Wave-front engineering by use of transparent elastomeric optical elements

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We describe a class of devices based on elastomeric optical phase gratings. These devices operate by reversibly controlling the phase of transmitted or reflected light by mechanical compression of the transparent elastomer. An optical modulator and an element in an optical display demonstrate two possible applications. © 1997 Optical Society of America

Key words: Phase grating, elastomer, modulator, spatial light modulator.

Optical modulators are important components of nearly all optical processing systems. Most current modulators use rigid inorganic materials and exploit changes in optical properties with electric, magnetic, and acoustic fields[1]; other classes of modulators operate by mechanical deformation of microfabricated suspended beams,[2] mirrors,[3] and Fabry–Perot cavities.[4] Here, we describe a new family of optical devices that manipulates the phase of light by controlling, through compression, the length of its optical path through a transparent elastomeric organic polymer. An optical modulator based on an elastomeric element with a relief grating embossed on its surface illustrates an application of this type of device (Figs. 1 and 2). Because of the attractive characteristics of these modulators—simplicity and economy of fabrication, continuous tunability of the intensity of light that they transmit, and flexibility of optical and mechanical properties of organic polymers—we believe that they will be useful in a range of sensors, displays, and other optical devices.

Elastomeric binary phase gratings were formed by casting and curing a prepolymer of poly(dimethylsiloxane) (PDMS) against photolithographically patterned lines of photoresist on silicon.[5,6] Once cured, the PDMS (with thicknesses between centimeters and micrometers) was peeled away from the patterned photoresist. The resulting patterned film of PDMS was an elastomeric phase grating that was transparent to visible and near-ultraviolet light.[7] The depth of the surface relief determines the modulation of the optical phase and therefore the pattern of diffraction (Fig. 1). The thickness of the photoresist (1–2 μm) determines the initial depth. This depth can be adjusted by mechanical compression.

Figure 1 illustrates how compression changes the optical properties of an elastomeric binary phase grating; Fig. 2 illustrates one method of compression and compares calculated and measured optical responses to this compression. Light emerging from a phase grating has a phase profile that is determined by the geometry of the grating, the difference between the index of refraction, Δn, of the material and the surroundings (air in this case), the wavelength of the light evaluated in air, λ, and variations of the thickness of the material.

For a binary phase grating with a depth of surface relief ΔL, the phase shift, $\Delta\phi$, in terms of these variables, is $\Delta\phi = 2\pi(\Delta n)(\Delta L)/\lambda$. For the experiments described here, $\Delta n = 0.43$ and $\lambda = 514$ nm. In the uncompressed state $\Delta L = 1.8$ μm, and the grating creates a periodic shift of the optical phase of 3π. In this configuration most of the light striking the grating is diffracted. In the compressed state (strain of 7.0%), $\Delta L \sim 1.2$ μm, the shift of the optical phase is 2π, and most of the incident light is passed without diffraction. Although this simple analysis ignores (i) distortions in the binary shape of the grating induced by compression, and (ii) changes of the index of refraction of the material caused by the mechanical strain, our experiments indicate that it accounts for most of the important characteristics of the elastomeric gratings.

The data shown in Fig. 2 demonstrate that compression permits reversible modulation of the intensity of the zeroth-and first-order diffracted beams;

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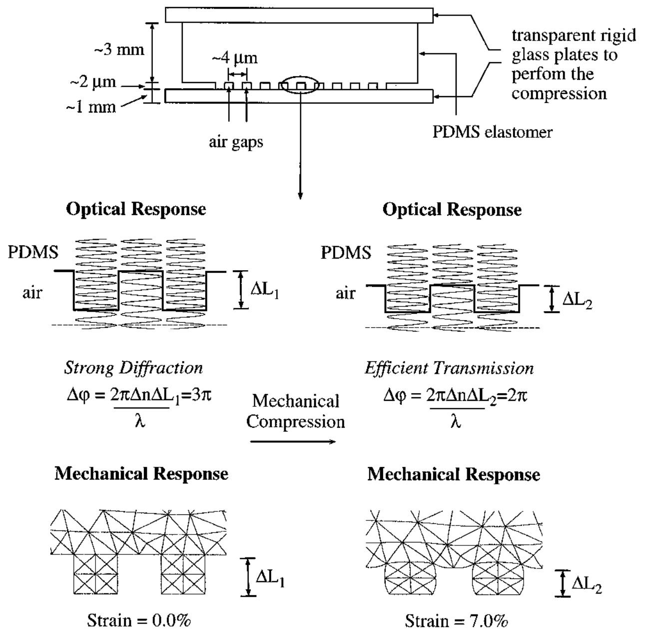

