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Optically addressed modulator for tunable spatial polarization control

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Abstract: We present an optically addressed non-pixelated spatial light modulator. The system is based on reversible photoalignment of a LC cell using a red light sensitive novel azobenzene photoalignment layer. It is an electrode-free device that manipulates the liquid crystal orientation and consequently the polarization via light without artifacts caused by electrodes. The capability to miniaturize the spatial light modulator allows the integration into a microscope objective. This includes a miniaturized 200 channel optical addressing system based on a VCSEL array and hybrid refractive-diffractive beam shapers. As an application example, the utilization as a microscope objective integrated analog phase contrast modulator is shown.

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1. Introduction

Reversible spatial polarization shaping devices are widely used in optical systems. They are either utilized to manipulate polarization properties or used to generate spatial phase or amplitude modulation. Examples for their application include dynamic beam shaping/splitting/steering, optical tweezers, pattern generation, information storage, optical processing, or holography.

Currently the most common technology for this purpose are electrically addressed spatial light modulators (SLM). Their working principle is based on the re-orientation of liquid crystals (LC) using pixelated electrodes. Those can be configured for transmission or reflection use. SLM devices can consist of several millions of pixels with sizes down to 3 μm and are available as commercial products [1, 2].

Benefits of SLM systems are the high amount of individually addressable pixels and the easy control by digital electrical interfaces. The drawback of those devices is the limited spatial resolution, crosstalk between neighbouring pixels, spurious diffraction orders and efficiency losses due to the electrode structure and pixelation [3].

Optically addressed spatial light modulators (OASLM) are based on optically addressed photoconductor layer. In combination with transparent electrodes and voltage sources, they cause the reorientation of a liquid crystal layer [4, 6, 7].

OASLMs have no pixelation and can be fabricated in large areas and high spatial resolutions [5]. But they need an external high-voltage supply and an external optical addressing system. The addressing principle is based on the same effect as SLMs (LC orientation by electrical fields, optical anisotropy caused by birefringence), but the voltage between the electrodes is altered through photoconductors and not by electronic means.

In order to simplify the system, avoid negative effects from electrodes (e.g. crosstalk or pixelation), and enable all optical systems, the tuning of birefringence via light would be advantageous.

The induction of anisotropy due to photo-orientation or photo-selection in polymer films upon exposure with polarized light [8] is used for the fabrication of static photoalignment layers and permanent polarisation elements. But for long-term and high cycle numbers, hysteresis and reversibility, switching times and durability are insufficient for applicable devices, with regards to the influence of the solid state matrix [9, 10].

A solution for these issues is the reversible photoalignment of liquid crystals with an azobenzene-containing optically addressed monolayer [11] (see also section 3.1). This enables the fast, reversible, wearless and reproducible optical induction of birefringence. Usually, the polarized light used for addressing is in the range between 366-532 nm with respect to the absorbance of conventional azobenzenes [12–15].

The usage of a photo-addressable light modulator also depends on the addressing system - mainly regarding wavelength, polarization and power density of the addressing pattern. Complex and compact micro-optical addressing systems need high-density switchable light sources, e.g. vertical-cavity surface-emitting lasers (VCSEL). But so far, such stable light sources are only available at wavelengths of >640 nm [16].

Currently the main disadvantages of electrically addressed SLMs are aberrations due to SLM unevenness, spurious diffraction orders, stray light generation and spatial resolution. Optically addressed modulators can overcome these limitations, but their application requires an optical addressing system. Optical addressing systems are voluminous and require often an additional SLM for pattern generation. VCSEL arrays and micro-optical components are enablers for compact multi-channel optical addressing systems. In contrast to edge emitters, VCSEL can be fabricated in precise positioned arrays. They emit linearly polarized light with is needed for optical addressing. But there are no fast (switching time <100 s [18]) and stable materials for reversible optical addressing at stable VCSEL emission wavelengths. The material development, especially with respect to the switching time, gets more and more challenging with increasing wavelengths, due to the energy of the addressing light. Therefore it is necessary to develop new fast optical addressable materials to obtain the benefits of compact optical addressing systems based on red light VCSEL arrays.

Here, we present the properties of a new red light photo-addressable cell in combination with a compact optical addressing module. The applications and benefits of such a system compared to SLMs are demonstrated by a tunable microscope objective integrated phase contrast device.

2. System design and principle of operation

The purpose of the system is to generate spatial reversible tunable birefringence patterns (spatial light modulator). It allows for the manipulation of polarization, phase or amplitude of transmitting light fields. The principle of operation (Fig. 1) is based on the optical addressing of a photo-addressable cell (PAC).

