# Modal wavefront correction with liquid crystals: different options

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## ABSTRACT

Liquid crystal (LC) wavefront correctors with modal addressing are described. Three different approaches are considered. The first one is based on a continuous thin-film resistive layer. This layer is used for forming of the local voltage profile that controls the phase distribution across the corrector's aperture. The second approach is a modification of the first one, where the continuous resistive coating is replaced by a network of discrete resistors. It is based on silicon technology. The third approach makes use of distributed electric field in thick dielectric layers for forming of the modal response of an actuator. Technologies, methods of control and experimental results are discussed for each case.

**Keywords:** wavefront correctors, phase modulators, liquid crystal optics

## 1. INTRODUCTION

Classic adaptive optics system uses a wavefront sensor to measure random phase deformations induced by a distorting media and a wavefront corrector to compensate them in real time. Traditionally, deformable mirrors that exist in a number of modifications represent primary technology for wavefront correctors[1].

Liquid crystal phase modulators were suggested as a low-cost alternative to deformable mirrors for budget-sensitive industrial and medical adaptive optics applications. They have wide potential opportunities: low control voltages (units of volts), which makes this technology compatible with CMOS processes), large stroke range (tens of wavelengths), low power consumption (0.1 mW/cm$^2$), no moving parts and low cost of materials.

There are a number of commercially available LC correctors with pixelated structure of actuators, whose operation is similar to that of piston-type segmented mirrors[2]. But this type of device requires large number of pixels to produce a good approximation to smooth continuous wavefronts. In this paper we present an overview of three different options in implementation of LC wavefront correctors with modal addressing based on different principles and different technologies. For all three approaches we discuss principles of operation, technologies and experimental results.

## 2. MODAL CORRECTOR BASED ON A RESISTIVE LAYER

First implementation of the liquid crystal modal wavefront corrector (LC-MWC) was suggested in [3,4]. It was proposed to introduce a high-resistance layer into the design of a standard sandwich-type LC cell. The schematic diagram of the device is shown in Fig. 1. A thin LC layer is sandwiched between two substrates, a transparent and a reflective one; spacers placed at the periphery provide homogeneous thickness of the LC layer. Special alignment coatings generate initial planar alignment of the LC molecules. Transparent indium-tin oxide (ITO) coating covers the transparent substrate, and the high-resistance layer is placed on the reflective substrate. The resistive layer (control electrode, or CE) plays an essential part in the formation of the local voltage profile that controls the phase distribution across the corrector's aperture. The device is driven by AC voltages applied through a set of point-like contacts connected to the CE, which ensures a smooth voltage variation across the aperture. The dielectric mirror covers the CE improving the LC corrector's reflectivity.

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Manufacturing of LC-MWC includes several stages: manufacturing of the front glass substrate, ITO deposition, manufacturing of the back substrate, deposition of the CE and the dielectric mirror, assembling of the LC cell and packaging of the whole device. Manufacturing of the back substrate from glass with embedded wire metal contacts is the most complicated and time-consuming stage. Earlier[5] we have developed a technology which we used to manufacture 37-channel LC-MWCs with 30 and 70 mm apertures.

We have identified several technological problems in the previous processes and modified the initial technology in order to solve them. At the moment, a new series of LC-MWCs with 61 actuators and a clear aperture of 38 mm is being produced according to the modified technology. The results will be reported soon.

A major problem we found for the large-aperture LC-MWCs was an overal spherical deformation of the substrates, which appears after assembling of the LC cell at a temperature above $100^0$C and cooling down to a room temperature. This deformation was caused by difference of thermal coefficients of linear expansion of the front and the back substrates; the coefficients were $33 \cdot 10^{-7}$ and $52 \cdot 10^{-7}$ $K^{-1}$, respectively, and the resulting deformation as high as 9 fringes. This figure was confirmed by the results of finite-element simulation, which was made using ANSYS simulation package.

In the new series of devices the front substrate was made from TK23 glass with a linear expansion of $58 \cdot 10^{-7}$ $K^{-1}$, and the back substrate from a molybdenum glass C52 (linear expansion $52 \cdot 10^{-7}$ $K^{-1}$). Thus, better matching of coefficients was provided. In order to prevent the back substrate from deformation and stress, coefficients of linear expansion of the glass and the wire were also carefully matched.

