Zinc Selenide-based large aperture Photo Controlled Deformable Mirror

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

The realization of large aperture deformable mirrors with high density of actuators is an important issue for many applications and Photo Controlled Deformable Mirrors (PCDMs) represent an innovation in this field. Herein we show that the PCDMs design is scalable in size realizing a 2" aperture device, with polycrystalline zinc selenide as the photoconductive substrate and a thin polymeric reflective membrane. Zinc selenide is electrically characterized and analyzed in the framework of a model that we previously introduced. The PCDM is optically tested demonstrating its capabilities in adaptive optics.

OCIS codes: *(230.0230) Optical devices; (110.1080) Active or adaptive optics; (160.5140) Photoconductive materials; (230.4040) Mirrors.*

http://dx.doi.org/10.1364/OL.99.099999

Adaptive optics (AO) is a powerful technique to improve the quality and the performance of optical systems used in many fields of science such as astronomy, microscopy, ophthalmology and laser pulse shaping [1–4]. In order to perform the desired wavefront correction, active elements are used and deformable mirrors are the most common ones. Among them, membrane mirrors have been proposed and widely used due to their relative construction simplicity and ability to take on a continuous shape [5–7]. Among these, Photo Controlled Deformable Mirrors (PCDMs) represent a simplification of the control system since the membrane deformation is governed by the light pattern projected on a photoconductive substrate [8,9]. This configuration, that deploys well developed light projection techniques allowing to relax the requirements and the per-channel cost of control electronics [8], is very advantageous in high resolution applications that usually require a large number of actuators, such as astronomy, ophthalmology and high power lasers [6]. Moreover, the absence of actuators on the back of the mirror makes PCDMs suitable for particular applications where high resolution and light weight or small volume is needed such as telescope secondary mirrors [10,11]. The working principle of PCDMs is reported in figure 1: a thin reflective membrane is suspended above a photoconductive substrate and the system is fed by an AC power supply.

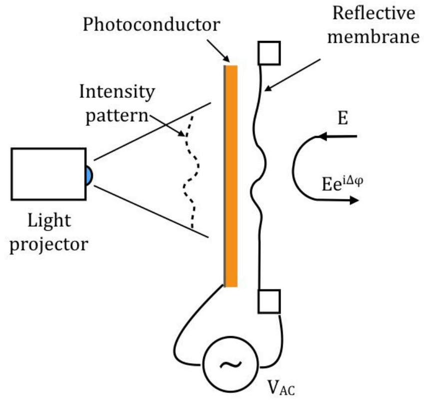

Fig. 1. PCDMs working principle

As a light pattern is shone on the photoconductor, the electrostatic pressure exerted on the membrane increases according to the light intensity, yielding a membrane deformation that is related to the light pattern. In the literature, the realization of PCDMs has been reported based on different photoconductive materials such as GaAs or $B_{12}SiO_{20}$ [6,8,12], but their optical aperture is still limited to about 1" diameter, limiting the possibilities to use such devices in fields where large apertures are required such as astronomy or high power lasers. In a recent study [11] we analyzed the working principles of PCDMs to find a correlation between their static and dynamic performances in terms of dynamic range and response speed, and the photoconductive material electro-optical properties, highlighting that high charge carrier mobility leads to a fast response time (large bandwidth), while a large thickness and a low relative dielectric constant lead to a high dynamic range (large membrane deformation). In this framework, the scalability of the device, that depends on the availability of large size photoconductive substrates has also to be considered . In this article we report the realization of a PCDM with a 2" diameter clear aperture based on zinc selenide (ZnSe). This semiconductor has a relatively high charge carrier mobility (540 and 30 cm^2/Vs for electrons and holes respectively in a single crystal), relatively low dielectric constant (9.25) and is available in form of large substrates [13]. As we previously reported, the performances of PCDMs are linked to the phtoconductance that, for a semiconductor with negligible dark conductance, can be defined as [14]:

$$\boldsymbol{\sigma} = \frac{\boldsymbol{\eta \tau_c I(\mu_e + \mu_h)e}}{h\boldsymbol{\nu L}} \quad (1)$$

where η is the photogeneration quantum efficiency, τ_c the charge carrier lifetime, I the light intensity, μ_x the mobility of holes and electrons, e the electron charge, hν the photon energy and L the photoconductor thickness. Since the values of η and τ_c are not known from literature for ZnSe, a setup simulating the working conditions of the PCDM (figure 2a) has been used to retrieve them. A polycrystalline ZnSe substrate is connected in series with a capacitor that simulates the presence of the membrane (Cm) and the current flowing in the circuit is measured as a function of light intensity, voltage bias and frequency. 20 nm gold electrodes were evaporated on the surface of the ZnSe substrate to provide a uniform semitransparent (T~50%) electric contact. The voltage applied to Cm (figure 2c) was calculated from current measurements and data were fitted using the photoconductor equivalent electric model shown in figure 2b. From the value of R, the conductance was calculated and it was found to be a linear function of the light intensity. Using equation (1), the value of $\eta\tau_c$ was obtained (1.88 x 10^{-7} s at 490 nm) assuming the literature carrier mobility. No significant dark conductance could be measured with this setup.

