Waveguide intensity modulators based on electrically actuated elastomers

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Abstract - *We present a new concept for optical waveguide intensity modulators, based on the thickness change in an elastomer in a parallel plate capacitor, squeezed due to the attractive forces exerted by the capacitor electrodes when charged.*

Introduction

Integrated polymer optics is of broad interest due to advantages like low costs and ease of fabrication and there are several components already commercially available. There is a variety of waveguide materials which can be structured, e.g., by photo lithography and which form waveguides with optical losses as low as 0.01 dB/cm [1]. Also available are organic light emitting diodes (OLEDs) [2] as well as organic photo-diodes [3]. In modulators and switches electro-optical (EO) polymers are used reaching a modulation bandwidth up to 100 GHz [4]. Thermo-optical (TO) modulators use the temperature dependent refractive index of polymers and achieve modulation speed in the range of a few kHz, significantly lower than that of EO-modulators. Nevertheless TO-waveguide modulators are discussed for applications in optical communication networks, for example in optical routing [5]. However, TO-modulators also significantly consume power for switching, with values of several mW for one element [5]. The small optical path length changes that can be induced by both the EO and TO effect require interaction length in the range of several mm to cm for both modulator types. Therefore, there is a clear demand for novel modulator principles that allow for short interaction lengths to reduce the size of optical chips.

Modulator Concept

Here we report on an electro-mechanical modulator relying on the properties of an elastomer as the dielectric medium in a parallel plate capacitor. The attractive forces between the differently charged capacitor electrodes compress that layer, representing a special type of electrostrictive effect [6]. The system of metallic electrodes with an elastomer in-between forms a metal-insulator-metal (MIM) optical waveguide, whose propagation properties can be tuned by the thickness of the elastomer layer and thus by the voltage applied to the electrodes. When optically coupled to a dielectric waveguide this MIM waveguide can act as a modulator. The thickness change of the elastomer in the MIM-waveguide directly affects the coupling conditions between the waveguide modes in the dielectric and in the MIM-waveguide. It causes a change in the maximum optical power which is transferred from the dielectric to the MIM-waveguide and a change of the coupling length (i.e. the distance within this transfer takes place). The achievable modulation depth can be optimized by two parameters, the initial thickness of the elastomer and the length of the MIM-waveguide, see Fig. 1.

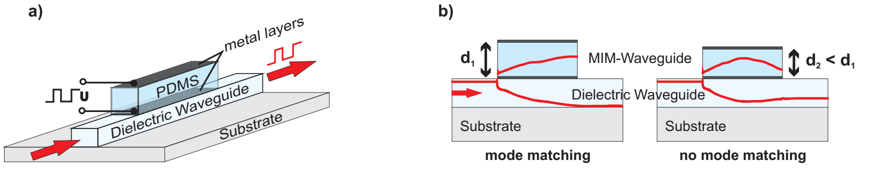

Fig. 1: Sketch of the proposed modulation device (a), PDMS is the squeezable elastomer in the MIM-waveguide and U is the voltage applied to the metal electrodes. Coupling between the dielectric and the MIM-waveguide (b). The arrow indicates the direction of the propagating light. The curves in the dielectric waveguide and the elastomer indicate the decrease and increase of guided optical power in the two waveguides due to coupling between them but also due to absorption in the bottom-electrode.

Realization

So far we investigated i) the coupling between the dielectric waveguide and the MIM-waveguide for an extended layer system and ii) the temporal behavior of the deformation of the elastomer in the MIM-system to estimate the response times of the modulator.

Coupling between dielectric and MIM-waveguide

To analyze the feasibility of mode matching between the dielectric and the MIM-waveguide we performed calculations using stratified media theory and compared them to angle resolved reflectance measurements.
Our model layer system consists of a Cytop layer (low refractive index fluoropolymer provided by Asahi Glass; used as the bottom cladding of the dielectric waveguide) on glass substrate. We used SU8-3010 (epoxy resin, MicroChem) for the dielectric waveguide, silver as bottom- and gold as top-electrode and for the elastomer we used polydimethylsiloxan (PDMS), namely a blend of Sylgard 527 and Sylgard 184 (provided by Dow Corning). We calculated the reflectivity of the layer system sketched in Fig. 2a (microscope cover slide / 500 nm Cytop / 370 nm SU8 / 40 nm Ag / PDMS / 40 nm Au) in dependence of the thickness of the PDMS-layer and the effective mode index N (Fig. 2b) which is related to the angle of incidence φ by $N = N_{glass} \sin\varphi$. The calculations were done for TM-polarized light of 633 nm wavelength.