The desired spatial addressing pattern is projected into the photoaligning layer of the PAC. Depending on the intensity of the addressing light the degree of birefringence is spatially altered in the PAC plane. Linearly polarized light with wavelengths 640-660 nm is used for addressing. The resulting birefringence pattern can be used with NIR and SWIR light (900-1800 nm wavelength). But visible light of low power density (< 10 mW/cm²) is applicable too.

The main components of the optical addressing system are a VCSEL array as light source, diffractive optical elements and an axicon for beam-shaping. The optically induced birefringence is generated in the photoaddressable cell.

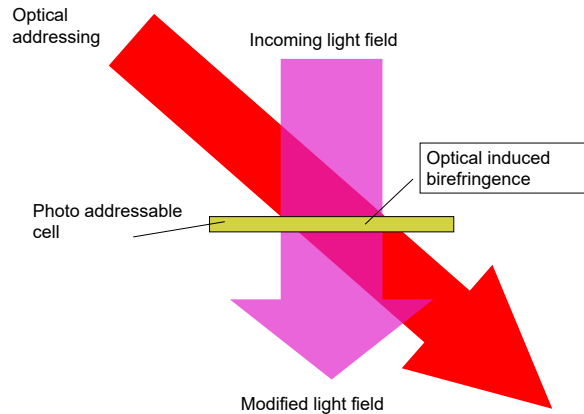


Fig. 1. Schematic of the optical addressed spatial polarization shaping system.

3. System components

3.1. Photoaddressable cell

The PAC (Fig. 2(a)) is formed by two glass substrates. The inner surface of the first substrate is covered with an azobenzene-containing optically addressable monolayer of 10 nm thickness achieving a reversible LC photoalignment, whereas the second substrate is covered with a rubbed polyimide film of 50nm thickness causing a permanent planar LC alignment. The thickness of the complete PAC is controlled by precise spacers based on microspheres (10 μm thickness). Due to the monomolecular addressing layer and the transparency of the LC mixture, the transmission of the assembled cell (Fig. 2(b)) is dominated by Fresnel losses.

So far, photoisomerisation and photo-orientation processes of azobenzenes are mainly reported using green, blue or UV light, according to the absorbance of conventional azobenzenes. Only a few publications have reported on the induction of anisotropy using red light mainly up to 633 nm [17–20]. Especially the reversibility and switching times (>100 s) of the used photosensitive polymeric azobenzene materials are too slow for technical applications.

Therefore, it was necessary to develop a new photo-addressable material with faster switching time, long lifetime and excellent reversibility. Based on our previous work, [21–23] the new photo-addressable material Silan IV (Fig. 2(c)) improves the switching time of the red addressable material.

The photo-addressable terminal substituted bis-azobenzene containing triethoxy silane (Silan IV) is covalently linked to the surface of one of the glass substrates (soda-lime-silica glass of 1 mm thickness). In order to control the interaction between neighbouring molecules and to ensure the reversibility of the optical addressing, the Silan IV monolayer is formed by self-assembling and proper post-treatment by rinsing with toluene.

In the initial state, the photosensitive aligning layer causes a homeotropic alignment of the nematic LC mixture E5 (Merck, Darmstadt). In combination with the planar alignment caused by the rubbed PI layer of the second substrate, it results in a splay orientation of the initial LC cell (Fig. 3(b)).

The exposure with polarized red light changes the splay orientation of the LC cell to a planar one (Fig. 3(a)). The related change of the optical properties of the LC cell is caused by two effects. Firstly, the photoisomerisation of the push-pull-substituted bis-azobenzene moieties changes the molecular shape of the initial rod-like EE isomer to the crooked EZ isomer. A steady state between both isomeric forms is established. The related modification of the monolayer causes

a change of the boundary condition resulting in a planar LC orientation, changing the splay to planar order of the cell.