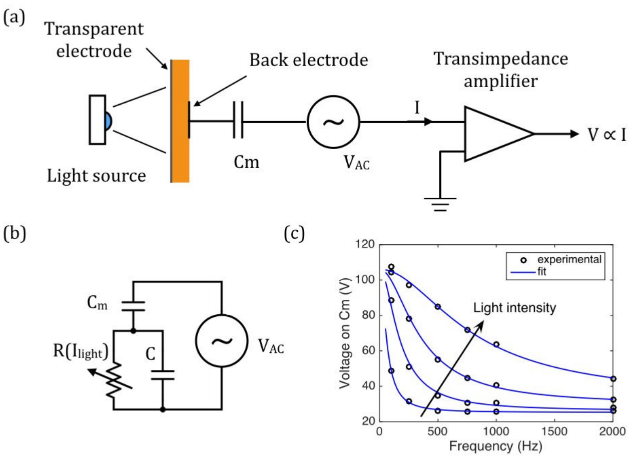

Fig. 2. (a) setup used for the ZnSe characterization, (b) equivalent electrical model of the PCDM, (c) voltage on Cm as a function of light intensity (indicare quali) and frequency. Empty circles represents experimental measurements whereas solid lines are obtained by fitting according to Equation (1) and electrical model (b).

Since the characterization showed that ZnSe has a good photoconductivity and its electro-optical characteristics are suitable for the realization of PCDMs, a 2" aperture PCDM was assembled using a 2" diameter, 2mm thick polycrystalline ZnSe substrate with a transparent ITO electrode (40 Ω/sq) on one side and a 5 μm (±10%) thick aluminized nitrocellulose membrane placed at 75 μm (±7 μm) from the photoconductor by means of suitable spacers (a picture of the assembled device is reported in figure 3).

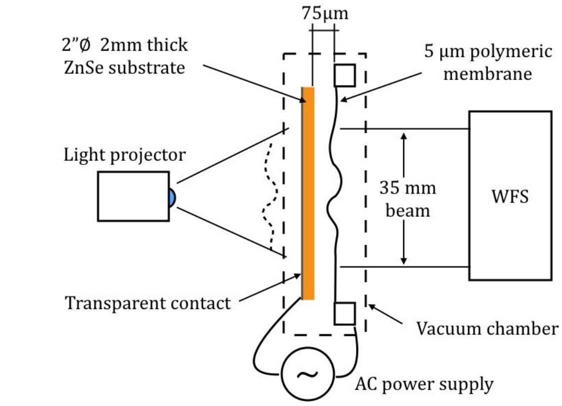

Fig. 3. 2" clear aperture PCDM construction details and setup for the optical characterization.

The 2" diameter PCDM was then characterized using an optical setup equipped with a 670 nm laser source and a Hartmann-Shack wavefront sensor allowing to measure the membrane shape (figure 3). The membrane tension was calculated measuring its maximum displacement at the center as a function of the applied electric field and fitting the data adopting the approximation of thin membranes [6,15,16] and resulted to be 68 N/m.

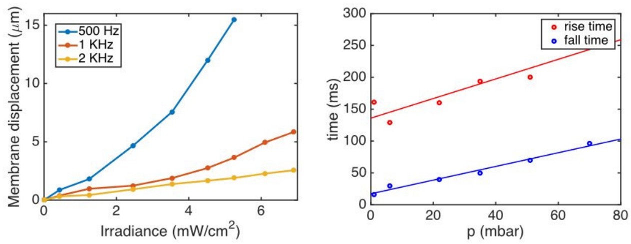

Fig. 4 PCDM membrane displacement as a function of light intensity (left) and PCDM 10-90% rise and fall times as a function of the vacuum chamber pressure at 400 Vpp, 500 Hz and their linear fit (solid lines).

The maximum membrane displacement at the center was measured as a function of light intensity at different frequencies in conditions of uniform illumination (figure 4 left). The displacement increases with light intensity and decreases with power supply frequency: this is in agreement with our previously reported electro-optical simulations [11].

