Preparation of rib channel waveguides on polymer in electric field

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Micro-sized patterns were created on oligomer (Su-8) films by the effect of external electric field, perpendicular to the film surface. Structures with varying parameters were prepared and the growth of continuous or dot-like structures was observed. The mechanism dominating the structure growth was examined and found to be a function of experimental conditions. The dependence of the form and the size of the created patterns on the intensity of the electric field, exposure time and initial distance between mask and polymer surface was investigated. Waveguiding properties of the linear pattern, produced by the above technique, were examined and the following parameters were obtained: propagation loss — 2–3 dB/cm, effective refractive index — 1.6276, number of supported modes — 30).

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1. Introduction

Polymers with their excellent light-guiding parameters and transparency at all important communication wavelengths can be used for preparation of optical components. Both passive and active polymer-based light-guiding devices prepared on different polymers have been described [1,2]. Polymer films can be spin-coated onto most optical materials and they can easily be integrated into various structures. A large thermo-optical coefficient and considerable photosensitivity are other useful properties of polymers which could be utilized in the construction of optical devices [3]. For application in integration optics polymers have to be formed into planar single-mode, multimode, and micro-optical waveguide structures with the dimensions ranging from hundreds of nanometers to hundreds of micrometers. Polymeric optical waveguide devices may be prepared in many ways. A distinct advantage of polymers in a manufacturing environment is their unique ability to be processed by fast turnaround techniques that are not possible for more conventional photonic materials such as glass and semiconductors. A direct photolithographical preparation scheme is the most conventional one, but it is significantly constrained by the light diffraction and limited to photosensitive polymers. Although other techniques such as reactive ion etching, excimer laser ablation, molding, and embossing were demonstrated to work [4–7], One relatively new and promising technique for polymer patterning is a process based on the hydrodynamic instabilities of a liquid polymer surface induced by an external electric field [8–11]. Recently thin film instability was reported which could be used for the creation of well-controlled patterns on thin polymer films [12–15]. This technique allows the creation, with a high accuracy and reproducibility, of well defined polymeric patterns with the dimensions ranging from a few tens of nanometers to a few millimeters. A lot of experimental work was done by Russel and Steiner [8–11] and by Chou et al. [12,13]. By the technique proposed by Chou and called LISC (lithography induced self-construction) [12,13] a remarkable pattern uniformity can be obtained over a large surface, but inevitable mechanical contact between polymer and mask introduces an additional degree of roughness to the waveguides which contributes significantly to the overall waveguide loss.

Here, we describe recent experiments on the electric field assisted patterning of thin epoxy novolak resin (Su-8) films. This polymer is an oligomer which can undergo photo-polymerization under the irradiation by UV light [16]. Conventional patterning of Su-8 polymer starts with irradiation with UV light through a mask and additional steps comprising removal of unirradiated material. In electric field assisted patterning the use of the UV light exposition and other subsequent procedures are avoided. Effects of the electrical field on the surface morphology of the polymeric film and on its refractive index are studied. The main goal of the work was the creation of linear waveguiding structures and examination of their parameters in dependence on experimental conditions.
2. Experimental details

The present experiments were performed on epoxy novolak resin, supplied by Goodfellow, Su-8. Polymer films, 2000 nm thick, were spin-coated (1500 rpm) from a solution onto a Si/SiO₂ substrate (SiO₂ layer thickness was 5 μm). Then the films were sandwiched between a conductive substrate and a glass mask with a conductive strip, 25–50 μm wide and a few millimeters long. Part of the sample was exposed to the electric field created between the strip electrode and Si backing. The distance between the upper electrode and the polymer film was chosen at 5 and 50 μm. The applied field intensities do not exceed a breakdown limit of about 5 · 10⁶ V/m. The whole assembly under the electric field was heated in an oven to a temperature of 160 °C. After exposure, the sample was allowed to cool down spontaneously to room temperature under the continued effect of the electric field and subsequently it was irradiated with UV light. A more detailed description of the experimental arrangement can be found in our previous work [16,17].

The shape and properties of the resulting structures created on the polymer layer were studied using upright laser confocal microscope Olympus Lext working with a 405 nm laser light. For the sample observation an objective lens with 20× magnification was used. Profiles of the structures were measured by the profile-meters Hommel 1000 and Talystep (standard deviation ± 10%).