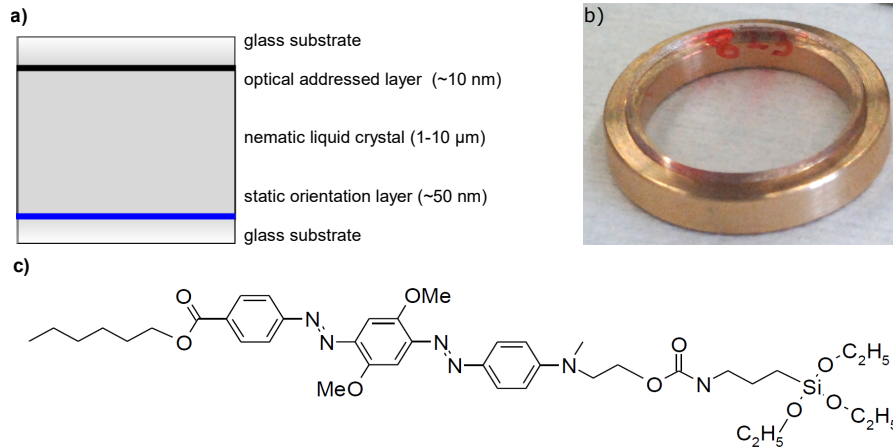


Fig. 2. a) Composition of the photo-addressable cell (PAC); b) Image of a PAC; c) Molecular structure of the initial material of the photo-addressable command layer: Silan IV with terminal attached push-pull bis triethoxy-bis-azobenzene.

By switching off the addressing light, the azobenzene relaxes thermally back on molecular level to the rod-like EE isomer in some ms. This results in the re-establishing of the homeotropic orientation of the EE bis-azobenzene monolayer and the related relaxation of the LC molecules close to this substrate, establishing the initial splay order of the cell again in 30 seconds. Such a "command surface effect" was already demonstrated by Ichimura in 1988, using monolayers with conventional azobenzenes and the exposure with UV and visible light [11].

Secondly, upon continued exposure with linear polarized red light the bis-azobenzene moieties undergo angle selective absorbance and corresponding EE/EZ photoisomerization cycles, depending on the angle between the transition dipole moment of the azobenzene unit and the electric field vector of the incident light. The polarized irradiation tends to orientate the chromophores perpendicular to the electric field vector of the linear polarized light in the steady state of the photoisomerization. Subsequently, the photochromic groups become orientated perpendicular to the electric field vector of the incident light, enriching the azobenzenes perpendicular to the electric field vector (which was perpendicular to the rubbing direction of the PI aligning layer). In this way, the planar order is being improved during irradiation.

Due to the low thickness of the monolayer addressing layer, (< 10 nm) the induced optical path difference change of Silan IV monolayer is extremely small. Therefore, the change of photo-induced birefringence is amplified by the alignment of the whole LC bulk layer.

The temporal response (Fig. 4(a)) of the optical addressing is initiated by optically addressing the cell with linear polarized red laser light (wavelength 660 nm, power density 500 mW/cm²). The birefringence change is measured with a fast (using photoacoustic modulators) ellipsometer (Horiba Jobin Yvon UVISEL). The change of birefringence ($B(t)$) is fitted to a first-order exponential decay function ($B(t) = A \cdot \exp(-t/tc) + B_0$). The value $t_{95} = 3 \cdot tc$ is used for characterizing the response time. The parameter t_{95} describes the time necessary to obtain 95 % of the birefringence limit value. For the cell with Silan IV addressing layers, a response time of t_{95} of $4,1 \pm 0,15$ s was reached at a power density of 500 mW/cm². This is significantly faster than previously known red light addressable materials (>100 s [18]), but still considerably slower than SLMs ($\approx 0,01$ s [2]).

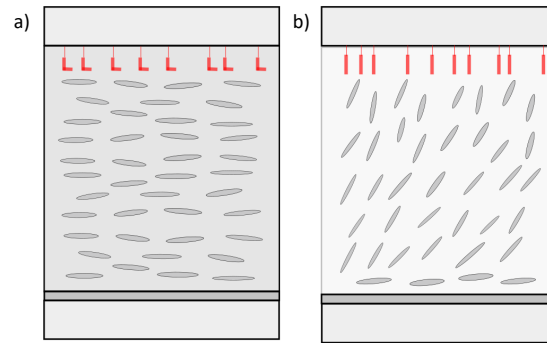


Fig. 3. a) Schematic illustration of planar orientation of liquid crystal molecules; b) Schematic illustration of splay orientation of liquid crystal molecules.

The switching time depends on the power of the addressing light. At a power density of 100 mW/cm^2 , which corresponds to that of the 200 channel optical addressing system, the switching time drops to $t_{95} = 6,5 \text{ s}$ (Fig. 4(d)).

After turning off the addressing light, the orientation of the LC layer relaxes thermally back (Fig. 4(b)) with a time constant of $t_{95} = 34 \text{ s}$ (at 22°C temperature). The maximum birefringence change generated is $\Delta n = 0,19$ for $10 \mu\text{m}$ LC thickness. The reversibility of the system is very high. After 22000 cycles of optical addressing, (500 mW/cm^2 , 660 nm) no change in the birefringence hub was detected.

