UV Light Induced Single Mode Waveguides in Polymer for Visible Range Applications

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Abstract: *In this paper we describe the fabrication of single mode waveguides in standard polymer substrates by a deep UV lithography technique. With regard to commercial applications the waveguides are designed to be used in the visible range. The paper shows the first results of the manufacturing process used to increase the refractive index for strip waveguide channels in the polymer substrate and the technique to cover the surface structures by a top layer to get buried waveguides. First results of refractive index step measurements as a function on the UV light exposure dose are discussed. Simulated mode profiles are compared with measured near field intensity distributions.*

Introduction

For the use in optical applications, low cost standard polymer substrates (PMMA) are available from many manufacturers. Material quality with respect to transparency, homogeneity and surface flatness is good enough also for waveguide manufacturing by standard UV lithography. Single mode applications in the NIR range from 1300 nm up to 1550 nm have been reported within the last years [1-5], whereas less publications can be found for applications in the VIS range, especially for RGB data signal applications.

In our work a simple UV lithography technique with structured slit masks is used to modify and adjust the refractive index of the polymer to fabricate single mode stripe waveguides for light in the VIS range from 400 nm up to 650 nm. The width of the slits varies around the order of some microns. To increase the refractive index by deep UV absorption the exposure time was optimized in the range of some minutes. In a first step we realised surface waveguides and in a second step we covered the substrate surface with a polymer substrate to get buried strip waveguides (Fig.1). An adapted index glue was used to connect the polymer substrate with the cover.

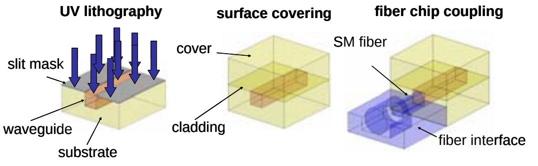

Fig. 1: Schematic picture of the manufacturing process for buried strip waveguides in polymer substrate.

Index profile discussion

To define the index profile distribution m-line spectroscopy and the index profile calculation (IWKB-method [6, 7]) is used after preparing unstructured film waveguides in polymer substrates. Therefore, the exposure doses are varied up tot values to get also multimode waveguides. The m-line spectroscopy with an Abbe refractometer was done at different wavelengths: a) 405 nm, b) 532 nm and c) 633 nm. Fig. 2 shows the normalized measured mode indices as a function of the substrate depth. The different markers represent the different wavelength. For this UV exposure dose 4-7 modes can be activated for the named wavelength. In a good approximation all markers follow a fitted exponential curve which decreases to a 1/e-value at a depth of app. 4.5 µm. We deduce that the UV light intensity absorption process is free from any important surface degradation for the exposure doses.

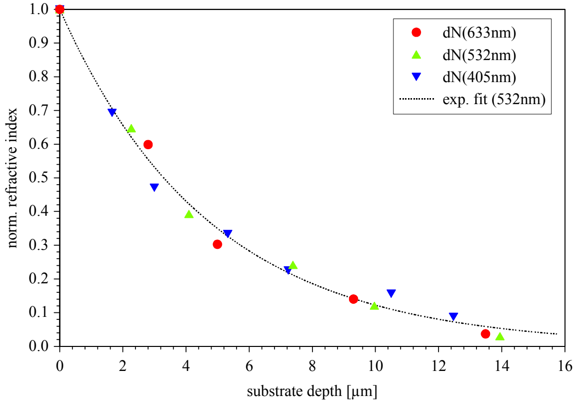

Fig.2: Normalized refractive mode indices of film waveguides as a function of the substrate depth for different wavelength.