The refractive index of the films after exposition to an electric field was determined in the spectral range of 250–750 nm using the refractometer Avaspec 2048. For refractometry a larger part of the sample was modified by an electric field using the top electrode with greater area. Then the polymer film was crosslinked by an exposition to UV light. Refraction spectra were obtained from the modified and non-modified parts of the sample [18] and the dependence of the refractive index (n) on the wavelength (λ) was determined with the computer code AvaSoft Full 6.1 including the code Spectra 3.

The waveguiding properties of the prepared linear structures were studied with 630 nm and 1550 nm laser light delivered by an optical fiber (polymer has negligible internal absorption of 630 nm light [16]). Measurements of the propagation optical loss were carried out using the cut-back method. In this method output optical powers from the waveguide are measured before and after sample breakings and corresponding to two different lengths of waveguide. The spatial distribution of the intensity of output light was obtained using a Ge detector — Anritzu ML910B with MA9302A.

3. Results and discussions

Application of the local electric field, produced by the strip electrode, to the melted polymer film results in a redistribution of material and growth of a new surface structure. In Fig. 1 a confocal microscope image of the typical pattern, created by exposing Su-8 film to the electric field is shown. Black and white areas, seen in the figure, are due to a light interference on the patterned polymer film. Pictures where taken in the light reflected from the surface of Su-8 films. The interference pattern occurs because of the difference in the optical way of the light reflected from the surface of polymer and Si backing.

In the present case a rich interference pattern with many interference lines reflects mostly the vertical variation of the structure thickness. For the sake of a better presentation the pattern profile, measured by profile-metry is also shown (white line). The profile consists of a Gaussian shaped central part where the polymer mass was pulled above the initial film surface and depleted wings. With the confocal laser microscopy, making use of coherent and monochromatic laser light, it is possible to image not only the planar structure of the pattern but also its height profile. The rich interference pattern allows the simple calculation of the structure height, like in the case described in [19]. The height of the structure can be calculated according to the simple relation: \( h = \frac{\lambda n}{2} \); where \( x \) is one half of the number of the interference lines taken across the structure, \( \lambda = 405 \text{ nm} \) is the laser wavelength and \( n \) is the refractive index of materials (see Fig. 2). The results of these simple calculations are in good agreement with the data obtained from the profilemetry. In the case shown in Fig. 6 the values from the profilemetry and that calculated from the diffraction pattern are 0.83 and 0.86 μm, respectively.

It is well known that the structure growth is controlled by two different mechanisms, leading to formation of a regular system of dots [12] and a homogeneous structure [13]. Confocal images of two different structures prepared in our experiments are presented in Fig. 3. Structures were prepared at the temperature of 160 °C and under the electric field with an intensity of 5 · 10⁶ V/m applied for 4 and 15 min. Surface profiles measured across the prepared structures are shown in the bottom of Fig. 3. It is seen that, depending on the experimental conditions, a homogeneous structure (4 min exposition) and a regular system of dots (15 min exposition) are created and we therefore come to the conclusion that both of the mentioned formation mechanisms play a role in our case.

A series of experiments were performed at two electric field intensities of 5.0 · 10⁶ and 2.5 · 10⁷ V/m and with exposure times ranging from 3–15 min with the objective to find the regime with dominating homogeneous structure growth. The images of the pattern obtained under different conditions are shown in Fig. 4. For the short

![Fig. 1. Laser confocal image of polymer structure prepared by 160 °C electric field intensity 1.1 · 10⁶ V/m, distance 50 μm and time 5 min. For comparison structure surface profile is given.](image1.png)

![Fig. 2. Spectral dependence of polymer refractive index (1000 nm layer thick) measured on oriented and non-oriented areas by electric field (2.5 · 10⁷V/m, temperature 160 °C, time 5 min).](image2.png)
exposure times longitudinal homogeneous channel structures are formed. For longer exposure times the homogenous structures disappear and a system of dots is created. It may therefore be concluded that the growth of the homogeneous structure prevails in initial stages of the pattern formation which is replaced by the formation of the regular dot system mechanism at longer exposure times. This transition appears earlier for higher field intensity.

The dependence of the width and height of the pattern on the exposure time, as measured by profilometry, is shown in Fig. 5. For the short exposure times, when the homogeneous structure growth dominates, the height is an increasing function of the exposure time in accord with theoretical predictions [14,15]. For longer exposure times the system of the regular dot formation mechanism results in the creation of highly non-homogenous dot structures and the pattern height decreases with the increasing exposure time. Pattern width is a monotonously increasing function of the exposure time. The similar dependence of the pattern width and height on the electrical field intensity is shown in Fig. 6 (electrode–polymer distance of 5 μm, exposure time of 5 min). It is seen that the pattern height increases with the increasing field intensity, while the pattern width remains practically constant. Maximum height was obtained for the electric field intensity of $5 \cdot 10^6$ V/m. Further pattern growth was limited by the mechanical contact between the polymer surface and the mask. From the observed dependences it can be concluded, that the size of the patterns which are created using the proposed technique is primarily determined by the experimental arrangement. In particular, the pattern width can be controlled by changing the metallic strip size, while the pattern height is largely dependent on the applied electric field and the initial distance between the mask and polymer surface.

