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Elastomeric optical elements with deformable surface topographies: applications to force measurements, tunable light transmission and light focusing

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Abstract

We fabricated and characterized three elastomeric optical devices whose optical properties are controlled by distorting the surface topographies of the elastomeric elements. In the force sensor, an applied force distorts the retroreflective corner cube surface pattern increasing the transmissivity of the device. The magnitude and the location of the force can be related to the intensity of the transmitted light. In the thermal light valve, the corner cube topography is distorted thermally; the transmissivity is controlled by the amount of heat delivered to the device. In the elastomeric Fresnel lens, heating of the elastomer results in defocusing of light passing through the lens.
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1. Introduction

In this communication we describe the fabrication and performance of three elastomeric optical devices whose optical characteristics are controlled by deforming their surface structures. This work is a continuation of our previous effort to use isotropic, transparent elastomers in optical components such as filters [1], light valves [2,3] and interferometers [4]. In the present study, we focus on how the transmissivity of the devices can be controlled by means of either a mechanical compression or a thermal expansion of the elastomer. Two of the devices use a corner cube surface topography [5], and are composed of a thin, rectangular slab of an isotropic, optically transparent polymer — polydimethylsiloxane (PDMS) — having an array of corner cubes embossed on the surface. This topography (Fig. 1) makes the polymer reflective in the direction perpendicular to the patterned surface, and for light meeting the surface of the corner cubes from the side of PDMS (the optically more dense medium). Deformations of the corner cube pattern result in light transmission. The first device (a force sensor) is suitable for measuring forces, torques and local pressures by relating the optical transmissivity of the device to local mechanical distortions of the corner cube pattern. In the second system (a thermal light valve), the PDMS is doped with a strongly absorbing dye (oil red ZMQ, American Cyanamid, Bound Brook, NJ). The topography of the surface is deformed by heat generated by adsorption of the incident light. In this device, light transmissivity is proportional to applied power. The third device (a Fresnel lens) is a transparent PDMS element with a Fresnel lens [6] surface topography. Upon heating, the surface structure flattens, and this flattening results in defocusing of light passing through the device.

The elastomeric optical components described in this communication are easy to fabricate, inexpensive and durable. They could have applications in sensor devices force, torque, pressure gradient, power) [7–10], in energy saving windows [11–13] and in optical filters and mirrors [14,15].

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2. Experimental

2.1. Fabrication of optical elements

The elastomeric force sensor was a rectangular block ($10 \times 10 \times 1$ mm) with 150 μm corner cubes embossed on its surface. This element was prepared by a two-stage procedure (Fig. 2). First, a rigid epoxy replica was fabricated by casting against a commercially available tape (Jogslite, Silver Lake, NH) whose surface presented an array of corner cubes. Second, PDMS (1:10, Dow Corning) was cast against this replica, cured thermally for 2 h at 60°C, and gently removed by peeling.

The light valve was fabricated using a similar procedure to give a $10 \times 10 \times 5$ mm rectangular PDMS slab. This element was then soaked in a saturated solution of oil red ZMQ dye (CALCO) in ethanol/hexanes (3:2) mixture for 2 h, and then dried at 60°C for 12 h to remove the solvent.

The fabrication of the elastomeric Fresnel lens started with preparing a PDMS replica by casting PDMS against an acetate butyrate 1-in. Fresnel lens (100 grooves per inch; Edmund Scientific, Barrington, NJ). PDMS was cured thermally, separated by peeling and silanized for 1 h with (tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane [16,17]. PDMS was cast against this replica, thermally cured and separated to give a PDMS Fresnel lens.

2.2. Measurement

2.2.1. Force sensor

The PDMS element was placed between two glass slides: one fixed and the other free to pivot around a supporting screw (Fig. 2). A thin metal spike (attached to a compressed, calibrated spring) was pressed against the glass plate to exert force on it. The optical response of the device to applied force was measured with a HeNe laser ($\lambda = 632.8$ nm) by monitoring the intensity of transmitted light.

2.2.2. Thermal light valve

A green laser ($\lambda = 532$ nm; 5 mW tunable power output) was used to measure the transmissivity of the device. The intensity of light transmitted in the direction of the incoming beam was measured with a photodiode detector (Newport, 1830 C) as a function of both the laser power and of time. (iii) Fresnel Lens. The PDMS lens was placed between two fixed glass plates and a laser beam having a diameter of ~2 cm was passed through it. The lens was uniformly heated with an IR source; the temperature of PDMS was recorded by two independent thermocouples (Omega DP462) embedded in PDMS, and positioned near the opposite edges of the PDMS block. Defocusing of light passing through the lens was monitored by a photodiode detector placed in the focal point (behind a pinhole of ~2 mm diameter).

