Transparent actuator made with few-layer graphene electrode and dielectric elastomer, for variable focus lens

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A transparent dielectric elastomer actuator driven by few-layer-graphene (FLG) electrode was experimentally investigated. The electrodes were made of graphene, which was dispersed in N-methyl-pyrrolidone. The transparent actuator was fabricated from developed FLG electrodes. The FLG electrode with its sheet resistance of 0.45 kΩ/sq (80 nm thick) was implemented to mask silicone elastomer. The developed FLG-driven actuator exhibited an optical transparency of over 57% at a wavenumber of 600 nm and produced bending displacement performance ranging from 29 to 946 μm as functions of frequency and voltage. The focus variation was clearly demonstrated under actuation to study its application-feasibility in variable focus lens and various opto-electro-mechanical devices.

Variable-focus lenses have been extensively considered in a wide range of applications, such as cameras, projectors, mobile phones, and machine vision.1,2 The focusing can be achieved by mechanical stress,2,3 electrochemistry,4 and electro-wetting.5 Various authors have studied electroactive polymer (EAP) actuators as variable-focus lenses. For example, an ionic polymer-metal composite (IPMC) was used as a lens which gave an actuation of 0.413–0.608 mm,6 and a cantilever-shape IPMC actuator exerted pressure on a liquid that was in contact with a transparent polydimethylsiloxane lens.7 A carbon-polymer composite actuator has been used to drive a liquid-based variable-focal lens device.8 In these EAP-based variable-focus lens systems, however, the actuator is typically used to tune the shape of a passive lens made of liquids. In contrast to the liquid tunable lenses, an all-solid-state and self-actuating polymer lens can very well to mimic the working principle of the human eye lens. Additionally, the solid-state lenses can better withstand fluctuations in temperature, pressure, and motion compared to liquid-based lenses, which offer a more robust approach to tunable optical systems.9

The lens effect is achieved when the optical paths of the light beams propagating through different parts of the medium are different. Thus, the lens can be formed either by varying the thickness of the material (as in conventional glass lenses) or by varying the refractive index across the light beam.10 If the dielectric elastomer is flat, there is no focusing effect. When voltage is applied across the elastomer while the edges are fixed, the expansions of the elastomer along the lateral direction would result in a deformed surface of the elastic elastomer which would eventually attain convex or concave shape. The origin of the actuation in this system is a mechanical pressure generated by the electrical potential across the dielectric material, known as Maxwell stress (see Fig. S1 in supplementary material11)

\[ P = \varepsilon_0 \varepsilon_r E^2, \]  
\[ E = \frac{v}{t}, \]

where \( P \) is the Maxwell stress and \( \varepsilon_0 \) and \( \varepsilon_r \) denote the permittivity of free space and the relative permittivity of the elastomer, respectively. \( E, V, \) and \( t \) represent the electric field, applied voltage, and thickness of the dielectric elastomer, respectively. Therefore, the key elements for the development of the variable-focus lens in the solid state are the transparency of the dielectric elastomer and electrode materials which would actuate and deform to generate various refractive indices. Indium tin oxide (ITO) is the most commonly used transparent electrode material in various display systems, such as organic light emitting diodes, touch screens, and liquid crystal displays. However, ITO is too brittle and stiff to be used in dielectric elastomer actuators (DEAs). Several alternative transparent electrodes have been investigated, including thin metal films,11 carbon nanotube random meshes,12 metal nano-wire random meshes,13 and conducting polymers.14 Poly(3,4-ethylenedioxythiophene) has been successfully deposited on the surfaces of silicone rubber elastomer to give a transparent solid-state actuator,14 demonstrating its capability as a compliant electrode for changing the focal length of the incident beam. While substantial progress has been made in those transparent and compliant electrode systems, many issues still remain to be addressed in terms of performance, durability, lifetime, surface roughness, manufacturability, etc.

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