The molybdenum wires were injected into a melted glass plate in a graphite mould, which is shown in Fig.2. We assembled it as follows. First, we took a graphite holder with a hexagonal pattern of holes corresponding to the specified positions of contacts and fixed molybdenum wires in the holes. Then we put a glass plate on top of the wires, covered both parts with a cylindrical graphite casing and closed the casing with a graphite lid. Finally, we turned the mould around and placed it into a specially designed furnace[5].

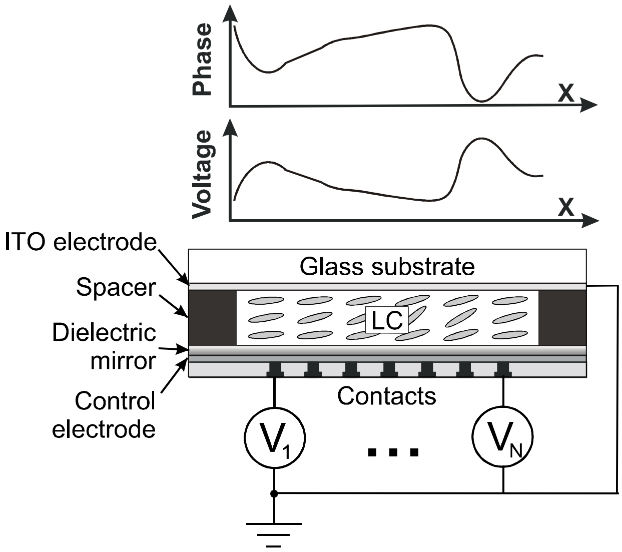



Fig.1. Schematic diagram of a resistive layer-based modal LC wavefront corrector.

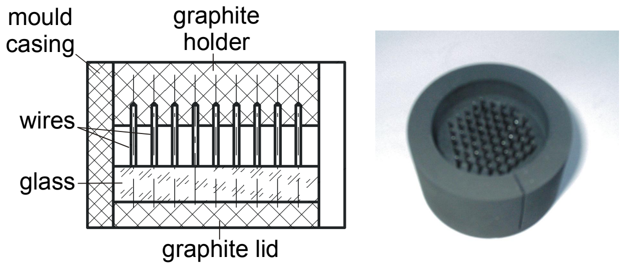



Fig.2. Mould for the melting of glass.

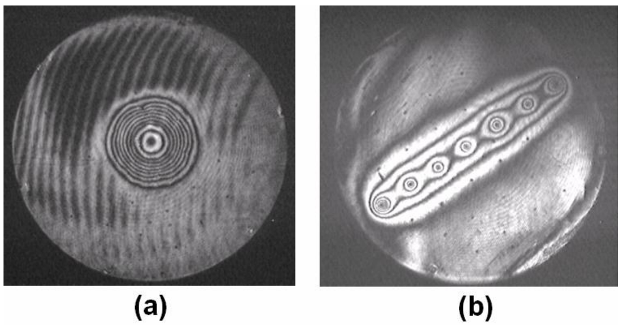



Fig.3. Polarization interferograms of the 70-mm LC-MWC driven with sine waves: 5.2 V amplitude and 20 kHz frequency at the central contact (a); 1.8…3.4 V amplitudes and 95 kHz frequency at the central row of contacts (b).

When the temperature in the furnace reached 1050-$1100^0$C, the holder with the wires was brought down to the stop. The wires easily penetrated the glass, which was rather viscous at this temperature, being able to wet the whole surface of the wires. By applying this procedure we managed to reduce the amount of cavities at an interface between the glass and the wires, which problem was present in the previous technology.