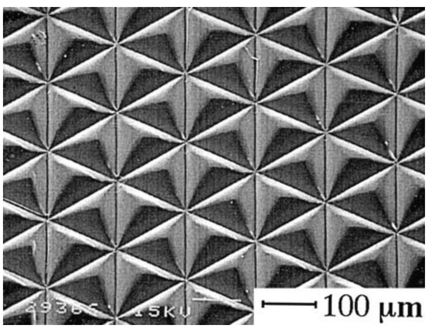

Fig. 1. Shows an SEM image of the corner cube pattern molded in PDMS.

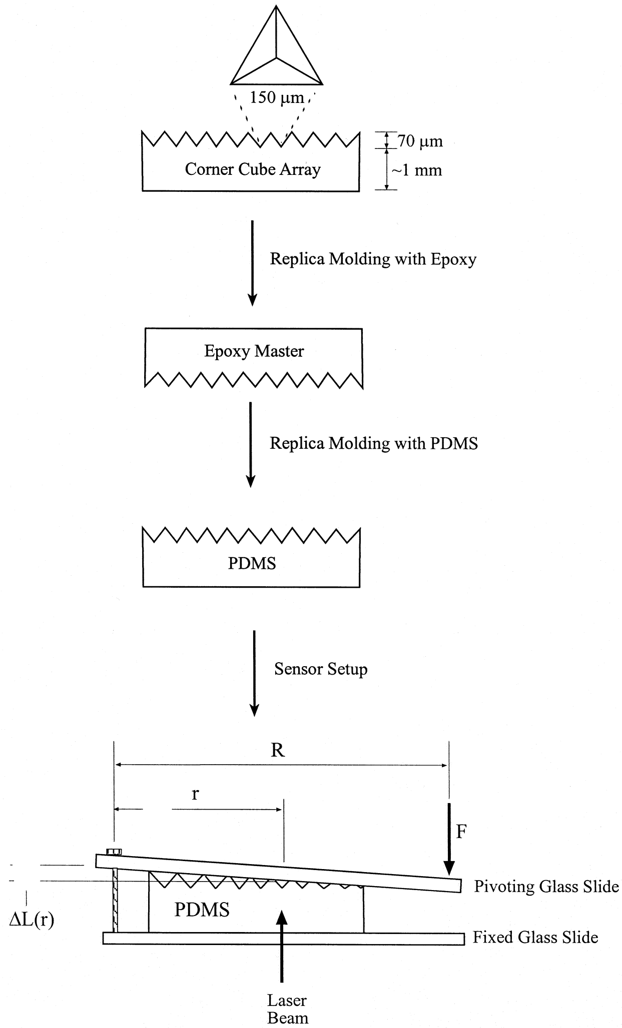

Fig. 2. Outlines the fabrication and the assembly of the force sensor.

3. Principle of operation

3.1. Force sensor

The intensity of light transmitted by an elastomer with a corner-cube pattern on its surface depends on the degree of

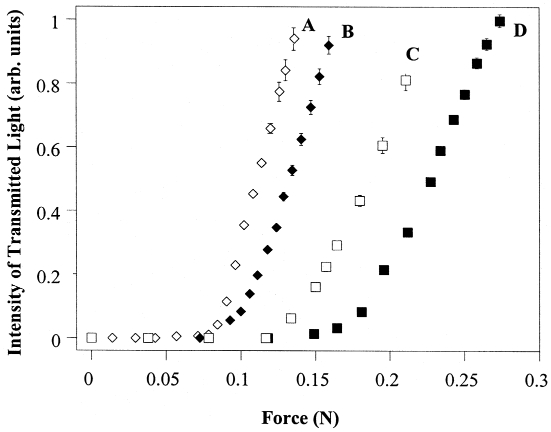

Fig. 3. Shows the experimental force-intensity curves for the force sensor. Each curve corresponds to different values of R (lever of force) and r (position of the probing beam): A ($R = 5.6$ cm, $r = 2.6$ cm); B ($R = 5.6$ cm, $r = 2.2$ cm); C ($R = 3.4$ cm, $r = 2.6$ cm); D ($R = 3.4$ cm, $r = 2.2$ cm). Each point is an average of five independent measurements. Error bars are shown for measurements, in which the relative error is smaller than the marker size. If the force were applied and released slowly, the device showed no hysteresis.

