Appl. Phys. B 85, 7–10 (2006)
DOI: 10.1007/s00340-006-2434-4

Applied Physics B
Lasers and Optics

N. GALLER[1]
H. DITLBACHER[1,✉]
B. STEINBERGER[1]
A. HOHENAU[1]
M. DANSACHMÜLLER[2]
F. CAMACHO-GONZALES[2]
S. BAUER[2]
J.R. KRENN[1]
A. LEITNER[1]
F.R. AUSSENEGG[1]

Electrically actuated elastomers for electro–optical modulators

[1] Institute of Physics and Erwin Schrödinger Institute for Nanoscale Research, Karl-Franzens University, Universitätsplatz 5, 8010 Graz, Austria
[2] Soft Matter Physics, Johannes-Kepler University, Altenbergerstr. 69, 4040 Linz, Austria

Received: 2 August 2006
Published online: 1 September 2006 •

ABSTRACT By using an elastomer as dielectric medium in a parallel plate capacitor, the attractive forces between the differently charged electrodes strongly compress that layer, representing a special type of electrostrictive effect. With an optical interference technique at the metal-insulator-metal layer system we studied the temporal behaviour of this mechanical deformation. We show that the deformation can be enhanced when the capacitor is laterally structured in order to allow the elastomer volume between the electrodes to move laterally, resulting in typical response times below 1 ms. The elastomer together with the metal electrodes is a metal-insulator-metal optical waveguide, whose mode properties can be tuned by electrically controlled mechanical thickness changes, suggesting applications for low-price electro–optical modulators with response speeds comparable to thermo–optical polymer modulators but with much smaller size.

PACS 78.20.Hp; 42.82.Bq

1 Introduction

Integrated polymer optics is a rapidly growing field which has reached a state where several devices are already commercially available. There are a variety of waveguide materials which can be structured for example by photo lithography and which form waveguides with optical losses as low as 0.01 dB/cm [1]. There are also organic light emitting diodes (OLEDs) [2] and organic photo-diodes [3] available. Electro–optical (EO) polymers are used in modulators and switches reaching a modulation bandwidth up to 100 GHz [4]. In thermo–optical (TO) modulators the temperature dependent refractive index of polymers is employed. The modulation speed achieved is significantly lower than that of EO-modulators, being in the range of a few kHz. Nevertheless TO-waveguide modulators are discussed for applications in optical communication networks, for example in protection switching and optical routing [5, 6]. TO-modulators also significantly consume electrical power for switching, with values of several mW for one element [6]. The small optical path length changes that can be induced by both the EO and TO effect requires interaction lengths in the range of cm for both modulator types. Therefore, there is a clear demand on novel modulator principles that allow for short interaction lengths to reduce the size of optical chips.

In this paper we report on a special type of "electrostrictive" effect in polymers and its application to electro–optical modulators. To avoid confusion we clarify how the term "electrostrictive" is used in this communication. In the narrower sense the electrostrictive effect refers to the strain response of a crystalline material in an electric field that arises from field-induced intramolecular forces. However, the term can be expanded to describe the reversible deformation behaviour of an elastomer material sandwiched between two electrodes when a voltage is applied to the electrodes [8]. The squeezing is only caused by the Maxwell stress generated between free charges at the electrodes. We term the whole element consisting of two electrodes and the elastomer electrostrictive element.

In contrast to the EO-effect, the electrostrictive effect is not based on optical anisotropy. This leads to a real simple (and inexpensive) fabrication process. Although not directly comparable, the electrostrictive effect is much larger than EO or TO effects with respect to the ability to create changes in optical path lengths. The EO-effect, for example, leads to a relative change in the refractive index on the order of 10^{-5} for applied fields of 10^6 V/m. On the other hand, the electrostrictive effect provides for the same field strength relative mechanical deformations in the range of some percent. How this mechanical deformation can be used for electromechanical–optical intensity modulators will be explained below. Here we want to note that modulators based on the electrostrictive effect could have interaction lengths below one millimeter as compared to the centimeter range in the case of both EO and TO polymer modulators.