Front surfaces of the back substrates were grinded and polished up to the optical quality with flatness error less than λ/2 (λ = 0.633 μm) and roughness less than λ/10. At the final stage of polishing, nitric acid was added to the polishing compound in order to etch the contact lugs. Then high-ohmic resistive layer was deposited onto of the polished surfaces. The deposition was done in vacuum by high-frequency magnetron sputtering from a target made from multi-component material ST-5015 (NIIMT, Russia) additionally alloyed with tantalum. Finally, a multi-layer dielectric mirror coating optimized for maximum reflectivity at 633 nm was deposited on the back substrates.

Interferometric patterns of the 70-mm device are shown in Fig.3. They were taken in the polarization interferometer, where the device was placed between two crossed polarizers oriented at $45^0$ to the initial LC alignment. Fig.3a shows response of the central contact, and combined response of several contacts is shown in Fig.3b. More experimental results can be found in [5] and [6]. Analysis of the operation modes of LC-MWC and its residual aberrations is presented in [7]. It was shown that the maximum flexibility can be achieved by control of two degrees of freedom per actuator – both the amplitude and the phase of the control AC voltage. Amplitude-only control allows application of linear control algorithms, similar to those applied for the deformable mirrors, provided that all control voltages have the same frequency and the same initial phase. The possibility to operate LC-MWC with several degrees of freedom per actuator make it unique among the modal correctors.

Closed-loop wavefront correction was demonstrated with a 30-mm LC-MWC; reduction of low-order aberrations from 0.531 to 0.200 λ was observed[5]. Besides, two 70-mm LC-MWCs were used in a laboratory multiconjugate adaptive optics system[8]. The system demonstrated closed loop correction in both single conjugate and dual conjugate modes; however, due to very strict tolerances to aberrations within the multi-conjugate system, the magnitude of correction was relatively small.

In the most cases, the wavefronts produced by LC-MWC feature spikes around the contacts; see, for example, Fig.3b. These spikes contain high spatial frequencies, which may complicate modal analysis of low-order aberrations with a Hartmann-type wavefront sensor in a general case. More correct and reliable results could be obtained by using a phase-shifting interferometer.

## 3. SILICON-BASED HYBRID-TYPE CORRECTOR

The glass-based technology described in the previous section can be extended to produce devices with apertures up to 10 cm and hundreds of actuators. Nevertheless, in its present state this technology is quite demanding and hardly suitable for serial production. Another option is offered by silicon technology, which allows forming the required structure of actuators on the surface of a chip using standard integrated circuit (IC) manufacturing processes. Another attractive feature of this approach is that on-chip implementation of the multiplexed control makes possible further scaling of this technology to hundreds thousands of actuators.

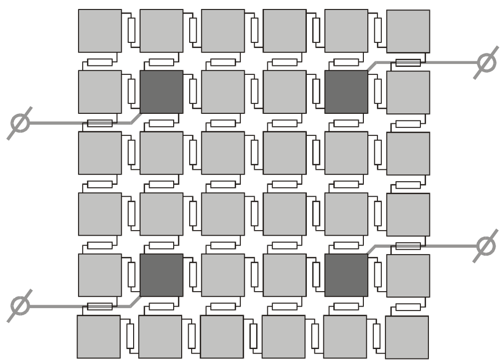
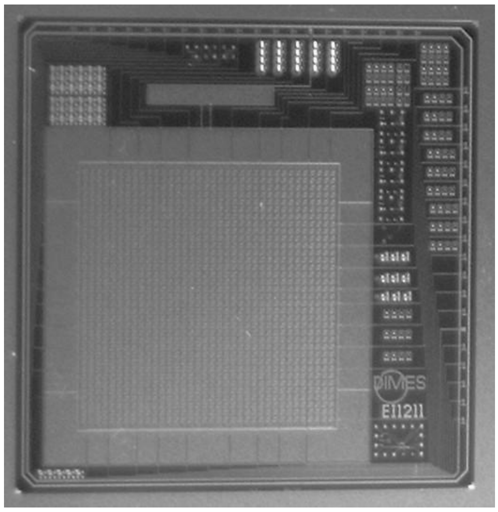


Fig.4. Structure of pixels of the hybrid LC-MWC interconnected by means of discrete IC resistors.