The investigation was carried out with the terminal attached bis-azobenzene, as shown in Fig. 2. In this case, the silane group is attached via a spacer to the p-methyl, alkyl-amino group. But the experiments were continued using a lateral attached p-dimethylamino bis-azobenzene. Upon red light exposure the initial splay configuration is transformed to a planar aligned LC-cell as well. But in contrast to the terminal attached azobenzene, the thermal back isomerization to the EE isomer does not result into the initial splay cell, switching off the light. As expected, the lateral attached bis-azobenzene has a much higher tendency for planar alignment in contrast to the terminal substituted bis-azobenzene. The continued exposure with an amended polarization direction, with respect to the rubbing direction, causes a change of the aligning direction. As a consequence, the planar cell is changed to a twisted planar aligned cell. This allows a continuous change of the birefringence (Fig. 4(c)). The nonlinear response of the PAC is very stable and can be compensated by a look up table in the control system. The resulting birefringence deviations are mainly introduced by fluctuations of the light source. In our setup (VCSEL light power stability 0.5%) birefringence resolutions of $6.9 \cdot 10^{-4} \pm 3.7 \cdot 10^{-4}$ could be achieved. This is comparable to a 8 bit LCOS SLM.

The PACs are fabricated by coating glass plates in a low temperature (50°C) chemical self assembled coating process. Therefore it is possible to use glassplates with small surface deviations and create PACs with low wavefront distortion. The PACs are characterized with an interferometer (Twyman-Green interferometer, Fisba $\mu\text{Phase DCI2}$, 633 nm wavelength) and show a typical transmission wavefront distortion of 120 nm PV over 10 mm diameter. The residual deviations are mainly introduced in the gluing process. But they are significantly lower than typical wavefront distortions introduced by LCOS SLMs ($\approx 3000 \text{ nm PV}$ surface deviation [1]).

The loss of light due to stray light, depolarization and spurious diffraction orders is very low due to the unstructured, non-pixelated PAC. The quality of the cell transmission is determined by measuring the degree of polarization after passing through the PAC with an ellipsometer (Horiba Jobin Yvon UVISEL ellipsometer, 900 nm measurement wavelength). These losses are mainly caused by impurities in the coating process. The Polarization degree increased from 92% to