Direct light-guiding is possible only in a homogeneous structure with the same geometrical parameters along its full length. For this reason only a homogeneous structure is acceptable for the creation of light-guiding structures. That is why only patterns prepared at short exposure times were chosen for further experiments.

Light-guiding properties of waveguide structures are strongly related to the refractive index of the material used. It is known that the refractive indices of polymers can be affected by the orientation of the polar groups in the polymer backbone. In our previous studies the effect of the electric field on the orientation of polymer side groups, and therefore, on the refractive index of polymer was studied [18,20]. It was found that the electric field applied on the polymer kept at higher temperature can increase polymer refractive index, which is conserved after polymer cooling. Molecules of the Su-8 have polar epoxy groups, which can undergo orientation under an external electric field. The orientation of these groups will cause a refractive index change, keeping the chemical structure of Su-8 untouched. Dispersion of the refractive index measured in the wavelength interval 250–750 nm, measured on the pristine and exposed to
electrical field parts of the polymer is shown in Fig. 2. It is evident, that the electric field affects the structure of the polymer and leads to an increase of the refractive index. The values of the refractive index at 405 and 632.8 (laser confocal wavelength and standard “red” laser wavelength) are 1.67 and 1.63 respectively. The change in the refractive index at 632.8 nm, determined by this method is estimated to be 0.05. It is expected that the changes in the refractive index observed on the light exposed Su-8 with a highly crosslinked structure will be more stable in comparison with those in the pristine, unirradiated polymer [21].

The above described technique was applied for the preparation of an optical channel waveguide. A waveguiding structure was prepared under the following conditions: an electric field intensity of \(2.5 \times 10^6\) V/m, a substrate temperature of 160 °C, distance between mask and polymer at 50 μm and an exposure time of 5 min. After pattern formation the sample was irradiated by UV light with the aim to improve mechanical properties and stability of the polymer structures. Upon exposure to UV radiation, the oligomer systems form highly crosslinked networks, which exhibit low intrinsic absorption in the wavelength range extending from 400–1600 nm. The longitudinal parameters of the created linear structure were controlled by profilometry and the height and width of the structure were found to vary within ±5% along the whole structure length. Within these limits the produced structures can be considered as homogeneous and continuous ones. It is evident, that the technique enables a simple fabrication of rib-type waveguide with the main disadvantages of traditional photolithography being eliminated.

Of utmost importance for the applications of polymers in optics is the thermal stability of their optical properties since organic materials may be subjected to yellowing upon aging at increased temperature. Typically, the aging results in the formation of partially conjugated molecular groups characterized by broad ultraviolet absorption bands, which tail off in intensity through the visible optical range. The yellowing is strongly influenced by the chemical structure of the pristine polymer. Because of their highly crosslinked nature, Su-8 polymers are particularly stable at elevated temperature. In
In our experiment, the structures apparently show waveguiding properties. The loss values at 1550 nm wavelength were obtained by fitting the data obtained from cleave back method to the equation \( \alpha = 10 \left[ \log(P_2/P_1)/(L_1 - L_2) \right] \), where \( P_1 \) is output optical power measured on whole length of the waveguide, \( L_1 \) \( P_2 \) is output optical power obtained after breaking of the waveguide, where \( L_2 \) is length of the break of the optical waveguide, and \( \alpha \) is the propagation loss coefficient. The loss values retrieved from the best fits were in the 2–3 dB/cm range. These values are close to the results obtained for intrinsic absorption of Su-8 [22] and can be improved by a reduction of the vibration absorption overtone of the C–H bonds by substituting fluorine for hydrogen [23]. Additionally, distribution of light intensity radiated from the end of channel waveguide was measured and is shown in Fig. 7A as a function of space coordinates. Fig. 7A shows the position of detectors points (X and Y directions) and the intensity of light, illuminating these points (Z direction). It is evident, that the output optical field represents a combination of two Gaussian peaks, one of which is broader in Y direction. Apparently, distribution of the intensity of light is given by waveguide geometry, i.e. by its thickness and height. It should be noted, that in the present experimental arrangement an expansion of the output light beam occurs between the waveguide end and the detector.