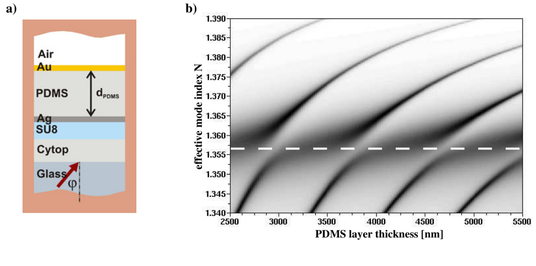

Fig. 2: Sketch of the layer system (a). φ is the angle of light incidence. Gray scale plot of the calculated reflectance against PDMS-thickness and effective mode index N (b).

The dark traces are reflectivity minima which display the guided modes in the dielectric and the MIM-waveguide. The dashed line refers to the mode in the dielectric waveguide, which intersects with the modes in the MIM-waveguide (sloping dark lines). For PDMS thicknesses where the dark lines are anticrossing the modes in the dielectric and the MIM-waveguide are perfectly matched.

Angle resolved reflectance measurements were performed for samples with PDMS thickness of about 3700 nm (mode matching case) and 4100 nm (no mode matching) and compared with calculated curves, see Fig. 3.

Sample preparation was done by spin coating Cytop onto a microscope cover slide. Before SU8 was spin casted, the Cytop surface was treated with an air plasma for 1 min to ensure adhesion. Onto the SU8 layer the MIM-system was produced by thermally evaporating silver, layer deposition of the PDMS by spin coating and thermally evaporating gold. 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 [7].

Fig. 3 shows experimental (dots) and calculated (line) angle resolved reflection curves for the two PDMS thicknesses. The reflectivity minima which are quite narrow correspond to the waveguide modes in the MIM-waveguide and the broad minimum in Fig. 3a correspond to the dielectric waveguide mode. When the dielectric waveguide mode and a mode in the MIM-waveguide are matched (Fig. 3b), the width of and the distance between the coupled minima are changed. That is, that the maximum optical power which can be transferred and the coupling length are changed. We found good agreement between measurements and theory.

First simulations using beam propagation method (BPM) suggest, that device lengths of tens of μm are sufficient for such a modulation unit if a possible thickness change of 10 % is assumed.

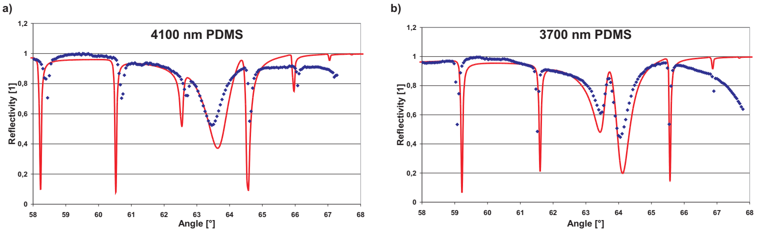

Fig. 3: Experimental (dots) and calculated (line) angle resolved reflection curves (λ=633 nm, TM-polarization) for the layer system depicted in Fig. 2a. (a) no mode matching, (b) mode matching case.

Response times

As an elastomer is practically incompressible the electrodes must be laterally confined to get a significant thickness change of the elastomer. The elastomer has to be "squeezed" to the area outside the electrodes (see Fig. 4). We investigated two different geometries: samples with bottom electrode structured only (Type 1) and samples where the whole layer system was structured by reactive ion etching (Type 2). Measuring the time dependent thickness changes of the PDMS we found response times in the order of 100 μs and thickness changes up to 7% for an initial elastomer thickness of 5 μm and an applied voltage of 120V, for details concerning sample preparation as well as experimental setup see [8].

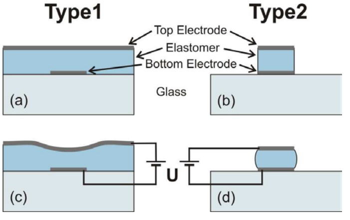

Fig. 4: Scheme of the two different geometries for time response measurements. (c) and (d) sketch the deformation which is induced by an applied voltage.

Conclusion

To summarize we could show that for an extended layer system coupling between a dielectric and the MIM-waveguide is indeed possible. We found response times of our modulation unit in the order of 100 μs and possible thickness changes of about 7 %. Such types of modulators may find application in the field of (low cost) integrated polymer opto-electronics. There are several advantages of the proposed modulator concept as compared to TO-modulators: Comparable switching times with a negligible power consumption on device length of mm instead of cm.

Acknowledgments

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