Direct implementation of the LC-MWC with continuous resistive layer cannot be accomplished in the framework of standard bipolar and CMOS processes, mainly because there are no standard technologies to produce layers with sheet resistances as high as it is required for the CE (0.1…1 MΩ/sq). We suggested an indirect implementation, which we called a *hybrid* approach, as it combines features of both the *zonal* and the *modal* approaches. Whereas a reflective backplane of the corrector has a pixel-type structure, which is typical for the *zonal* approach, *modal*-type control of the pixel array is implemented, which means that addressing of one control channel causes the whole array to respond. It is provided by interconnection of pixels using a network of discrete IC resistors, as shown in Fig.4. Only some of the pixels are addressed directly from the control unit (we call them *active* pixels), whereas the resistive network provides gradual voltage variation between the other pixels (*passive* ones). Such an approach results in a modulator with a large number of pixels driven by much smaller number of control channels and with performance comparable to that of the modal correctors.

Earlier[9] we have conducted numerical simulation based on the Kirchhoff's rules defined for all nodes of the resistive network. We carried out analysis of the correction efficiency and investigated effect of mismatch of the resistances; we found that rather poor matching with 10…20% mismatch and 1…2% of open-circuit resistors can be tolerated. We also demonstrated the possibility for improvement of the correction efficiency by adjustment of individual resistances. With respect to electro-physics of the problem, operation of the hybrid corrector is very similar to that of the LC-MWC with continuous resistive layer. It means that similar control methods can be applied to both types of devices.

For experimental realization of the hybrid approach we chose a standard technology – bipolar process DIMES03, which is available in DIMES Technology Center, TU Delft. Diffusion-type resistors with a resistance of 29.4 kΩ were formed by selective doping of 4 μm-wide stripe areas on the surface of the silicon substrates. All resistors in the network were matched by geometry and total length of horizontally and vertically oriented pieces in each resistor. In order to control electrical parameters of the process, test structures were placed on the chip. Electrical measurements of the test structures have shown good matching of the resistors with resistance mismatch less than 2%. Besides, the resistance of the network was measured between two arbitrarily chosen active pixels; the experimental value was in agreement with those calculated in the framework of numerical model with an error of 1.5%, which result confirms the validity of the model.

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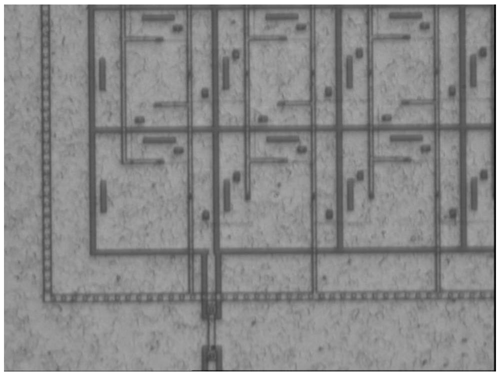
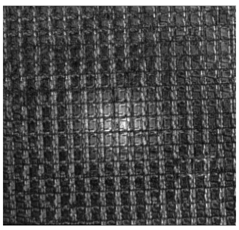
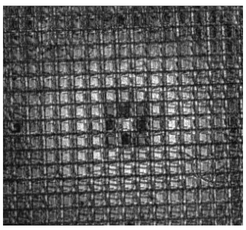
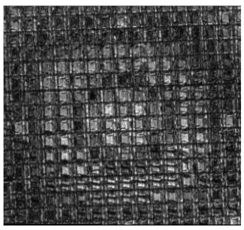
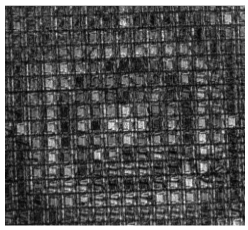
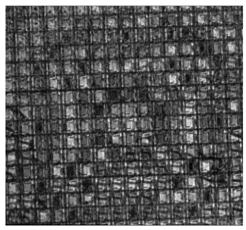


**(b)**

Fig.5. Backplane of the hybrid LC corrector (a); structure of pixels (b).