Previous results were used for computer simulation of the optical properties of the fabricated structures. Using the measured polymer refractive index and the structure surface profile the output optical field distribution were calculated with R-Soft software using beam propagation method. The refractive index profile in a cut of the simulated waveguide structure and the calculated output optical field intensity is shown in Fig. 7B and C. It is evident, that the shapes of calculated (7C) and measured (7A) output optical field are in good agreement, with regards to the optical beam expansion mentioned before. In addition, calculation proved that the effective refractive index for the fundamental mode is approximately 1.6276 at 632.8 nm. Computer simulation indicates that the prepared structures can support the propagation of 30 modes at wavelength 632.8 nm. However, some devices of integration optics, X-junction for example, need the light-guiding structure to be a single-mode waveguide. Based on a beam propagation method analysis, we determined the dimension of a single-mode device. In order to achieve single-mode propagation the height and width of a waveguide should be 6 and 8.4 μm respectively. According to this consideration the top electrode 2 μm in width will be necessary for the preparation of a single-mode waveguide. The preparation of such waveguides and some more sophisticated structures of integration optics and their characterization will be an objective of our future studies.

In our previous work [17] we demonstrated the preparation of the linear structures on thin polymethylmethacrylate (PMMA) films. In this work we investigated the preparation of rib channel waveguides by electric field assisted patterning of thin Su-8 films and extend our previous results by optical and waveguide measurements and computer simulations. Comparison of our previous results on PMMA with those presented here indicate significant differences in the mechanism of structure formation. In the case of the PMMA films the structure growth starts at random spots which later join each other and the homogeneous structure was created after some exposure time. The resulting PMMA structures never decay into the systems of regular dots, regardless of the time of the electrical and thermal treatment. In the case of the Su-8 polymer the pattern growth starts simultaneously along all the exposed length, but only for a short exposure time a homogeneous channel structure is formed. It is apparent, that only one of the possible mechanisms of structure growth is dominant for PMMA films, but two mechanisms are observed at Su-8 films — leading either to formation of a homogeneous channel or a regular system of dots. The different behavior can be attributed to a difference in the molecular weight of both polymers by feeding it with laser light (for experimental details see ref [17]).

![Figure 7](https://example.com/figure7.png)

**Fig. 7.** (A) Output optical field (632 nm) distribution radiates from the end of rib channel waveguide. (B) Cross-section refractive index profile for typical rib waveguide, numbers at the figure gives the refractive index value of layers. (C) Optical far field distribution for rib channel waveguide calculated in R-Soft software.

In the next step waveguiding properties of the created structure were calculated using a R-Soft software and examined experimentally in the present case no yellowing was observed after thermal aging at 200 °C during 10 h. It was also observed that the Su-8 polymers are mechanically robust at high temperatures; no mechanical failure such as cracking or delamination of prepared structures occurs after thermal aging.
(*high* molecular weight of PMMA and *low* of Su-8). The low molecular weight of Su-8, in comparison to PMMA, facilitates easier and faster structure formation. The lower temperature for pattern formation is needed and better reproducibility is obtained too. A possible disadvantage of the inferior mechanical properties of the Su-8 polymer can be compensated by subsequent UV exposition and polymer crosslinking. These conclusions are in agreement with those done in previous studies [23,24].

4. Conclusions

Thin Su-8 films were patterned by exposition to the external electric field at a fluid temperature. Two different mechanisms, leading to a continuous structure and a regular system of dot formation were observed. For short processing times continuous structures are produced and with increasing times the continuous structures disintegrate into the system of dots. The form and shape of the structures were examined as a function of the exposure time, electric field intensity and the initial distance between the mask and film. In addition, a significant change in the refractive index of the polymer affected by electrical field is observed.

The technique of the polymer patterning, described in this work, is more simple than the traditional photolithography and can be applied for the preparation of optical waveguide structures. Optical properties of the prepared structures was examined and found to be satisfactory from a practical point of view. Additional computer simulations allow to predict the parameters of a single-mode waveguide and to propose experimental arrangement necessary for its formation.

The proposed technique seems to be prospective for the fabrication of polymer-based optical devices. It gives highly reproducible results and is suitable for the production of high-quality polymer waveguides. However, it should be noted, that the response to the external electric field is different for different polymers. Apparently, the quality and the shape of the structures created by the effect of the external electric field depend on the polymer type, its molecular weight, temperature of flow, its molecular structure etc. Therefore, the conditions of the pattern preparation must be optimized for each particular case.

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