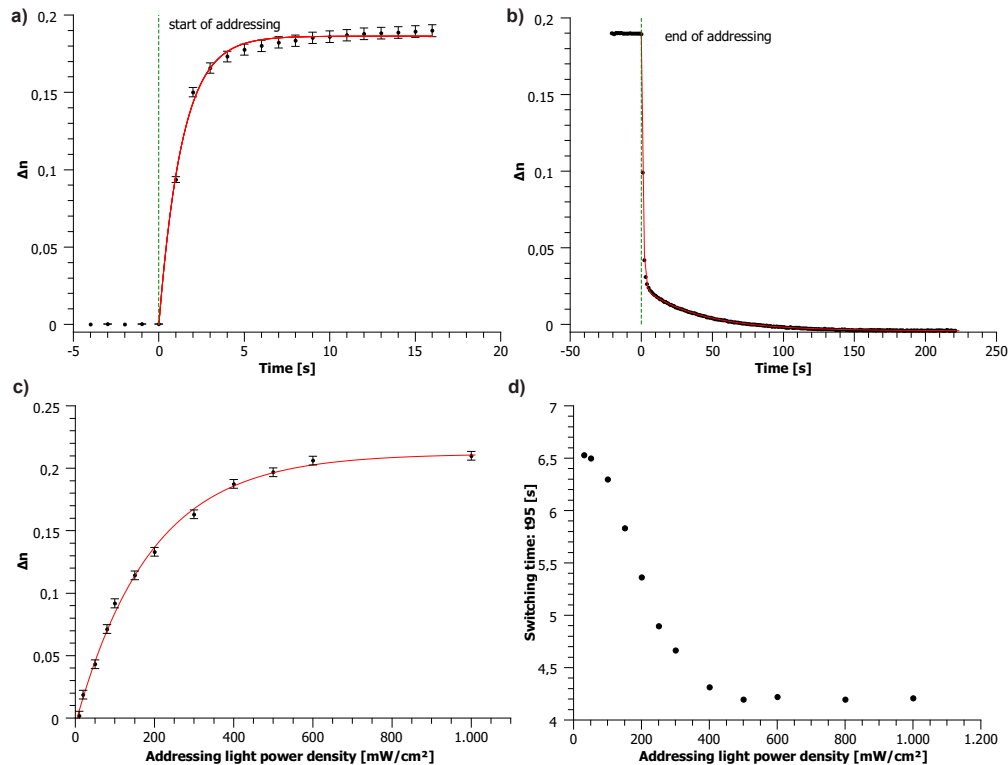


Fig. 4. a) Temporal optical addressing response of the PAC. Addressing wavelength: 660 nm. Measurement wavelength 900 nm measurement vector parallel to the planar orientation; b) Thermal relaxation of the PAC after turning off the addressing light; c) Induced birefringence as a function of addressing light power density d) Switching time t_{95} depending on the addressing light power density.

98.7 \pm 0.2 % by processing the PACs in a clean room. Typical LCOS SLMs show polarization degrees in the range of 80-90%, due to their micro-structured setup and temporal fluctuations [25].

The spatial resolution of a PAC depends mostly on the resolution of the optical addressing system. The resolution also depends on the thickness of the LC layer. Systems with a similar material setup (photo-alignment of a LC layer by photo-addressing an azo dye) at 405 nm addressing wavelength have achieved minimal feature sizes of 0.1 μm [26]. First resolution estimations under a polarization microscope (Leica Ergoplan, NA 0.7) showed a spatial resolution $<3 \mu\text{m}$ (minimal contrast based on the Rayleigh criterion). Typical pixel sizes of LCOS SLMs are in the range of 4-20 μm [1, 2]. The demonstrated use of 200 channel optical addressing system projects minimal features sizes of 210 μm , which are far away from limitations of the PAC or addressing wavelength.

3.2. 200 channel optical addressing system

In addition, controllable light sources and beam shaping elements are necessary for the application of the PAC. In our system VCSEL arrays are used as a light source, diffractive optical elements for beam shaping, and an refractive axicon element for beam steering.

For a high degree of freedom and a small footprint, we used an array of red VCSELs as a light source, and diffractive optical elements in combination with an axicon for beam shaping.

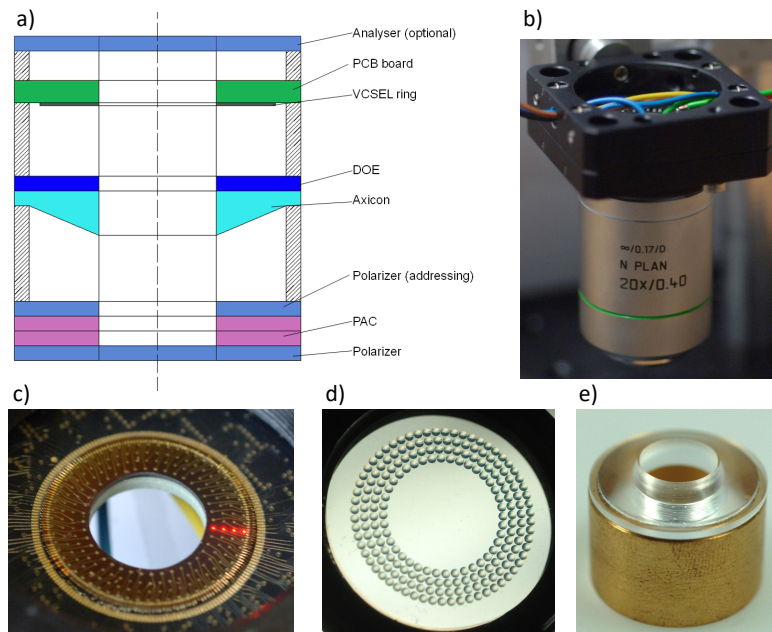


Fig. 5. a) Schematic depiction of the 200 channel optical addressing system; b) Image of the addressing system integrated into a microscope objective; c) Array of 200 VCSEL light sources mounted onto a PCB board; d) array of diffractive optical elements; e) Axicon mounted onto distance ring.

The light source is a VCSEL array on a ring (Fig. 5(c)). It contains 200 individual controllable VCSELs. Each VCSEL is designed to emit 0,8 mW optical power in a Gaussian fundamental mode at 650 ± 10 nm wavelength. They emit linearly polarized with identical polarization direction. Unfortunately, the yield of these light sources was only around 40 %, due to epitaxy inhomogeneities, contamination, and mechanical strain. The outer diameter of the VCSEL ring is 15.5 mm, the inner diameter 8.5 mm. The ring is fabricated by ns pulsed laser cutting of the thinned wafer. The ring is mounted on a gold-coated ring on a printed circuit board (PCB) as a backside contact (n-contact). The individual VCSEL mesas are connected with conducting paths on the wafer and wire-bonded to contact pads on the PCB (p-contact).