compression [2]: no light is transmitted for low compressive strains; above some threshold value of strain, the intensity of transmitted light increases linearly with compression (Fig. 3). The empirical dependence of the intensity of transmitted light, I, on the compressive strain can be expressed by Eq. 1, in which α and β are constants, L is the thickness of the uncompressed elastomer, and ΔL is the change in thickness upon compression.

$$I\left(\frac{\Delta L}{L}\right) = \begin{cases} 0 & \text{for } \frac{\Delta L}{L} < \beta \\ \alpha \frac{\Delta L}{L} - \beta & \text{otherwise} \end{cases} \quad (1)$$

In this work, we created a gradient of compressive strain across the surface of the elastomeric corner cube array (the notation used in further calculations is explained in Fig. 2). Since local deformation (and thus optical transmissivity) of the elastomer depends on r and R, Eq. 1 can be modified to give Eq. 2.

$$I\left(\frac{\Delta L(r,R)}{L}\right) = \begin{cases} 0 & \text{for } \frac{\Delta L(r,R)}{L} < \beta \\ \alpha \frac{\Delta L(r,R)}{L} - \beta & \text{otherwise} \end{cases} \quad (2)$$

We experimentally verified that up to $\sim 20\%$ compressive strain, the deformation of the elastomer is proportional to the applied force, $\Delta L(r,R) \propto F(R)$. From a simple geometrical argument of similar triangles, it follows that $\Delta L(r,R)$ is proportional to r and that β is proportional to r^{-1}. Because the total moment of force on the system must be equal to zero (i.e., $Fr - \int dF(r) = 0$), it is also true that $\Delta L(r,R) R \propto$ and $\beta \propto R^{-1}$. Combining these relations, we obtain Eq. 3 which describes the optical transmissivity of the elastomer (a,b are constants).

$$I(F(R)) = \begin{cases} 0 & \text{for } F(R) < b/rR \\ arRF(R) - b/rR & \text{otherwise} \end{cases} \quad (3)$$

3.2. Thermal light valve

In this device, the corner cube topography of the surface is distorted by delivering heat to the elastomer by a laser beam passing through it. Because PDMS is doped with a dye strongly absorbing visible light, green laser light can be used for efficient heating. When the device is illuminated, the thermal expansion of the elastomer (PDMS

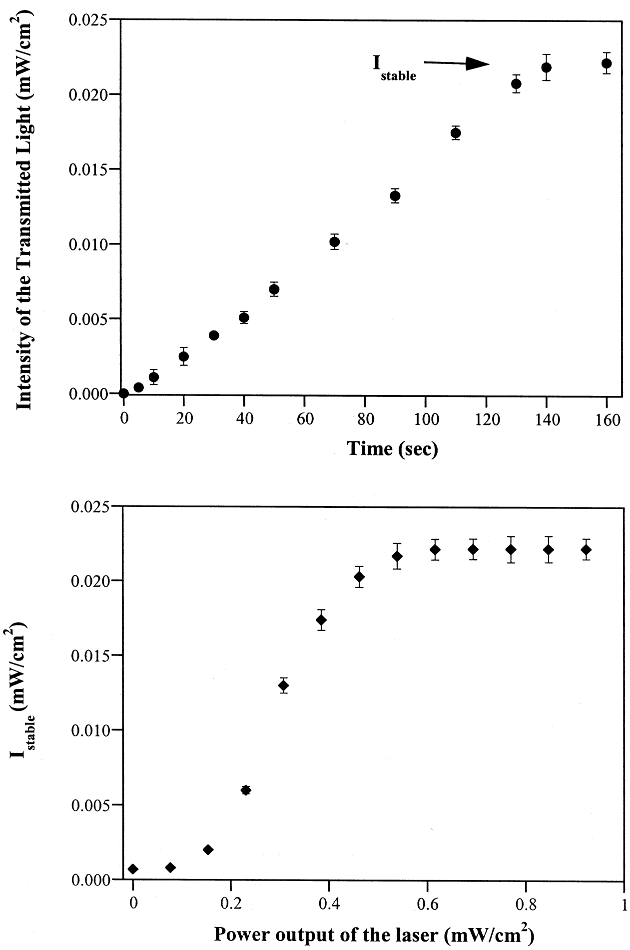

Fig. 4. The curves give the intensity of the transmitted light as a function of time (top) and of the power output of the laser (bottom). A green laser ($\lambda = 532$ nm) was used in the experiments. In (A) the laser power output was tuned to 2 mW/ cm^2. Each point is an average of four independent measurements; error bars correspond to the relative errors of these measurements.