The first prototype (see Fig.5) had 1296 (36x36) pixels with 36 inputs; the pixel size was 220x220 microns; thus, the total area occupied by pixels was 8.2x8.2 mm. The pixels were formed by patterning of an aluminium metallization layer, namely, the second metallization. Size of the whole die, including bondpads, was 15x15 mm due to restriction of the lithographic equipment. To facilitate assembling of the LC cells, the substrates were made slightly larger than the die, 18x18 mm size. Calculated fill factor value was 82.8%; it is estimated as a percentage of the flat pixel area with respect to the total area, which also includes gaps between pixels, contacts to the resistors and grooves imprinted from the lower metallization layer. The whole structure of pixels was covered with silicon nitride, which is used in DIMES03 for scratch protection.

**(a)** **(b)** **(c)** **(d)** **(e)**

Fig.6. Visualization of the influence function of an active pixel; frequency of the square waves 1 kHz, amplitude $V_1$ = 4.5 V for the active pixel in the center and $V_2$ for other active pixels. Values of $V_2$ are 4 V (a), 3.5 V (b), 3 V (c), 2.75 V (d) and 2.25 V (e).

Homogeneous 25 µm spacing between the silicon substrate and the cover glass was provided by teflon spacers. Planar alignment of the LC was generated by exposure of linearly photopolymerizable polymer (LPP) to the polarized UV light. Commercially available LPP Staralign™ 2100 from Rolic, Switzerland, and BL006 liquid crystal mixture from Merck, Germany, were used. Birefringence of BL006 is 0.286 ($\lambda = 589$ nm), which results in a maximum range of phase variation for this modulator of about 22 λ. The assembled LC cell was mounted on a custom PCB mount and electrically connected to it by wire bonding.

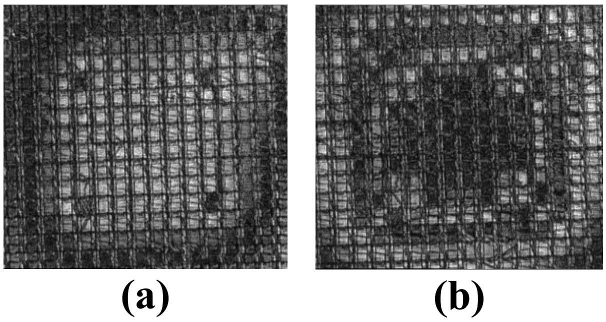



Fig.7. Combined influence of four active pixels; frequency of the square waves 1 kHz, amplitude $V_1$ for 4 adjacent active pixels in the center and $V_2 = 4.5$ V for other ones. Values of $V_1$: 3.5 V (a) and 2.5 V (b).

To drive the modulator, we used two 24-channel DAC boards from OKO Technologies (Delft, the Netherlands). Reliable multichannel generation of rectangular pulses was provided by custom control software developed using Venturcom RTX, a real-time subsystem for Windows NT/2000/XP. The system generated 36 meander AC voltages with amplitudes up to 5 V and frequencies up to 5 kHz. Phase profiles generated by the modulator were studied using polarizational interferometer.

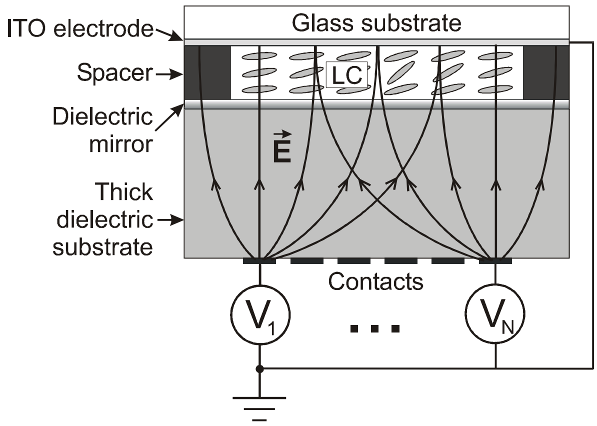



Fig.8. Schematic diagram of a modal LC corrector with thick dielectric substrates.