In order to minimize the amount of external wires and generate the individually controllable currents, 22 Austrian Semiconductors AS3665 ICs (μ BGA 25 form factor) are soldered on the back side of the PCB (6 layers, 30 mm diameter) as digitally controllable current sources. The ICs can control the current by analogue modulation and pulse width modulation (PWM) at 1 MHz. The PWM was used for tuning the output power. The external interface consists of three I2C serial interfaces and power supply (5 wires in total). By interfacing the I2C buses with a microcontroller, the currents can be controlled by a PC software. In order to create a compact, flexibel optical addressing system, a hybrid refractive-diffractive beam shaping approach is used. Each VCSEL is combined with an individual diffractive optical element (DOE). The function of the DOE consists in VCSEL collimation, beam shaping, and correction of errors caused by the refractive component. The DOEs are fabricated as continuous (256 levels) elements in an array by gray scale lithography (laser direct writing) of photoresist (Fig. 5(d)). The minimum feature size of the DOE is 4 μ m.

In order to lower the average feature size of the DOEs that would lead to an increase in diffraction efficiency, a refractive axicon was used for deflecting the light of the VCSEL ring

into the centre. The axicon is fabricated by diamond turning low stress PMMA (Fig. 5(e)). In order to filter out depolarized light due to residual birefringence of the PMMA or stray light, a thin film polarizer (nanoparticle polarizer from Codixx AG) is mounted in front of the PAC. The overall light transmission efficiency of the addressing system is 64 % (including Fresnel effects).

The outer diameter of the beam shaping optics is 19.5 mm and fits into the mechanics of a Leica N Plan 20x/0,4 microscope objective lens. The length of the complete system including the PAC is 23 mm. The PCB board has an outer diameter of 30 mm. The clear transmission aperture of the system is 8,5 mm.

By exchanging the DOE plate, different addressing patterns can be achieved. In this approach, we divided an 8 mm active diameter into 200 individual controllable segments of equal area size (Fig. 6(b)).

The overall system including the PAC is called 'active micro-optics for polarization control' (AMiPola) and is mounted in a microscope objective (Fig. 5(b)).

4. Application: Tunable phase contrast

The optical addressing system is designed to fit into a microscope objective. The PAC is placed on the exit pupil plane of the objective. There, it is possible to influence the imaging. One possible application is an element for tunable phase contrast.

There are many different phase contrast techniques. Depending on the application and specimen, different phase contrast techniques and settings create the best results. In conventional microscopes this requires laborious changing and mechanical shifting of several components. Electrically addressed SLMs can be used for tunable phase contrast [24]. But light efficiency, especially for imaging living cells, is too small. In addition, stray light generation, aberrations due to SLM unevenness, and spurious diffraction orders degrade the image quality.

Warber et al. [24] realized the tunable phase contrast methods with a LCOS SLM. They used a carrier frequency of 4 pixels per period to separate the spurious diffraction orders by an aperture. This leads to additional light losses due to the fringing field effect [3]. Also the aberrations induced by the unevenness of the SLM had to be compensated by difficult to obtain correction phase functions. The use of a reflective high performance SLM made an integration into an existing microscope impossible.

Non-pixelated optically addressed light modulators can improve those issues. Especially the reduction of stray light, improved light efficiency and reduced wavefront distortion enhance the performance of imaging systems. Additional microscope objective integrated system can be used in existing microscopes, just by changing the objective. For most of the phase contrast techniques, the high degree of freedom of SLMs is not necessary, due to the simplicity of the required phase structures.

The schematic setup of the tunable phase contrast microscope is shown in Fig. 6(a). The sample in the object plane is illuminated with linearly polarized light (wavelength 850 nm). A polarization-maintaining microscope objective (Leica N Plan 20x/0,4) is used to image the specimen. The optical addressing unit and the PAC are integrated into the objective mechanics. The PAC modulation plane is placed in the exit pupil of the objective. A polarizer reduces depolarized stray light. The specimen is then imaged with a tube lens onto a CMOS camera.