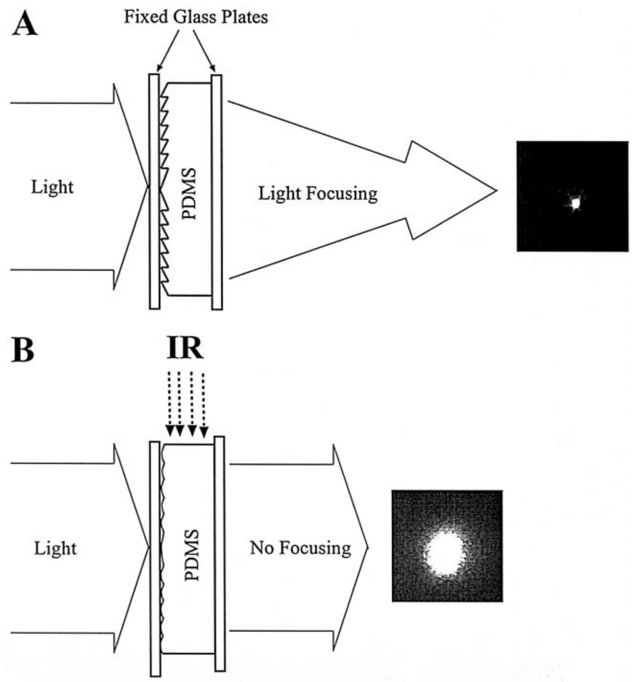

Fig. 5. Shows a scheme of the Fresnel lens device. In the resting state (A), the lens focuses light. When the device is heated with an IR source (B), the PDMS expands and the surface topography flattens; as a result, the light defocuses. The inserts show the optical images of the focal plane where the laser beam is focused (A) and defocused (B).

has a high value of the coefficient of thermal expansion: 0.0003°C^{-1} [4]) flattens the corner cubes (specifically, the edges of the corner cubes and the trenches between the cubes), so that they are no longer totally reflective.

For a given laser power, the transmissivity of the device depends on time in a sigmoidal fashion. For small times, heat diffusion flattens the surface topography, and transmissivity increases; when the device comes into thermal equilibrium with the surroundings, the transmissivity stabilizes (the intensity of transmitted light stabilizes at I_{stable}; Fig. 4a).

The maximum degree of distortion (and thus I_{stable}) depends on the amount of heat delivered: at low power outputs of the laser, the distortion of the surface topography is small, and I_{stable} is low. An increase in the power output of the laser results in more pronounced flattening of the cubes, so that I_{stable} increases. When the laser power is increased even further, I_{stable} reaches a roughly constant level: at this stage the portions of the surface that are easily distorted (edges and trenches) have been already "rounded", and additional heat does not produce a marked additional distortion of the surface topography. The power–I_{stable} dependence is therefore sigmoidal (Fig. 4b).

3.3. Fresnel lens

In the resting state, the elastomeric Fresnel lens focuses light. When PDMS is heated, the elastomer expands and presses against the glass plates between which it is held (Fig. 5). As the result, the surface structure of the device is flattened, and the element simply transmits light without focusing it; the intensity of light in the focal point decreases.

4. Results

4.1. Force sensor

The experimental force–intensity curves (Fig. 3) are in agreement with the functional dependence derived in Eq. 3: (i) the "threshold force" (i.e., a minimum force at which the device starts transmitting light) is inversely proportional to the product of the lever of force R and the location of the probing laser beam r. (ii) for larger forces, the intensity of transmitted light increases linearly with force, and the slope of this line is proportional to rR. Because the proportionality constants are the same for all values of r and R, the device can be calibrated by choosing one force–intensity curve as a reference (here, we chose $R = 5.6$ cm and $r = 2.6$ cm, Table 1). After calibrating one force–intensity curve, the device can be successfully used for direct force readout. If the lever of force R is known the intensity of transmitted light can be related to the magnitude of applied force by Eq. 3. If neither the magnitude nor the lever of force are known, the transmissivity of the elastomer has to be probed at two different locations; giving two independent equations that can be solved for R and F. The characteristics of the sensor can be altered by modifying elastic properties of PDMS. Adding more curing agent to the prepolymer increases the Young's modulus of the polymer making it suitable for measuring larger forces. Increasing the thickness or surface area of the PDMS slab has similar result.