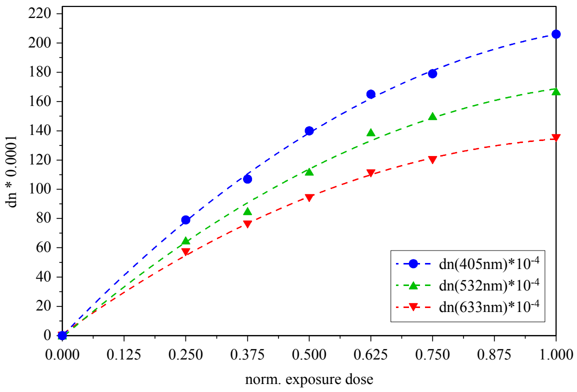

Fig. 3: Surface index change of film waveguides in polymer as a function of the exposure dose for different wavelength.

The maximum values of the refractive index change of the film waveguides at the surface of the polymer substrate are shown in Fig. 3. The index changes in units of 10^{-4} for different values of the UV exposure dose are significantly different for the measurement wavelengths. By these curves the index change for single mode waveguides can be fitted for any dose values within this range. The index profile can be written as

$$n(\lambda, y) = n_{sub}(\lambda) + dn(\lambda) * e^{(-y/\alpha)} \qquad (1)$$

with a decay constant α = 4.5 µm at the 1/e point, given from Fig 2. For small values of the normalized UV exposure doses the measured index change $dn(\lambda)/[1{*}J/cm^2]$ can be linearised (see Fig. 3) for different wavelengths of 405 nm / 532 nm / 635 nm. The calculations of the index profiles for e. g. a normalized exposure dose of 0.0625 are shown in Fig. 4 for some specified wavelengths.

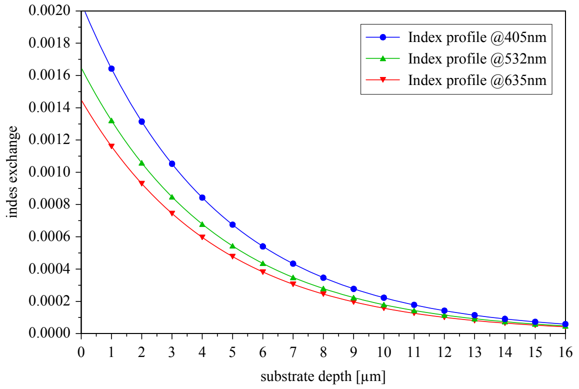

Fig. 4: Calculated index profiles for polymer waveguides for specified wavelengths.

Effective mode index calculation

The well known index profile function is necessary for index simulation by standard BPM methods for structured single mode strip waveguides. The effective mode index curves for the first and second TE mode are plotted in Fig. 5 for a wavelength of 405 nm. A single mode waveguide can be obtained up to a normalized exposure dose of app. 0.1. The basic parameters for the presented calculation are a mask slit width of a few microns, the cladding index above the surface strip waveguide is equal to the substrate index, a layer thickness of 10 µm has been assumed.

If the refractive index for the cladding above the structured waveguide matches not exactly the substrate index then the mode index decreases to lower values and the single mode range becomes smaller. Therefore, a good index matching of the cladding glue is necessary. Unfortunately such glue is not always available from stock.

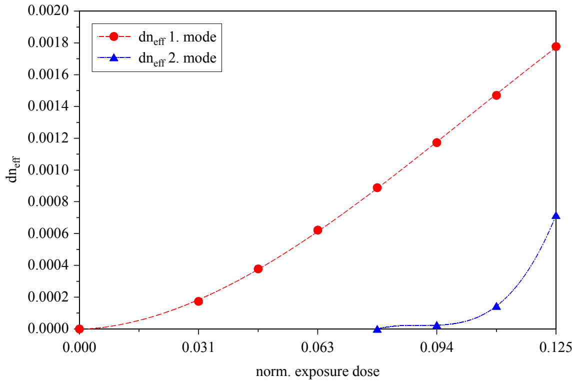

Fig. 5: Effective TE-Mode index distribution as a function of the UV exposure dose for strip waveguides in polymer operating at 405 nm.