Here, we use a variant of the differential interference contrast (w-DIC [24]). The pupil is divided in two parts, a phase wedge and flat phase offset (Fig. 6(b)). Tunable parameters are orientation, pattern, phase offset and wedge slope. The nematic LC of the addressing system is operated in the phase modulation configuration. The addressing pattern is generated and tuned by digitally controlling the intensity of the 200 VCSELs.

A resulting phase contrast image of a phase USAF target (86 nm step height in quartz glass) is shown in Fig. 6(c). Due to the 45° orientation, both perpendicular edges of the lines are contrasted. Slope and offset are optimized to increase the contrast.

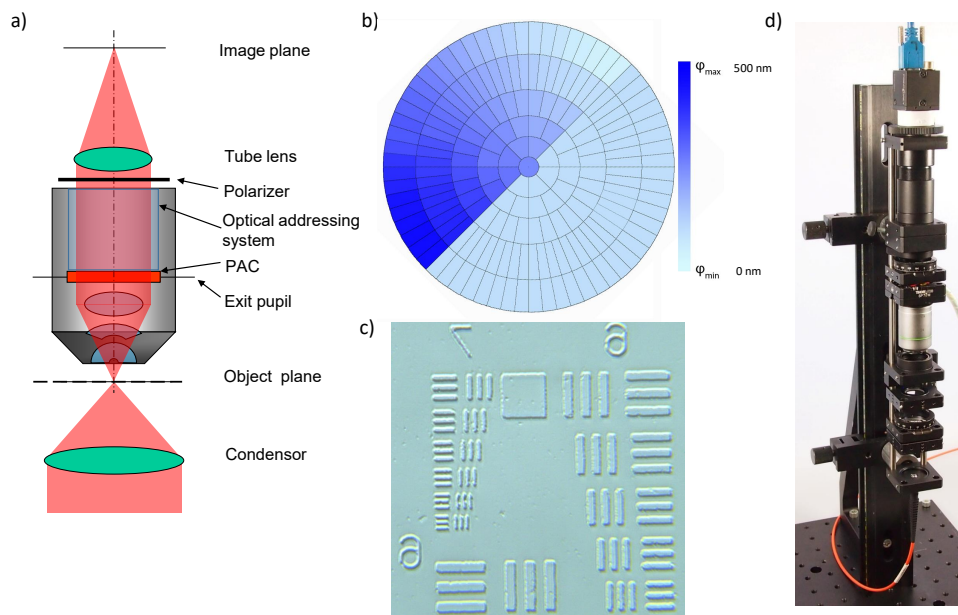


Fig. 6. a) Schematic diagram of the tunable phase contrast microscope; b) Addressing area of the individual light sources with an overlay of the target phase distribution for the phase contrast image; c) Phase contrast image (w-DIC) of a 86 nm stepheight USAF quartz phase target; d) Image of the microscope setup.

Besides the unidirectional w-DIC phase contrast technique, it is possible to implement other methods by changing the illumination pattern of the VCSEL array. For example the vertical differential interference contrast (v-DIC [24]). The pupil is also divided in two parts, a flat phase offset and a spherical phase function (Fig. 7(a)). The v-DIC phase contrast technique creates omnidirectional phase contrast images (Fig. 7(b)). But like other phase contrast techniques, the results depend on the parameters of the phase contrast system. The object adapted optimization of the phase contrast parameters (offset and magnitude of the spherical part) improves the image contrast (Fig. 7(d)).

5. Conclusion

We have developed an optically addressed light modulator; it works, for example, as reversible and segmented retardation plate. The system is based on a nematic LC cell with a photosensitive azobenzene aligning layer. The element is completed with a miniaturized light source carried out as an array of 200 individually controllable VCSELs emitting linearly polarized red light, and a miniaturized hybrid refractive-diffractive beam shaping element based on a DOE array and an axicon.

The exposure with polarized red light causes the photoisomerisation of the push-pull-substituted bis-azobenzene, changing the orientation of LC within the cell by the command surface effect due to formed cis isomers and the photoorientation of the azobenzene moieties upon continued exposure. Switching it off, the azobenzene relaxes back to the E isomer in some ms, the aligning monolayer and the LC above relax back in some seconds.

