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Spatially and Temporally Tunable Window Devices on Flexible Substrates

Kezi Cheng^a, Aftab Hussain^a, and David Clarke^a

^aJohn A. Paulson School of Engineering and Applied Sciences, Harvard University,
29 Oxford Street, Cambridge, MA 02138

ABSTRACT

Windows whose transmittance can be modified by an applied voltage have previously been fabricated from soft, transparent elastomers sandwiched between ITO coated glass and a compliant, silver nanowire top electrode.¹ In this contribution we extend the capabilities of the tunable window so that the optical transmittance can be varied spatially over the window according to voltage signals applied to different segments of the back electrode of the window, defined by patterning of individually addressable electrodes. The actuation signals are controlled using TTL-level input signals applied to high voltage switches. We also show that the spatially tunable window can be fabricated on a flexible substrate, such as PET, and the optical transmittance is not affected by bending of the substrate. The use of a polymer substrate not only increases possible applications of this class of voltage controlled light modulation device but also has the potential of reducing cost at an industrial scale by replacing more costly ITO coated glass substrate.

Keywords: Dielectric elastomers, light modulation, spatially-tunable, bendable substrates, compliant electrodes

1. INTRODUCTION AND MOTIVATION

Electrically tunable windows are emerging as important components of smart, energy efficient buildings. The opacity of such windows can be tuned algorithmically according to the time of the day, incoming radiation or privacy needs. Thus, these windows enable a smart building to save energy on HVAC, while providing the same functionality of manual blinds. Moreover, if the optical tunability can be achieved in a spatially controllable manner, many interesting applications can be enabled. One such application is the partial tuning of windows for better optical controllability or dynamic tuning for mimicking manual blinds. Another interesting application is the use of windows or glass panes in large buildings such as stadiums and concert halls for tunable signage. Existing electrically tunable windows employ technologies such as electrochromic,² gasochromic,³ liquid crystal⁴ and magneto-active liquid.⁵ These technologies generally employ high cost materials or complex fabrication processes.

One class of electrically tunable windows is based on the coupled electro-mechanical deformation of a soft, flat, transparent elastomer sheet when a voltage is applied to a percolative network of nanowires or carbon nanotubes lying on the surface of the elastomer. When the network is charged relative to a conducting back-plane, for instance an Indium tin oxide (ITO) coated glass substrate, the Coulombic attraction of the nanowires to the ITO thin film, locally deforms the elastomer surface in the vicinity of the individual nanowires in proportion to the charge. The surface deforms from its initial, zero-voltage flatness producing refraction and hence scattering of incident light. As the percolative network consists of a random arrangement of nanowires over the surface, the optical scattering is random and uncorrelated. Consequently, applying a voltage decreases the in-line transmittance and produces an optical haze so that otherwise transparent elastomer window appears opaque. The degree of opacity, strictly the decrease in the in-line transmittance, depends on the applied voltage and is also reversible when the voltage is decreased to zero again.

Further author information: (Send correspondence to K.C.)
K.C.: E-mail: kezi_cheng@g.harvard.edu

Such voltage tunable windows have been demonstrated on ITO coated glass and typically consist of at least three layers.¹ The bottom layer is a conducting electrode on a stiff substrate (ITO coated glass), a layer of a highly transparent but soft elastomer and a top electrode formed by a percolative network of nanowires. Other layers with different functionalities can also be included, for instance to increase the breakdown voltages or to increase the adhesion or wettability of the layers.

In this contribution, we extend the capabilities of the tunable window in two ways, demonstrating that the tunable window can be fabricated on a flexible substrate and patterning the electrodes so that the transmittance of individual areas of the window can be altered spatially and in different controllable sequences. This not only facilitates the use of tunable window technology for flexible windows and displays but also opens up the possibility of tunable forms of camouflage and wearable technologies.