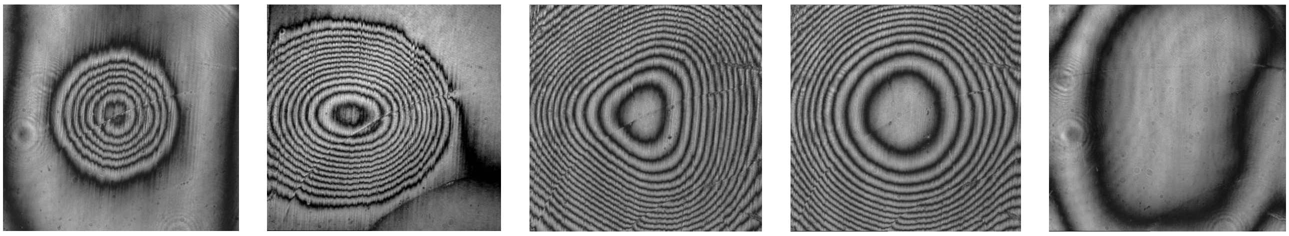
Responses of an arbitrarily chosen active pixel are shown in Fig.6. Square wave signal with 4.5 V amplitude and 1 kHz frequency was applied to that pixel, whereas the amplitude of the bias AC voltage applied to other active pixels was varied in the range from 4 to 2.25 V. Rotationally symmetric character of the interferometric patterns in Figs.6a-6c shows that, despite the discretization, the distribution of the optical phase across the array of pixels has a modal character. Moiré patterns appear in the interferogram when the phase variation between two adjacent pixels exceeds 2π, as seen in Figs.6d-6e. An example of combined influence of four active pixels is shown in Fig.7.

Detailed consideration of the interferometric patterns shows significant roughness of the reflective surface of the aluminium pixels and rather poor quality of the LC alignment with many dislocations. Both these factors cause scattering of light, which results in a weak contrast of the interferometric patterns in a large scale. The most likely reason of the poor quality of the LC alignment is roughness of the protective silicon nitride coating. This roughness arises naturally during the bipolar processing, as the process in general is not targeted to produce optical devices and no special measures were undertaken in the present design to improve the surface quality up to the optical standards.

In the next design we are intending to take appropriate measures in order to improve the optical quality of the reflective backplanes. First of all, the protective layer on top will be planarized by ion beam etching; then, a multilayer dielectric coating will be deposited on the planarized surface. Structure and dimensions of the pixels, the wires and the resistors will be optimized in order to increase the fill factor. Besides, we are also going to implement the structure of the resistive network which would provide the smoothest fitting of an arbitrary combination of low-order aberrations.

## 4. MODAL CORRECTOR WITH A THICK DIELECTRIC SUBSTRATE

Recently[10] we have proposed another implementation of the modal LC-MWC based on a different principle. It can be realized on a much lower budget with a higher efficiency for both reflective and transmittive configurations. Modal operation of the suggested device is based on using of dielectric substrates much thicker than the LC layer, so that the AC voltage, which is applied between the actuator on the back side of the dielectric substrate and the ITO electrode,



**(a)** **(b)** **(c)** **(d)** **(e)**

Fig.9. Influence function of the central contact (a); joint responses of 2 (b), 4 (c), 7 (d) and 19 (e) contacts; amplitude is 110 V and frequency 1 kHz for all addressed contacts.

would produce a non-localized electric field distribution over the bulk of the back substrate and the LC layer – see Fig.8. We could expect extension of the distributed electric field outside of the actuator area to be comparable to the thickness of the dielectric substrate. Since the ITO electrode is equipotential, the direction of the field is perpendicular to the ITO electrode and the LC layer. A ceramic material with high dielectric constant, similar to those used in ceramic capacitors, can be used to minimize the range of control voltages. Dielectric constants of these ceramics may be as high as 20000.

To model the electric field across the LC layer and evaluate the range of control voltages, we have performed finite element simulation using ANSYS simulation package. The LC mixture we used (BL006) has a dielectric constant in the range from 5.5 to 22.8, depending on the polarization state. The dielectric constant of our ceramic samples was in the range of 12000…15000, which far exceeds those of the LC mixture.

