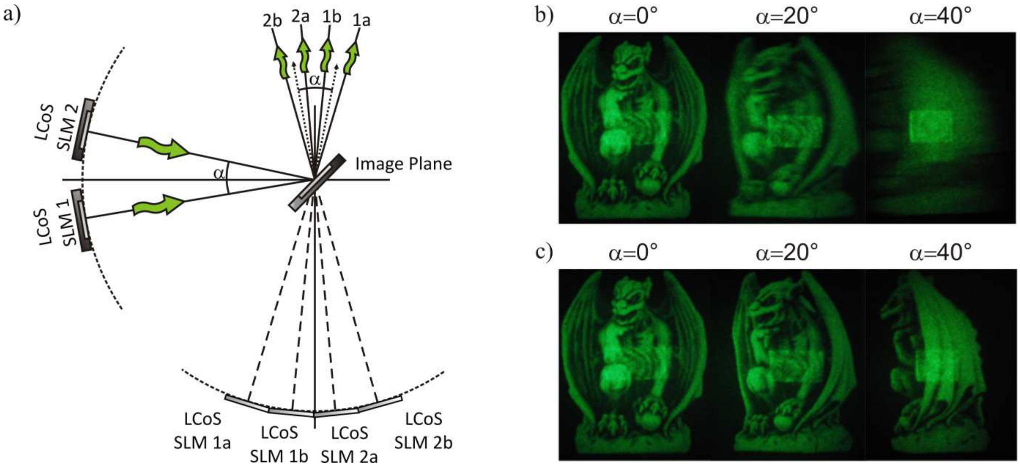

Fig. 11. Multi-SLM holographic display employing LCoS SLM setup arrangement with dynamic beam steering (a) and optical reconstruction for an inclined illumination without (b) and with tilted planes algorithm use (c) for a tilt angles α = 0, 20, 40°.

4. Conclusions

This paper presents some of the most popular applications of LCoS SLMs where the authors gained experience in. It has been shown that these devices highly contribute to the development and implementation of a wide range of applications in optics.

We have shown that the calibration of each LCoS SLM is crucial in order to obtain the best performance for the specific application. The most important parameters to be taken into consideration are: the careful calibration of the relation between linearity in the phase modulation, compensation of wavefront aberrations, wavelength, polarization and angle illumination. Notably, depolarization of the illumination may also be observed and considered carefully.

It is worth mentioning that although LCoS SLMs have already an outstanding performance there are still challenges in the fabrication of SLMs, e.g. the time response and the ability to modulate accurately the phase and amplitude with high resolution. The ability to modulate amplitude and phase simultaneously (complex-valued transmittance of the SLM) of an incoming wavefront is desirable for many applications, e.g. digital holography.

However, it is expected that such devices with these capabilities may be available in the near future.

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