2. FABRICATION AND DESIGN PARAMETERS

2.1 Spatial Control of Transmittance

The basic structure of the tunable transmittance window we have used is shown in Fig. 1. It consists of two elastomer layers, spun-coated onto ITO glass with a top, electrically conducting and compliant layer consisting of a percolative network of either single walled carbon nanotubes or silver nanowires. The ITO coated glass, with a resistivity of 15 ohms/sq was obtained from University Wafers. The elastomer layers consisted of a stiff layer of 10:1 (elastomer to cross-linker ratio) and a softer (50:1) layer of silicone elastomers (Sylgard 184, Dow Corning). The stiffer layer was selected to increase the overall electrical breakdown field. The top electrode was deposited as described below.

To produce a spatial variation in the voltage tunable transmittance, the continuous ITO coating of a glass substrate has been patterned by etching away lines in the ITO, thereby defining the geometry of the addressable electrodes. For the examples shown in this contribution, we created a mask for five rectangular electrodes parallel to one another with a separation of about 50 microns, and then removed the ITO by etching in an HCl-based solution. The width of the electrode separation was found not to be critical but as it is designed to prevent electrical connection between adjacent electrode segments, it typically has to be a few tens of microns in width.

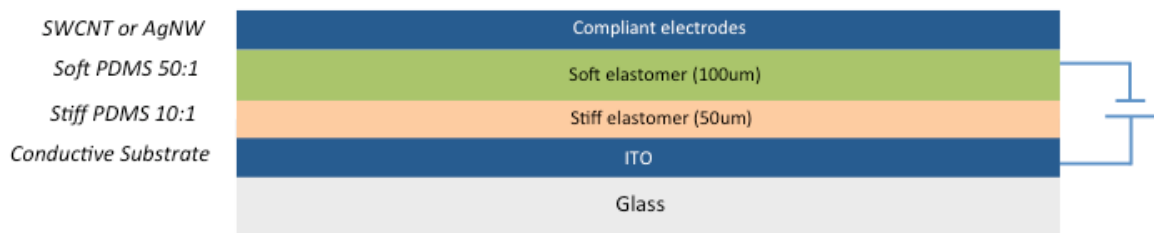


Figure 1. Electrodes sandwich two active layers in a light modulation device. Sylgard 184 of different elastomer to cross-linker ratio is spun-coated onto ITO coated soda-lime glass, with a thin layer of randomly oriented SWCNT sprayed onto the surface.

A compliant electrode, such as carbon nanotubes (P3 SWCNT, Carbon Solutions) or metal nanowires is then sprayed over the top of the elastomer layers and connected to the negative terminal (Fig. 2). (The electrodes do not extend to the edge of the elastomer so as to avoid electrical breakdown). The carbon nanotube solution was prepared using ultrasonication and suspended in isopropyl alcohol (IPA) before spray coating. Suspensions of the carbon nanotubes were then fed into an industrial spray head at the rate of 0.08mL/min where an atomizing air flow produced a suspension mist. The mist deposits on the window devices mounted on a stainless steel platform maintained at a temperature of 100C suitable for the immediate evaporation of the IPA, following the concept of spraying a fugitive carrier liquid.⁶ To produce depositions of uniform thickness over the entire substrate area, the spray head was moved at a constant spray height and speed over the substrates.

Once the device is completed and electrical connections are made to the window, individual or groups of individual segments of the patterned ITO electrodes can be electronically activated using high voltage solid-state