Based on the results of numerical simulation, we have designed and assembled a 19-channel modal LC corrector and a PC-based control unit. Square-shaped 3 mm-thick ceramic substrate with 20x20 mm dimensions was polished to a flatness of $\lambda/4$ for $\lambda = 633$ nm and coated with a multi-layer dielectric mirror optimized for maximum reflectivity at 633 nm. A layer of BL006 LC mixture had a thickness of 25 µm; planar alignment was provided by rubbed polyimide coatings. A 19-element hexagonal structure of contacts with 3 mm pitch was attached to the back side of the ceramic substrate. The electrode structure was borrowed from OKO Technologies (Delft, The Netherlands) where it was originally fabricated to control micromachined membrane mirrors.

The modulator was driven by 24-channel DAC board with 20-channel high voltage amplifier board, both from OKO Technologies. The software was similar to those we used for the hybrid LC corrector. The system provided control of square waves by 19 channels with amplitudes up to 150 V and 5 kHz maximum frequency.

The response of the device was investigated in a Twyman-Green interferometer relative to a flat reference. The interferometric patterns are shown for ~15x15 mm aperture. The direction of polarization of light from He-Ne laser operating at $\lambda = 633$ nm was adjusted by means of a polarizer to coincide with the direction of the initial alignment of LC molecules. When observing interferometric patterns for the polarization component perpendicular to the initial LC alignment, we did not notice any changes with the signals applied. It means that the substrate was not deformed in response to high voltages.

As it is seen in Fig.9a, addressing of a single contact results in a nearly rotationally symmetric response. Localization of the response is due to the fact the LC does not respond to electric fields below a certain threshold level, which is about 1.2 V for BL006. After comparison of the influence functions for different frequencies we found that at least in the range 100…5000 Hz they were not frequency-dependent.

As the influence function is rather broad, superposition of the influence functions of several contacts results in smooth wavefronts with no spikes, as shown in Figs.9b-9e. Absence of high spatial frequencies makes them suitable for analysis with a Hartmann-Shack sensor. An example of wavefront reconstruction using a Shack-Hartmann sensor with 127 microlenses is shown in Fig.10. In this example the wavefront was approximated by 44 Zernike polynomials. The reconstruction result (Figs.10b-c) was in agreement with interferometric data shown in Fig.10a.

Fig.10 also demonstrates the possibility to use phase of the driving AC voltage as an additional degree of freedom. In this example the AC voltage applied to the central actuator was inverted with respect to other voltages, which corresponds to a phase shift of π. Thus, this LC-MWC, as well as the resistive layer-based one, can be operated with several degrees of freedom per actuator.

Although the frequency of the AC voltage did not affect the influence functions, it is important to consider the case when the frequencies are different for two or more control voltages. In this case we deal with "incoherent" composition of the influence functions. Unlike the "coherent" case (equal frequencies), where the phase response of the modulator will correspond to the complex-valued sum of the voltage distributions generated by the contacts, in "incoherent" case it will correspond to *rms* composition of the influence functions. This problem was studied in [7] in application to the voltage divider-based LC-MWC. As seen from Fig.11, this interpretation is also applicable to the dielectric-based device. "Coherent" composition of three influence function shown in Fig.11a was not dependent on frequency; we got similar results when the common frequency was equal to 625, 1250 and 2500 Hz. However, we observed considerable change of the interferometric pattern after setting different frequencies to different contacts (Fig.11b). As it was found in [7], linear control algorithms may not work in "incoherent" case.