Elastomers are characterized by a bulk modulus K comparable to that of polymeric materials, combined with extremely small Young's and shear moduli on the order of only MPa and below. Therefore elastomers are practically incompressible with a Poisson ratio extremely close to 0.5. For a laterally ex-

✉ Fax: +43 316 380-9816, E-mail: harald.ditlbacher@uni-graz.at

tended electrode geometry on a rigid substrate, the stiffness of the elastomer layer is determined by the large bulk modulus, since the elastomer cannot be strained in lateral direction. In order to allow for a significant deformation of the elastomer film in such a case the electrodes must be laterally confined so that the elastomer volume between the electrodes is reduced by "squeezing" elastomer material to the area outside the electrodes (see Fig. 1a and c). Another possibility to allow for a volume conserving deformation is the application of compliant electrodes on freely suspended elastomers. In the literature compliant electrodes were investigated as mechanical actuators and are often called artificial muscles [7–9]. Also devices with structured electrodes were used as spatial light modulators [10]. As a central task in this paper, we propose as a third scheme to additionally structure the elastomer layer laterally in order to provide space for the material squeezed out between the electrodes (see Fig. 1b and d).

Our electrostrictive element consists of three layers representing a metal-insulator-metal (MIM) waveguide supporting propagating in-plane modes with mode parameters depending on the thickness of the dielectric layer. The distance of the two metal layers and thus the propagation constant of the supported mode can be controlled by the applied voltage. By attaching the MIM waveguide directly onto a dielectric waveguide a pair of coupled waveguides is formed. The coupling of light from the dielectric to the MIM waveguide can in principle be controlled by electrically varying the propagation constant of the mode in the MIM waveguide.

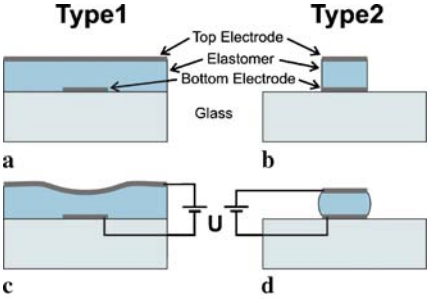

FIGURE 1 Sketch of two different geometries for the electrostrictive element. For type 1 only the bottom-electrode is structured (**a**) whereas for type 2 all three layers are structured (**b**). *Panels* (**c**) and (**d**) show schematically how the elements respond to an applied voltage for type 1 and 2, respectively

2 Experimental

Experimentally we analyzed electrostrictive elements of two different geometries (see Fig. 1). Both types are fabricated on a clean glass substrate. For the element of type 1 (Fig. 1a) first a 40 nm thick silver film is thermally evaporated onto an electron beam lithographically prepared mask. After the lift-off process a silver stripe with a width of 15 μm and a length of 100 μm remains on the substrate acting as bottom-electrode. As elastomer we used a 5 μm thick polydimethylsiloxane (PDMS) layer deposited by spin coating. Before evaporation of the 40 nm thick gold top-electrode the PDMS surface was treated with an air plasma for 20 s to prevent diffusion of the gold atoms into the polymer [13]. For the elements of type 2 (Fig. 1b) the two metal and the PDMS layers were deposited on the substrate analogous to type 1 but without any lateral structuring steps. After deposition a transmission electron microscope (TEM)-grid is attached on top of the layer system acting as a mask for a reactive ion etching (RIE) process. The top-electrode is removed with an argon plasma, the PDMS layer with a mixture of O_2 and CF_4. Figure 2 shows a SEM-image of an etched sample after removing the TEM-grid. The 15 and 30 μm wide ridges of the TEM-grid are reproduced in the three layer system.