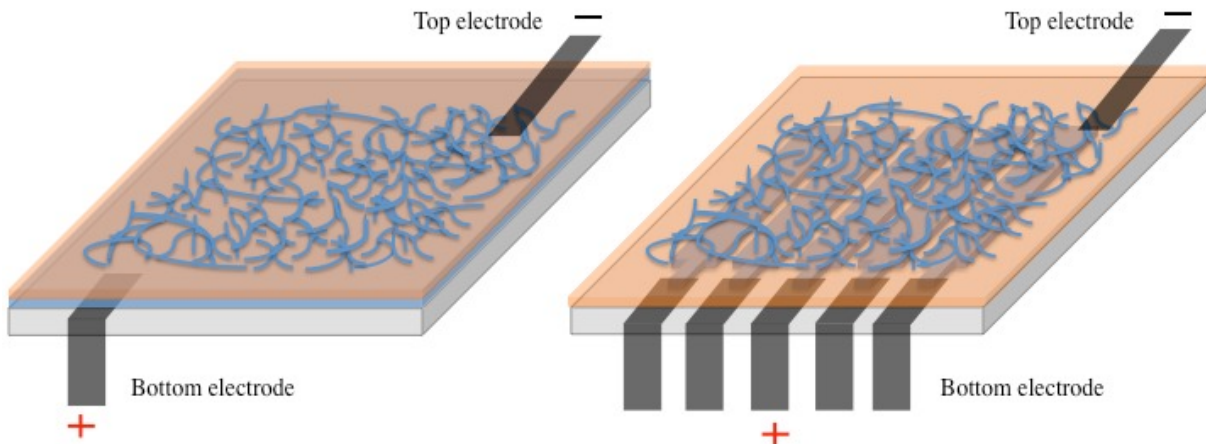


Figure 2. Perspective views of electrically controlled light modulating devices. The left diagram depicts a light tunable device that actuates the entire surface when voltage is applied. The right depicts a spatially controllable tunable device that actuates in panels separated by a 50 micron or narrower etched regions to separate the electrode segments and create a spatial variation in optical transparency.

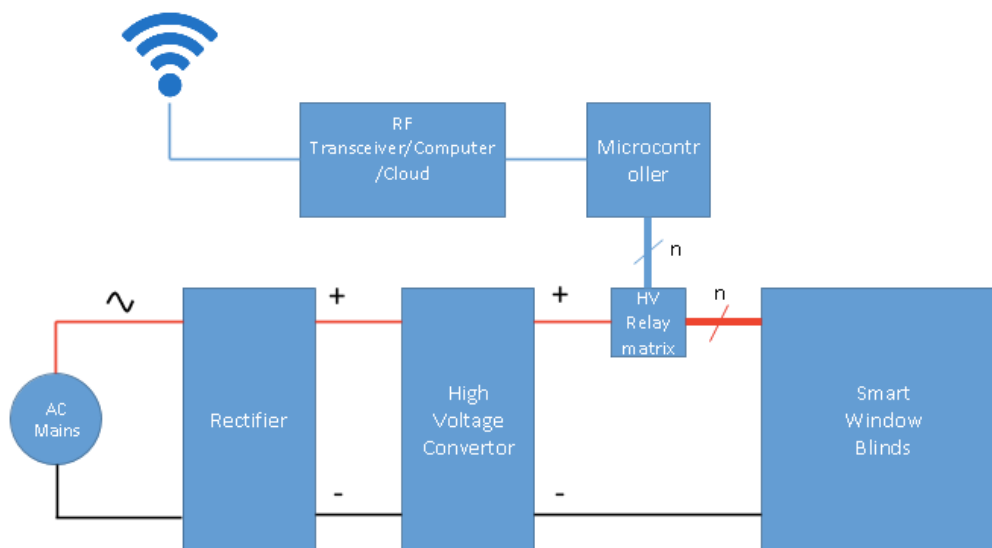


Figure 3. Block diagram of the electronic circuit control for the smart window blinds. The HV supply is generated through AC mains and the HV relay matrix can be operated with low voltage signals to energize the individual electrode segments. The control signals can be from a computer or in future from the cloud, a smart phone or from a hand-held controller.

switches to control the actuation of individual electrode segments using TTL-level input signals. In our current work, these signals were generated using a programmable microcontroller. The electronic control also makes it possible to discharge the addressed electrode segments, returning them quickly to their transparent state. In future, the microcontroller could be connected to an RF transceiver device for programmable control over Bluetooth or Wifi.

2.2 Flexible Structure

To create a flexible window device, the stiff ITO coated glass was replaced with a flexible substrate, a polyethylene terephthalate (PET) film coated with silver nanowires of different sheet resistance (10 ohms/sq and 50 ohms/sq).