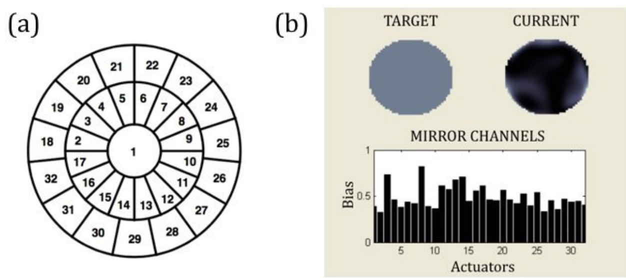

Fig. 5. (a) 32 discrete actuators geometry on a diameter of 45 mm used for the AO loop tests, (b) Example of interferograms of the target and current wavefront during the attempts to maintain a flat wavefront in the closed loop AO tests. At the bottom, the light bias (i.e. the normalized light intensity) applied to each actuator is shown.

The largest measured displacement (16 μm) was actually limited by the dynamic range of the wavefront sensor. The temporal response was characterized by illuminating the PCDM locally on an area of 1 cm^2, simulating the action of a single conventional actuator and measuring the membrane shape during time. Very slow response times (rise and fall time 10-90% > 300 ms) were measured for the PCDM in air due to its high viscous damping. For this reason, reduced pressure measurements were performed placing the PCDM in an airtight mount. A consistent decrease of the response time was measured decreasing the pressure as reported in figure 4 on the right (minimum rise and fall times: 129 ms at 6 mbar and 16 ms at 1 mbar), however a substantial difference was noticed between rise and fall times. This difference that can be tracked back to the membrane elastic force that acts against the electrostatic pressure and hinders the actuation but promotes the original membrane shape restoration.

Adaptive optics closed loop tests were performed to determine the PCDM capabilities. PCDM was driven by means of a DMD (Digital Micromirror Device) light projector equipped with a blue led (peaked at 450 nm) using a light pattern constituted by 32 discrete light actuators (figure 5a) covering a diameter of 45 mm. The maximum light intensity was 13 mW/cm^2 and working conditions of 400 Vpp and 500 Hz were chosen as a good compromise between a large displacement for relatively small light intensities and membrane vibration around its equilibrium position that tends to be more important at lower frequencies. Air pressure was 22 mbar. The test optical beam was chosen to illuminate only a portion on the active area of (∅ 35 mm). Influence functions were measured for each actuator and AO closed loop tests were performed. The control software was able to operate at a speed of 1 Hz. The PCDM was tested in order to maintain a flat wavefront (figure 5b) and allowed to maintain a wavefront error within $\lambda/60$, hence well within the Marechal criterion ($\lambda/14$). To demonstrate the capabilities of the PCDM to generate complex shapes, Zernike polynomials were generated up to Zernike number 14 (tetrafoil $Z_{4,-4}$), except for number 0, 1 and 2 (piston, tip and tilt) [17] as reported in figure 6.

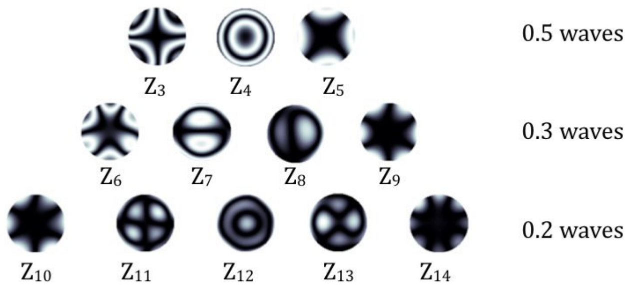

Fig. 5. Interferograms of the membrane shape when using the PCDM to generate first 14 Zernike polynomials (except for number 0,1 and 2) in the AO closed loop.

Even in this case the wavefront error was low (within $\lambda/10$) and the Zernike mode amplitude was decreasing for increasing order, as expected due to the low pass behavior of the membrane when assuming shapes with a high number of features.

In conclusion, a 2" diameter clear aperture PCDM was realized using zinc selenide as the photoconductive substrate. Electro optical characterization of the photoconductive material was performed and the PCDM was assembled and optically tested, giving a predictable response to light and relatively slow response time at low pressure. These results show that zinc selenide is a suitable material for the realization of PCDMs with large optical apertures. Since the PCDM response time has a complex dependence on the electro-opto-mechanical characteristics of the device, further work is necessary and will be undertaken in order to characterize and improve this aspect, thus extending the applicability of PCDM to fields where a large bandwidth is required. The possibility to drive the mirror using a high resolution illumination system, allowing to deploy all the resolution available with these devices will also be undertaken.

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