Especially the reversibility and switching time of 4 s are very promising compared to previous approaches. The required optical power density of 50-500 mW/cm² is in a technically usable range for apertures of several mm². However, the switching time and required power density

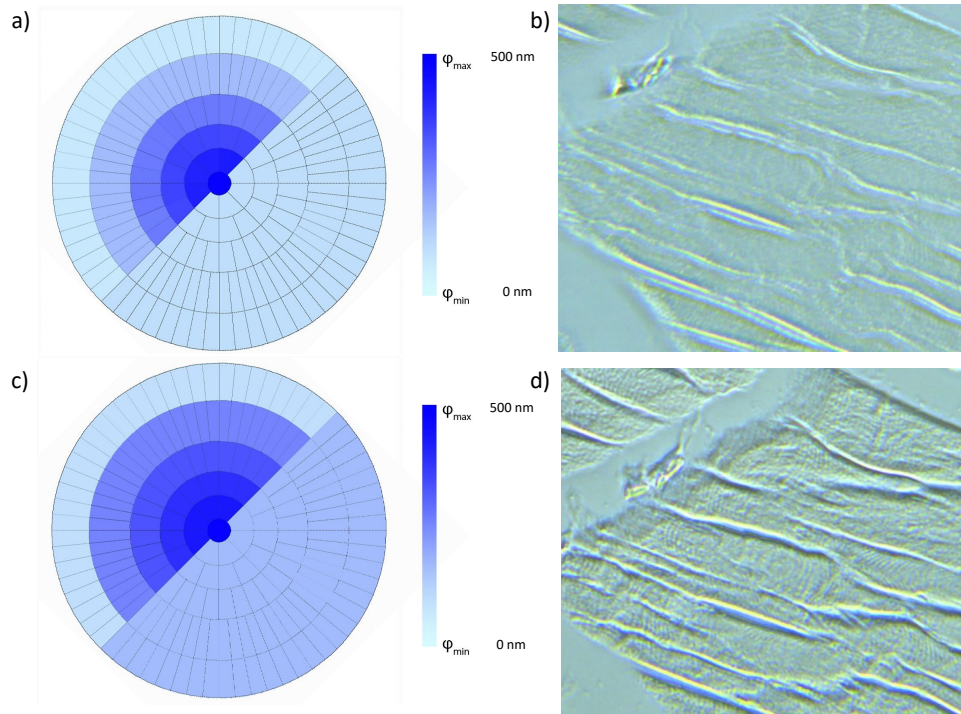


Fig. 7. a) Un-optimized addressing pattern of the individual light sources with an overlay of the target phase distribution for the phase contrast image (b); b) Un-optimized v-DIC phase contrast image of rabbit taste bud cells c) Optimized addressing pattern for the phase contrast image (d); d) Optimized v-DIC phase contrast image of rabbit taste bud cells.

might be further decreased by optimizing the molecule structure, LC material, and self-assembled monolayer parameters. Also, spatial resolution and behaviour in a wider addressing wavelength spectrum might be characterized in detail.

The 200 channels offer the possibility to create high density optical addressing systems. The transmission efficiency can be further increased by optimising the DOE fabrication and application of anti-reflection coatings. Particularly the yield of the VCSEL light sources could be improved to create entirely usable systems. In addition, more application-specific and complex addressing patterns will extend the degree of freedom of an optical addressing system.

Compared to conventional electrically addressed SLMs the proposed optically addressed system has several advantages. The light efficiency of the modulator based on a PAC is higher, due to the absence of stray light and spurious diffraction orders generated by conducting wires and electrodes. Wavefront distortion by the elements of the modulator is smaller because of the simple low temperature coating fabrication process. The shape of the modulator can be adapted easily to different sizes and forms. It can be used with high efficiency as a transmission element, this makes integration in existing optical systems easy. Modulator area and spatial resolution can be tuned by the optical addressing system.

Electrically addressed SLMs have several millions of individual addressable pixels, higher switching speed and do not require an optical addressing system. They are favored devices for fast switching of complex patterns. Optical addressed systems based on PACs can generate higher modulation quality and introduce less aberrations. But due to the optical addressing system they are preferred applicable to use cases with medium pattern variation complexity.

Especially imaging applications benefit from those advantages. Besides tunable phase contrast, dynamic aberration compensation, polarization imaging or scatterometry are possible uses. In illumination systems, the low stray light level is beneficial to dynamic polarized illumination patterns e.g. in semiconductor inspection systems. This setup can be also used for tunable beam shaping e.g. for optical tweezers or polarized laser scanning microscopes.

The application of an integrated microscope increases possible uses. The implementation of other phase contrast techniques, like Zernike phase contrast or the tuning of polarization properties in imaging or illumination of technical surfaces, might be other applications. In the future, the system enables the creation of all-optical systems. Properties of light like polarisation or phase can be altered directly with light, without using electrical components.

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