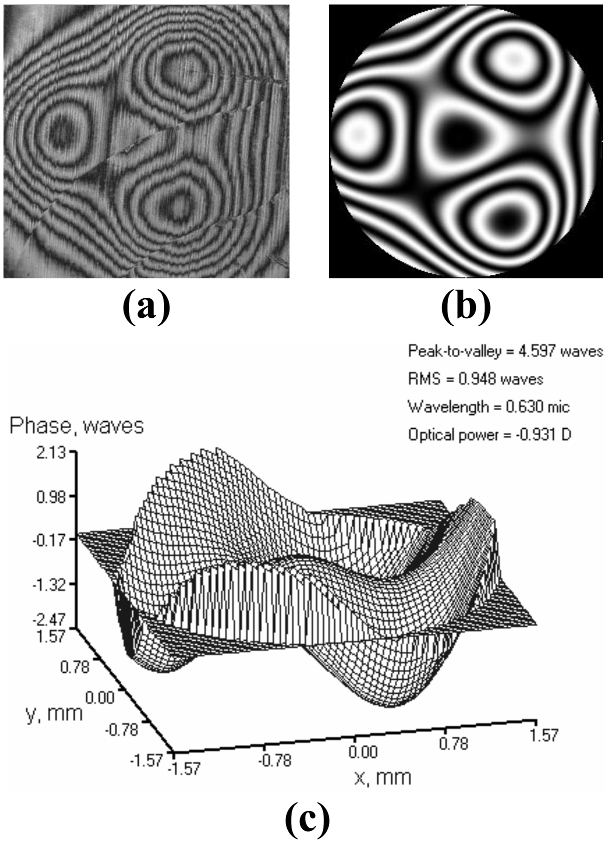



Fig.10. Response of four contacts with the signal inverted for the central contact; amplitude 110 V and frequency 1 kHz for all four contacts. Interferometric pattern (a); same calculated from the Shack-Hartmann sensor data (b); wavefront reconstruction (c).

The advantages of the reported device compared to mechanical deformable mirrors and to the voltage divider-based LC-MWC include simplicity of fabrication, low cost per actuator and easy integration of very large numbers of actuators with high density for both reflective and refractive (using optically transparent ceramics) configurations. The technology has a potential for realization of stackable multi-layer multi-conjugate correctors.

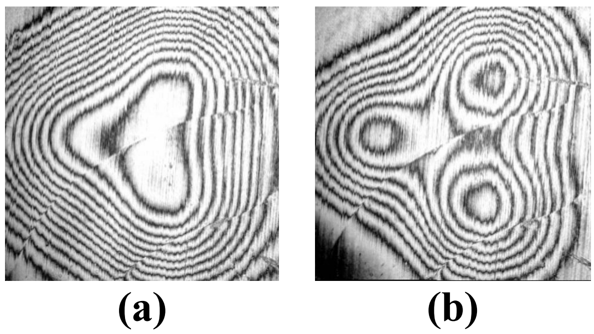



Fig.11. "Coherent" and "incoherent" composition of the influence functions of three contacts: amplitude 110 V and frequency 625 Hz for all three contacts (a); same amplitude, frequencies 625, 1250 and 2500 Hz (b).

## 5. CONCLUSION

An overview of three different options in implementation of LC wavefront correctors with modal addressing is presented in this paper. In the first approach, multiple pixel electrodes are replaced by a continuous resistive layer. Control voltages are applied to the contacts connected to the resistive layer, which serves as a distributed voltage divider. Special technology was developed for manufacturing of glass back substrates with embedded metal electrodes. Experimental 37-channel devices with 30 and 70 mm apertures and a modulation depth about 22 λ for λ = 0.63 μm were reported earlier. At the moment the technology is being improved to produce correctors with more actuators.

The second approach is based on a silicon technology. We will refer to it as a hybrid approach, as it combines features of both zonal and modal approaches. Structure of pixels is formed on the surface of a silicon chip by patterning of metallization layers. The voltage divider is implemented as a network of discrete resistors. Some of the pixels are addressed directly, whereas the resistive network provides distribution of voltage throughout the whole array of pixels.

Implementation in the framework of standard bipolar or CMOS process allows further scaling of this technology by integration of elements of control electronics into the backplane. We report preliminary experimental results of implementation of this approach based on the bipolar process. Forming of the modal-type influence function has been demonstrated. Improvement of the optical quality of the reflective backplanes will be targeted in the next design.

The third approach makes use of distributed electric field in thick dielectric layers for forming of the modal response of an actuator. We have assembled and tested 19-channel reflective device with a back substrate made of a ceramic material with a very high dielectric constant. The device can be implemented in transmissive (window) and reflective (mirror) mode. Low costs and simplicity of control make it a good alternative to continuous face-sheet deformable mirrors and the most efficient of the proposed solutions.

## 6. ACKNOWLEDGEMENTS

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