For both types of electrostrictive elements the electrostatic forces generated by an applied voltage squeeze elastomer material out of the volume between the two electrodes. But only in the case of an electrostrictive element of type 1 the surrounding material has to be repressed, leading to a larger volume of elastomer involved in the deformation process as compared to elements of type 2 (Fig. 1). Therefore we expect the elements of type 2 to exhibit larger mechanical amplitudes and shorter response times as compared to elements of type 1 under identical experimental conditions.

In addition to the geometry of the devices, we also varied the type of the elastomeric material. We used PDMS provided by Dow Corning under the names Sylgard 184 and Sylgard 527. The two types of PDMS differ dramatically in their Young's modulus, most probably because of their different molecular weights and degree of cross-linking. By blending the two types of Sylgard the Young's modulus can be tuned over a wide range. For the two blends we used in the electrostrictive elements presented here, measurements of the Young's modulus were performed by a standard method [11] on macroscopic samples (cylinders with diameter and height of 1 cm). Table 1 shows the obtained values for material A (pure Sylgard 184) and material B (a blend of Sylgard 184 and 527 with a volume ratio of 1 to 13). Table 1 also shows the calculated thickness changes in percent by applying a voltage of 24 V to a 1 μm thick layer.

The dynamic response of the electrostrictive elements was monitored by time-dependent optical transmission measurements at a wavelength of 633 nm. Figure 3a shows a sketch of the experimental set-up. A microscope objective (40×, numerical aperture = 0.12) focuses a HeNe-laser beam onto the top of the sample. The intensity of the transmitted light was detected by a photomultiplier tube and observed

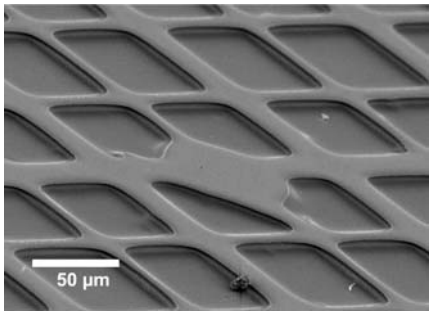

FIGURE 2 SEM-image of the structured layer system (type 2). Sample inclined with respect to the electron beam. A TEM-grid was used as mask for RIE

Material	Young's modulus MPa	Thickness change %
A	2.37	0.21
B	0.068	7.44

TABLE 1 Measured Young's modulus and calculated thickness change by applying an electric field of 24 V/μm to the electrostrictive elements. Material A: Sylgard 184 (Dow Corning), material B: a blend of Sylgard 184 and 527 with a volume ratio of 1 to 13

with a storage oscilloscope. The corresponding voltage signals applied to the MIM system were amplified by a high-frequency voltage amplifier, supplying voltage signals from −120 to 120 V with a bandwidth of 1 MHz.

For light incident normal to the substrate surface the three layers of the electrostrictive elements represent a Fabry–Pérot etalon. Figure 3b shows a typical white light spectrum of an electrostrictive element, exhibiting the characteristic features of a Fabry–Pérot etalon. The spectral position of the transmission maxima depends on the thickness of the PDMS-layer. By applying a voltage to the electrodes the thickness of the PDMS-layer is reduced and the transmission maxima are blue-shifted. The change in transmission of the laser light is only linear with respect to the thickness change of the PDMS-layer if the transmission curve is linear to good approximation near the laser wavelength. This can be achieved by choosing an appropriate initial thickness of the PDMS-layer and by keeping the amplitude of the electrical signal low enough not to leave the linear range (Fig. 3b and c).