It was found that free-standing, silver nanowire coated PET substrates have comparable high transmittance, low haze, and low sheet resistance to that of the ITO coated glass substrates. Window devices were fabricated in the same manner as those made on ITO coated glass with the exception that the PET films had to be taped down to a piece of glass so as to remain flat during the spin-coating of the elastomer layers and the subsequent spraying coating of the SWCNTs as the top electrode. Electrical contacts were then made to the AgNW/PET base and carbon nanotube top electrode. Electrical insulating tape was then used on all four sides of the PET sample to prevent shorts between the top electrodes from contact with the edge of the AgNW PET film (Fig. 4).

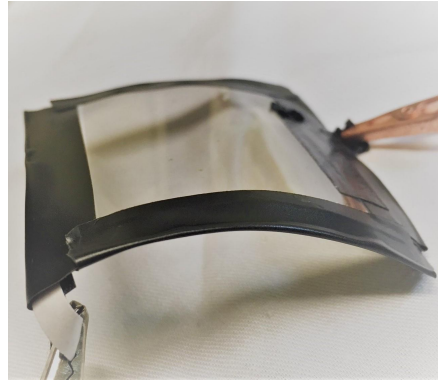


Figure 4. Flexible tunable window fabricated using silver nanowire coated PET as the transparent substrate. The black tape around the edges is electrical tape with electrical connections made to carbon contacts on the left and right.

3. CHARACTERIZATION AND PERFORMANCE

The in-line spectral transmittance at different applied voltages was measured using the arrangement shown schematically in Fig. 5. White light from a Mikropack Halogen light source (with 0.6 OD neutral density filter) was collimated and the transmitted light was collected and sent by an optical fiber into an Ocean Optics spectrometer where the light at 550 nm was recorded. The electrodes of the window devices were connected to a high voltage power supply (Trek Model 610E) which was used to amplify inputs from a waveform generator (Wavetek 5 MHz, Model 75A). For the measurements reported in this contribution, a constant ramp rate was used to increase the voltage from 0 to 5 kV over a period of 20 seconds.

For measurements of the devices prepared on ITO coated glass or AgNWs coated PET on glass, they were placed directly above the optical fiber collimator with the collecting lens approximately 4 cm above. For the flexible devices on PET, they were deformed by bending into a parabolic shape and held by supports to maintain their shape while their optical transmittance was measured. In this way, the effect of curvature on transmittance was determined.

To investigate whether the optical transmittance of a flexible tunable window was degraded on bending, the transmittance was compared for a flat flexible window and the same window when bent. Some of the comparison data in Fig. 6 shows change in transmittance with applied voltage for PET samples of 10 and 50 ohms/sq resistivity with and without glass support. The four samples, whether flexed or not, indicated similar transmittance decrease from ~70% to 15% when voltage was ramped up to 4kV. They also showed similar onsets for the decrease in transmittance at around 3kV. As expected, both of the 50 ohms/sq AgNW coated PET samples have slightly higher initial transmittance than their lower resistivity counterparts, whether flat or flexed.

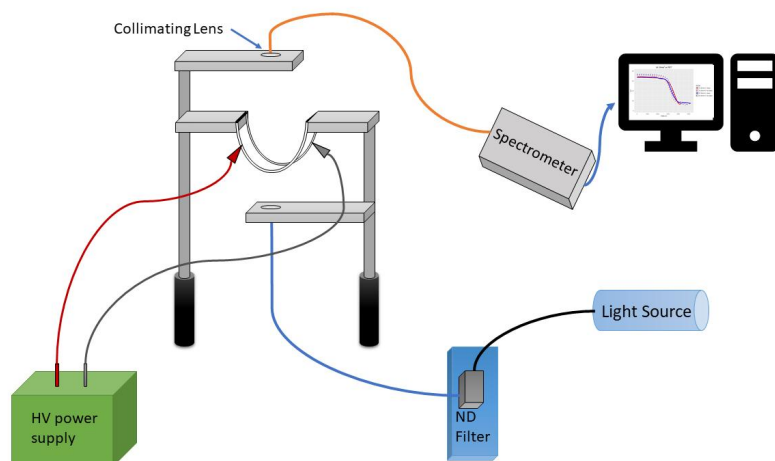


Figure 5. Schematic of the optical transmittance measurement system. In this schematic the window in the optical path is bent.