Fig. 1. Finite-element analysis of the mechanical response of a surface-relief grating to compression and schematic illustration of the influence of this mechanical response on the phase of light passing through the compressed element. The finite-element results illustrated here were obtained by use of the plane strain approximation. The Poisson ratio was 0.45.

modulation of the zeroth-order beam was in excess of 17 dB. For the PDMS elastomer, the pressure required to switch the grating from the diffracting to the transmitting state was of the order of 0.2–0.5 MPa.

Elastomeric phase gratings can be used for spatial light modulation; local compression of a thin grating that diffracts light out of the zeroth order in its uncompressed state allows light to pass at the point of compression. To demonstrate the response of a grating to localized compression, we fabricated a thin (~10–100-μm) grating that efficiently diffracts light out of the zeroth order by adjusting the depth of the surface relief to give a phase shift equal to an odd multiple of π (Fig. 1). For green light (wavelength of 514 nm) passing through a grating made of PDMS (index of refraction of 1.43) and surrounded by air, the appropriate depths are odd multiples of ~600 nm.

Adjustment of the speed of rotation used in application for spincoating the photoresist permitted the formation of gratings with depths of surface relief equal to 1.8 μm (=3 × 600 nm). In their uncompressed state, these gratings diffracted ~98% of the incident light out of the zeroth-order beam; with a compressive strain of ~7%, ~70–80% of the light appeared in the zeroth-order beam (Fig. 2). When light passed through such a grating and the grating was compressed locally, bright and dark images of the compressed region appeared in the dark field of the zeroth-order beam and in the bright field of the first-order beams, respectively. Figure 3(a) illustrates the reversible formation of a spot at three different spatial locations by compression with a curved piece of glass. Figure 3(b) shows a bright image of a diamond shape that appeared in the field of the zeroth-order beam when a transparent stamp shaped like the diamond compressed the grating.