3 Results

The results of the time dependent transmission measurements at four different types of electrostrictive elements (two different geometries, two different materials) are shown in Fig. 4 (curves are normalized). The applied square wave voltage ranged from 0 to 120 V and from 0 to 60 V for elements made from material A and B, respectively. For all curves the temporal behaviour during compression (−0.9 to 0 ms) and relaxation (0 to 0.9 ms) is roughly symmetric. A closer analysis of the dynamics shows, that the time dependence is neither single nor double exponential for none of the curves. This can be attributed to the rubber-like elasticity of PDMS. For this reason we do not give any time constants, the dynamics of the response is taken directly from the measurement curves. The non-oscillatory response of the modulators also show that the modulator response is largely determined by the loss modulus of the PDMS. This is a typical feature of elastomeric materials, where the storage modulus exceeds the loss modulus at low and high frequencies, whereas the loss modulus is larger than the storage modulus at intermediate frequencies [12]. A comparison of the response curves for the elements of type 1 shows, that the one made of material A (with the larger Young's modulus) reacts much faster than the one made of material B. This is attributed to the larger viscoelastic losses in material B, since the viscoelastic losses typically increase when the Young modulus of the elastomer is lowered. If we look at the elements made of material A and compare the response curves for the two geometries (type 1 and 2) we can not see any difference in the temporal behaviour, whereas for material B type 2 is obviously faster than type 1.

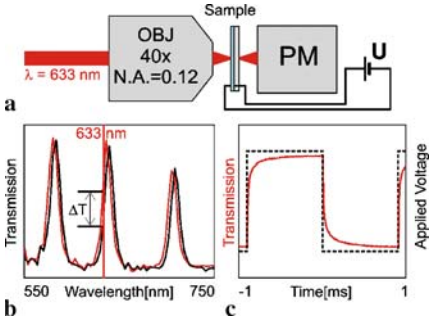

FIGURE 3 Measurement principle for detection of the time dependent response of electrostrictive elements. (**a**) Sketch of the setup, OBJ microscope objective, PM photomultiplier tube, (**b**) white light transmission spectrum of the electrostrictive element with and without voltage applied to the electrodes. The *vertical line* indicates the wavelength of the laser used for the time dependent transmission measurement shown in (**c**); (**c**) *dashed line*: applied voltage, *full line*: optical transmission of laser light

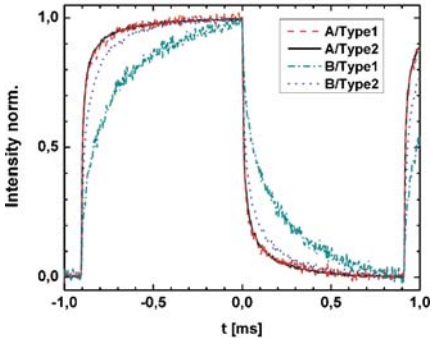

FIGURE 4 Time dependent transmission of four different electrostrictive elements; a voltage was applied to the electrodes (switched on at $t = -0.9$ ms and off at $t = 0$ ms). All curves are normalized to 1. Legend: The letters A and B indicate the elastomeric material as defined in Table 1, the types 1 and 2 correspond to the geometry of the elements as depicted in Fig. 1a and b

To understand this phenomenon, we have to take the deformation amplitudes into account. In the case of electrostrictive elements made of material A the measured relative electrically induced transmission change (which is proportional to the thickness change of the PDMS-layer) for elements of type 2 is 2.5× higher than for elements of type 1. This can be attributed to the large volume of PDMS involved in the deformation process for type 1 as compared to type 2 leading to an increase of the effective Young's modulus (as mentioned above). In case of material B we observe the opposite behaviour: elements of type 2 show 5× lower amplitudes than elements of type 1. As this effect cannot be assigned to the geometrical differences between the two types of elements, we take it as an indication for a change in the elastic properties of the PDMS-layer (increase of the Young's modulus) by the ion bombardment during RIE. Effects supporting this interpretation have already been reported in literature [13, 14]. Looking again at the time resolved transmission curves for elements made of material B, we have to interpret the shorter response time of type 2 elements compared to type 1 elements mainly as a consequence of RIE induced stiffening of the PDMS layer.