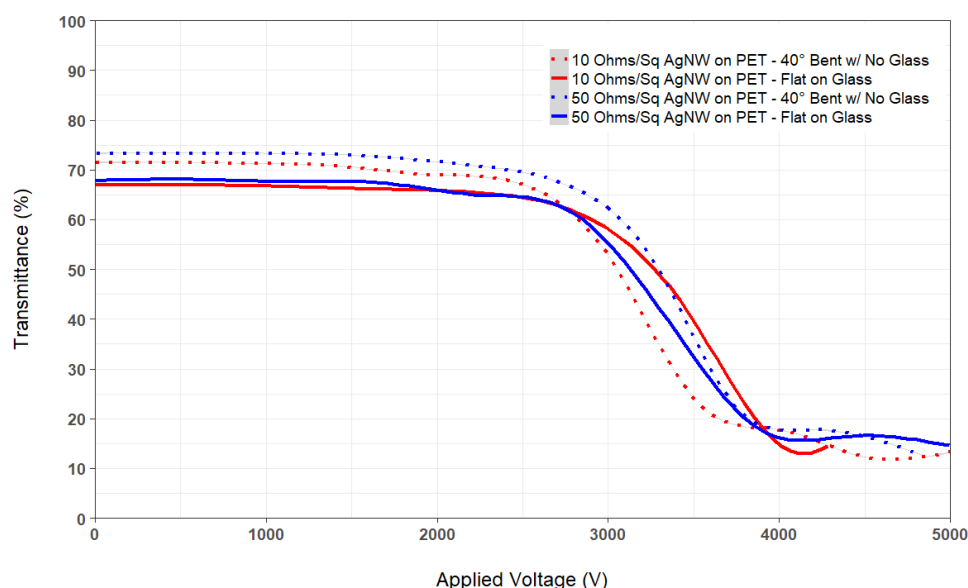


Figure 6. Optical transmittance at 550nm as a function of voltage for devices made with AgNW coated PET as the conducting substrate. Some samples were supported with glass while others were bent upwards to form a semi-cylindrical shape. Irrespective of whether the PET substrate was bent or not, the transmittance function was constant, being almost independent of voltage with the onset of tenability of transmittance at 3 kV.

Measurements of the transmittance response with changes in applied voltage are still underway but preliminary results are shown in Fig. 7 when successive voltages of 2 kV, 3 kV, and 4 kV are applied and then turned off. As shown, the transmittance decreases abruptly as the voltage is applied with the decrease in transmittance dependent on the voltage, consistent with the measurements in Fig. 6. The transmittance returns to the transparent, zero-voltage value but the recovery time depends on the magnitude of the applied voltage consistent with previously reported measurements made on windows prepared ITO coated glass. As in previous literature, there is an instantaneous increase in transmittance with the voltage being turned off but then a slower recovery characteristic of a visco-elastic response of the elastomer to the sudden change in local strains created by the deformation of the elastomer in the vicinity of the nanowires.