4.2. Thermal light valve

Fig. 4 shows the dependence of the intensity of transmitted light on time for a laser power of 2 mW (at a beam diameter of ∼5 mm). The intensity of transmitted light increases for about 2 min before it reaches a plateau at

Table 1
Values of the slopes and threshold forces for the force-intensity curves of the force sensor. The values for $R = 5.6$ cm and $r = 2.6$ cm were taken as a reference.

(R,r) [cm]	Slope (theory)	Slope (experiment)	Threshold force [N] (theory)	Threshold force [N] (experiment)
5.6, 2.6	c_1	–	c_2	–
3.4, 2.6	0.607 c_1	0.61 c_1	1.647 c_2	1.64 c_2
5.6, 2.2	0.846 c_1	0.84 c_1	1.180 c_2	1.19 c_2
3.4, 2.2	0.514 c_1	0.52 c_1	1.945 c_2	1.95 c_2

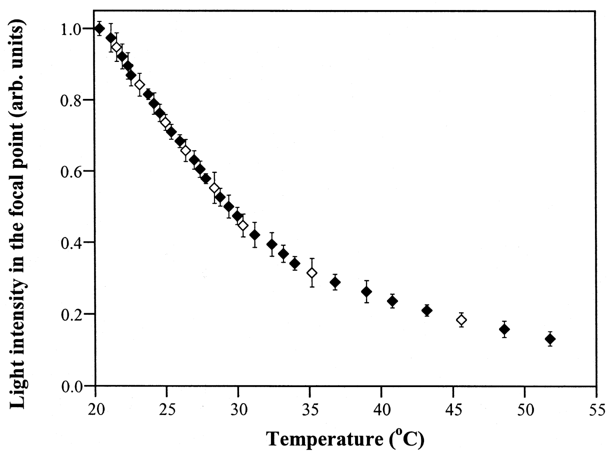

Fig. 6. Gives the dependence of light intensity at the focal point of the elastomeric Fresnel lens on temperature (measured by two independent thermocouples embedded in PDMS). Each point corresponds to five independent measurements; error bars give the relative errors. Solid markers correspond to measurements performed while heating the device, open markers — while the device was cooling; no hysteresis was observed.

I_{stable}; its rate of increase is relatively slow, because of low thermal conductivity of PDMS [4]. When the intensity of the illuminating laser beam is varied, the maximum intensity of transmitted light changes (Fig. 4b). In accordance with the analysis presented earlier, the curves are approximately sigmoidal. The device gives reproducible readings over many (> 100) cycles, indicating that changes in the elastic properties of PDMS (e.g., crosslinking) caused by the heating laser beam are negligible. When the device is allowed to cool down, the intensity of transmitted light decays approximately exponentially with $t_{1/2} \sim 90$ s.

4.3. Fresnel lens

Fig. 6 shows the dependence of the intensity of light in the focal point of the lens on the temperature of PDMS: as the temperature increases from 20°C to 50°C, intensity decreases roughly by the factor of 6. The device shows no signs of hysteresis. The intensity of light in the focal point at a given temperature is the same irrespective whether the lens was heated or cooled to this temperature. The performance of the device is stable over many (> 50) focusing–defocusing cycles.

5. Conclusions

The optical elements described in this paper are easy to fabricate, cheap and durable. The optical characteristics (range of operation) of our devices could be easily adjusted by changing either the mechanical properties of PDMS (by changing the ratio of the curing agent to the prepolymer), or by altering its absorption characteristics and/or heat conductivity. Because the working element of the device — the PDMS corner cube array or Fresnel lens — is resistant to most chemicals, this type of a sensor might be useful in certain adverse environment situations (e.g., in aerodynamical tunnels where the corner cube "skin" could be placed over the object, and the forces acting on this object could be remotely measured). The thermal light valves might be useful in switches or panels of thermally controlled transmissivity. Transmission of light of a desired wavelength could be achieved by an appropriate choice of the doping dye. The Fresnel lens device might have uses in either sensor or beam-directing optical instruments.

Acknowledgements

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