Since the achievable change of the PDMS layer thickness is crucial for possible applications of the electrostrictive elements to electromechanical–optical intensity modulators, we performed measurements of this quantity utilizing atomic force microscopy (AFM). For electrostrictive elements made from material B in the geometry type 1, we observed a squeezing of the PDMS-layer of 5.2% of its initial thickness by applying a field of 24 V/μm to the element. This is in quite good agreement with the calculated value (see Table 1) if we consider the expected increase of the effective Young's modulus due to the geometry of type 1.

4 Conclusion

To summarize we performed measurements of the dynamic response of four different electrostrictive elements consisting of a PDMS layer sandwiched between two metal electrodes. Two types of PDMS (differing in their

Young's modulus) were used in two different geometries of the element. The temporal response of the elements monitored by time dependent transmission measurements is non-exponential. Fall- and rise-times are in the order of 100 μs and compare therefore very well with response speeds of polymeric TO-modulator schemes. The achievable change on the PDMS-layer thickness by applying a voltage of 120 V to the electrodes ranges from 0.1 to 7% of the initial thickness of 5 μm. Lateral structuring of the PDMS-layer leads to larger amplitudes in the thickness change as compared to unstructured layers but no evidence for a reduction of the response time by structuring was found. We suggest to optically couple this electrostrictive elements to dielectric waveguides thereby forming an electromechanical–optical waveguide modulator. Such types of modulators may find applications in the field of (low cost) integrated polymer opto–electronics, and may replace TO-polymer modulators. There are several advantages of the proposed modulator concept as compared to TO-modulators: Comparable switching times with a negligible power consumption on device lengths of mm instead of cm.

ACKNOWLEDGEMENTS Work supported within the project cluster ISOTEC of the national Austrian nanoinitiative. We are indebted to Dr. Bauer-Gogonea, Linz for many stimulating discussions. We thank Ursula Haas and Anja Haase from the Institute for Nanostructured Materials and Photonics, Weiz for preparing the RIE samples.

REFERENCES

1 L. Eldada, L.W. Shacklette, IEEE J. Sel. Top. Quantum Electron. **6**, 54 (2000)
2 G. Grem, G. Leditzky, B. Ullrich, G. Leising, Adv. Mater. **4**, 36 (1992)
3 C.W. Tang, Appl. Phys. Lett. **48**, 183 (1986)
4 D.T. Chen, H.R. Fetterman, A. T Chen, W.H. Steier, L.R. Dalton, W.S. Wang, Y.Q. Shi, Appl. Phys. Lett. **70**, 3335 (1997)
5 N. Keil, H.H. Yao, C. Zawadzki, K. Lösch, K. Satzke, W. Wischmann, J.V. Wirth, J. Schneider, J. Bauer, M. Bauer, Appl. Phys. B **73**, 469 (2001)
6 N. Keil, H.H. Yao, C. Zawadzki, Appl. Phys. B **73**, 619 (2001)
7 R.E. Pelrine, R.D. Kornbluh, Q. Pei, J.P. Joseph, Science **287**, 863 (2000)
8 R.E. Pelrine, R.D. Kornbluh, J.P. Joseph, Sens. Actuators A **64**, 77 (1998)
9 G. Kofod, M. Paajanen, S. Bauer, Appl. Phys. A, unpublished
10 S. Sakarya, G. Vdovin, P.M. Sarro, Sens. Actuators A **108**, 271 (2003)
11 T.A. Osswald, G. Menges, *Materials Science of Polymers for Engineers* (Hanser Publishers, Munich Vienna New York, 1995)
12 M. Rubinstein, R.H. Colby, *Polymer Physics* (Oxford Univ. Press, Oxford, 2003)
13 H. Hillborg, J.F. Ankner, U.W. Gedde, G.D. Smith, H.K. Yasuda, K. Wikström, Polymer **41**, 6851 (2000)
14 P. Bodö, J.-E. Sundgren, Thin Solid Films **136**, 147 (1986)