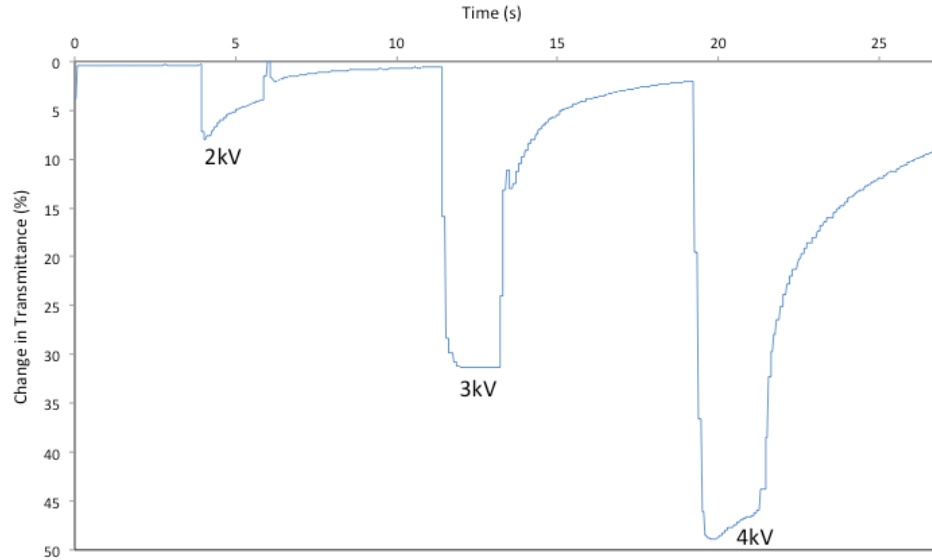


Figure 7. Response to three successive high voltage pulses of a tunable window having a 50 ohms/sq AgNW electrode on a PET substrate supported on glass.

To demonstrate the control of the spatial variation in optical transmittance, a series of images were viewed through a window of five individually addressable rectangular electrodes were recorded. The orientation of the electrodes was horizontal with respect to the image. The top left image in Fig. 8 was recorded when none of the electrodes was activated and so the window was transparent revealing all the words to the left of the vertical bar. Then, as voltage was applied to each electrode in turn, with the voltage remaining on the others, opaque bars successively obscured the lettering in the image. (No electrodes were activated to the right of the vertical bars). In this particular example, an equal voltage was applied to each electrode so the opacity was the same. This sequence mimics the action of a vertical blind being pulled down in front of a conventional glass window.

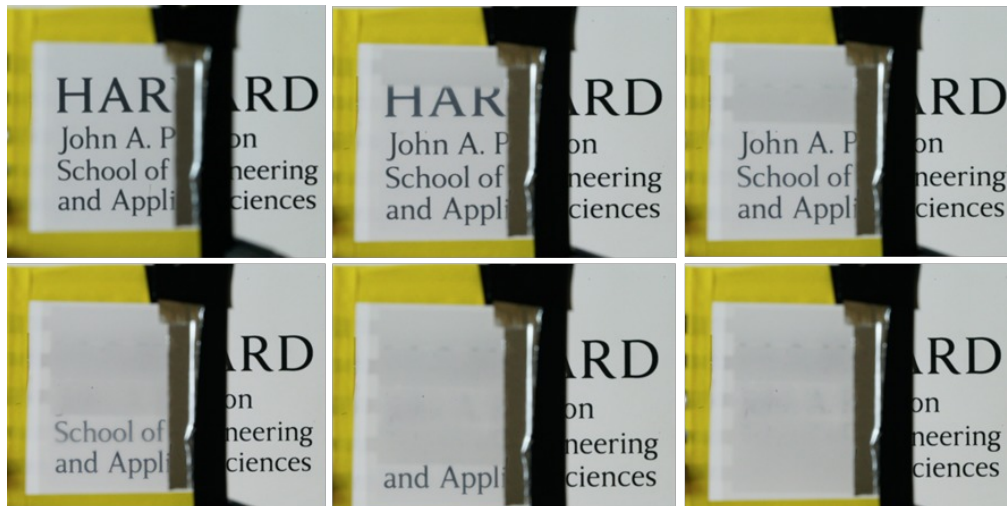


Figure 8. Sequence of images recorded as voltage is applied to five individually addressable electrode segments (clockwise). The electrode segments are horizontal so the sequential appearance is equivalent to a window blind being pulled down and obscuring the lettering located well behind the window. The black vertical features are the electrical contact to the top and bottom of the window.