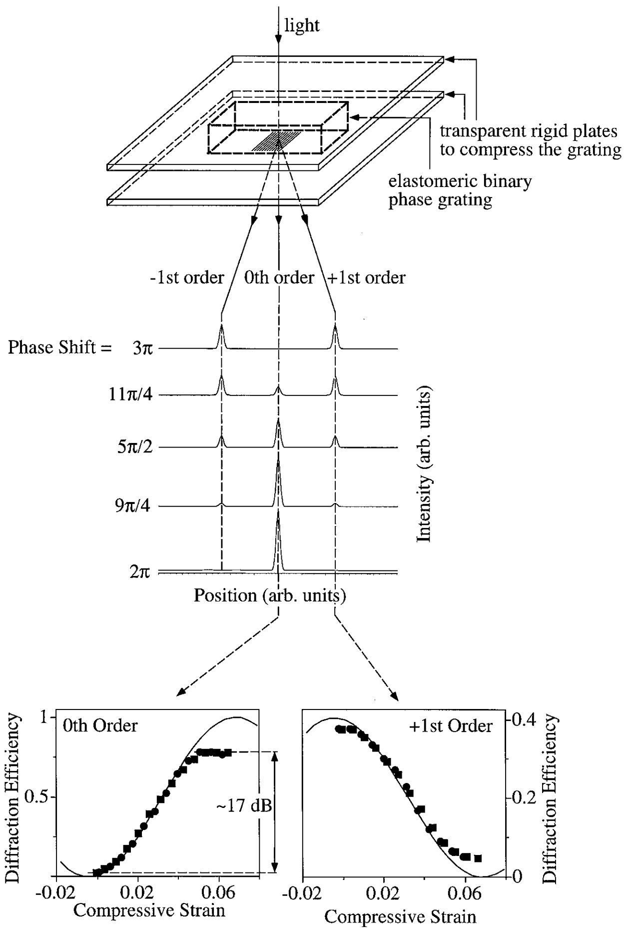

Fig. 2. Measured and calculated optical response of a binary elastomeric phase grating to mechanical compression. Pressure applied to two transparent rigid plates compresses the grating and decreases its relief. The intensities of the zeroth- and first-order diffracted beams measured as a function of compressive strain appear in the two frames at the bottom of the figure. The data (collected during compression and release and illustrated by circles and squares, respectively) illustrate modulation of the intensity of the zeroth-order diffracted light by ~17 dB. The calculations, which were performed with the assumption of a binary surface relief and a linear relation between the phase and the strain, are consistent with the data. Error bars are of the order of the size of the symbols.

Figure 3 also illustrates the ability of elastomeric phase gratings to form complex optical images and indicates possible applications as spatial light modulators (SLM's). A SLM requires a programmable and easily reconfigurable means for compressing the grating. Figure 4 illustrates a design for a modulator that consists of a thin (3–5-μm) elastomeric binary phase grating placed between two transparent conducting plates; voltage applied to the plates compresses the grating and modulates light passing through the de-