A similar control of opacity is illustrated in Fig. 9 with a flexible AgNW coated PET window bent between two supports. When electrical contact is made to the electroded areas of the bent window, the transmittance changes and appears opaque in comparison with the areas where no voltage is applied.

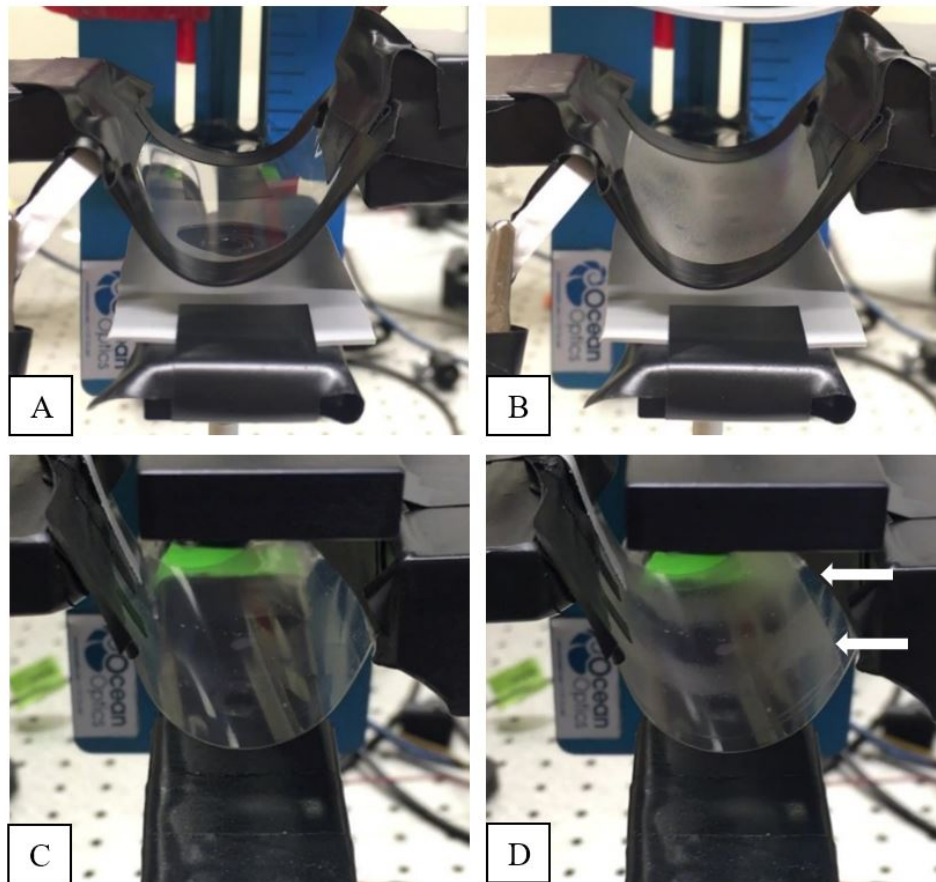


Figure 9. Tunable light modulation device on conductive PET a) at 0kV and b) at 4kV showing full haze; Spatially controllable tunable light modulation device on conductive PET c) at 0kV and d) at 4kV showing two opaque slabs where electrical contacts are made.

4. CONCLUDING REMARKS

The observations described above show that the voltage tunable window, originally developed for glass substrates, can also be implemented on flexible substrates without any degradation with bending. Furthermore, by using patterned and individually addressable set of electrodes, it is possible to vary both the spatial variation in opacity and its magnitude with position. Although only rather simple electrode patterns have been illustrated to mimic the action of a common set of horizontal blinds, other more complex shapes and patterns can be produced. Because only low resolution electrode patterning is required and the technology can be implemented on silver nanowire electroded plastic rather than ITO coated glass, there is significant potential for the development of considerably cheaper, larger and more versatile tunable windows manufactured using existing roll-to-roll techniques and spray technologies.

ACKNOWLEDGMENTS

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