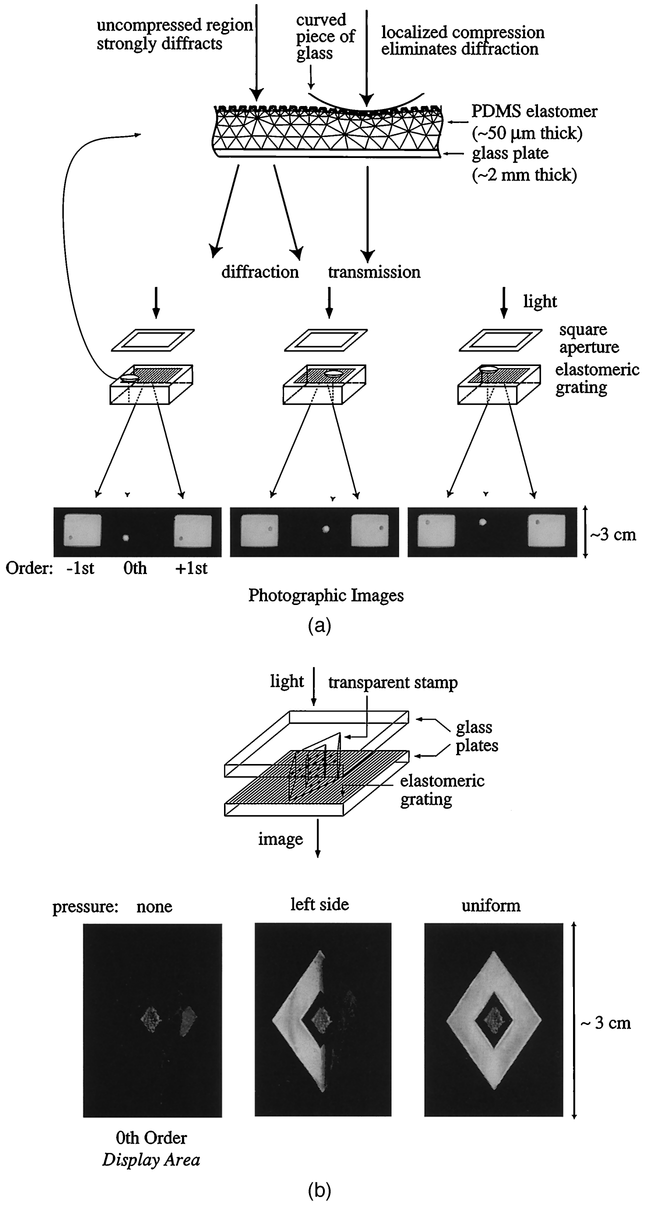

Fig. 3. Schematic illustration and photographic images showing the effects of localized compression of an elastomeric phase grating. Monochromatic collimated laser light passes through an elastomeric grating that efficiently diffracts light out of the zeroth order in its uncompressed state. When the grating was locally compressed with a piece of curved glass, bright spots appeared in the field of the zeroth order beam and dark spots appeared in the first-order beams. As the location of the compression changed, so did the positions of the bright and dark spots. (b) Schematic illustration and photographic images showing how an elastomeric phase grating might be used for spatial light modulation. Compression of an elastomeric grating that efficiently diffracts light out of the zeroth order in its uncompressed state creates a bright image in the field of the zeroth-order beam. The shape of this image mirrors that of the compression. The frame on the left-hand side shows a photograph of the zeroth-order beam when there is no compression. The frames in the center and the right-hand side show photographs when there is nonuniform and uniform compression, respectively, applied with a transparent stamp having a diamond shape. (The original photographs contained a patterned background that was subtracted from the images shown here.)

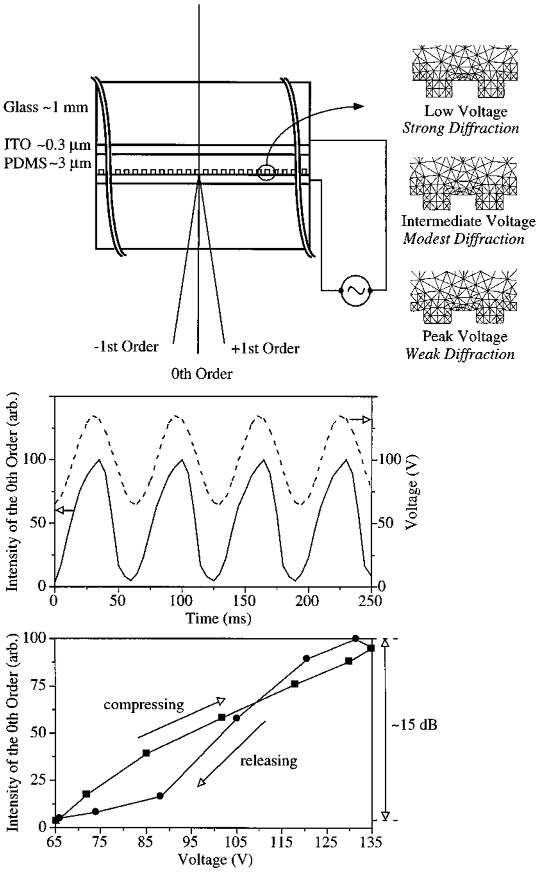

Fig. 4. Schematic illustration and data showing the design and performance of a simple modulator that uses a thin elastomeric phase grating placed between two transparent conducting plates consisting of a thin layer of indium tin oxide (ITO) on a glass substrate. Data collected during compression and release are illustrated by circles and squares, respectively. The error bars are of the order of the size of the symbols. Modulators that operate in reflection can be constructed by replacement of one of the transparent conducting plates with a reflective one.

vice. The amount of light passing through the grating undiffracted is proportional to the applied voltage. Modulators with this design show a depth of modulation of >15 dB when ~100 V is used to charge the plates. Depths of modulation remained greater than 12 dB for driving frequencies up to 1 kHz.

The modulators have long lifetimes; we observed no degradation in the performance of these devices during tests that involved more than 10 million cycles of compression. A SLM or display based on an array of these modulators would be constructed such that diffracted orders other than the zeroth would be blocked by the aperture of the display element or the detector.

The optical modulators described in this report provide an alternative to conventional technologies and they have many desirable characteristics: they involve a small number of parts and are easily fabricated; they demonstrate depths of modulation >15 dB; they can be electrostatically actuated with ~100 V; they can take advantage of the wide range of optical and mechanical properties available to organic materials; they allow continuous gray-scale modulation of the intensity. We believe that elastomeric phase gratings and other systems that accomplish wave-front engineering by use of deformation of transparent elastomeric optical elements have potential applications in a range of optical systems, including devices for wavelength-tunable beam splitting and coherent laser beam summation, variably chirped gratings, adjustable masks for phase mask photolithography,[8] and sensors that measure strain, stress, displacement, and acceleration.

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