Calculation of the mode field distribution

The standard BeamProp software from RSoft presents a tool for a full vector calculation of the TE/TM mode field distributions. Our interests are on single modes behaviour within the VIS range especially the RGB signal performance. The conditions for the calculation are the same as described in the last chapter.

Field distributions for buried single mode strip waveguides in polymer are presented in Fig. 6-8. The small Box in the figures marked the area of the index change between –x/2…+x/2 and $y_0 \ldots y_{1/e}$ wheras x is the slit width of the mask. At the waveguide entrance a Gaussian field was launched. The relative mode intensity becomes stable in values of 79 % / 82 % / 73 % compared to the launched intensity after a propagation lengths of app. 300 µm / 800 µm / 1800 µm at 405 nm / 532 nm / 635 nm wavelengths respectively. Thus, app. 20 % to 25 % of the launched intensity is lost due to mode mismatch between the Gausssian field and the mode filed in the waveguide.

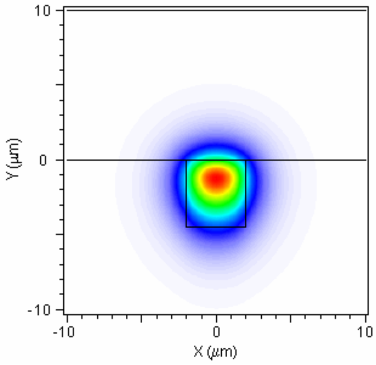

Fig. 6: Calculated transversal TE-Mode field distribution for 405 nm with a mode index step of $dn_{eff} = 0.0012$.

On one hand a normalized UV exposure dose of app. 0.1 gives a smaller mode field dimension for the blue light and the mode propagation is stronger with an effective mode index step of $dn_{eff} = 0.0012$ compared to green and red light (see Fig. 6-8). On the other hand a better mode propagation for the red light by increasing the exposure dose resulting in an increased index change would result in a more instable light propagation in the blue because for this wavelength the second mode comes up.

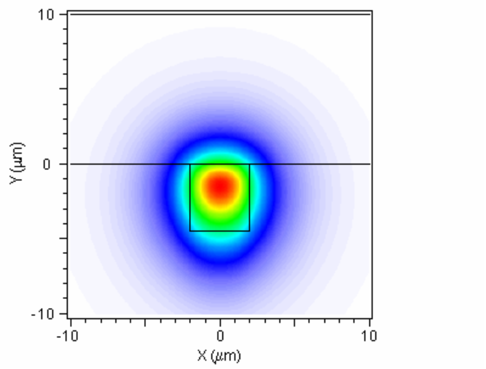

Fig. 7: Calculated transversal TE-Mode field distribution for 532 nm with a mode index step of $dn_{eff} = 0.0006$.

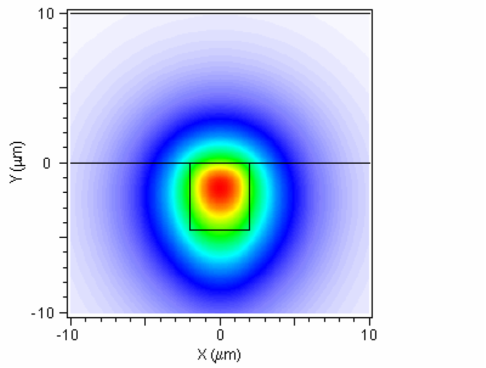

Fig. 8: Calculated transversal TE-Mode field distribution for 635 nm with a mode index step of $dn_{eff} = 0.0003$.

Measurement of the mode field distribution

The first interest is the quality of single mode surface waveguides without any cover material. For better understanding first we compare the well known measurement results of mode field distribution in the range of 850 nm down to 635 nm. In this range the waveguides show losses of app. 0.15 dB/cm. Fig. 9 shows three mode field measurement results for surface waveguides at wavelengths of 808 nm, 635 nm and 407 nm. For 808 nm and 635 nm the mode field distribution compares to fibre. In case of 407 nm the exposure dose has not yet been optimized resulting in a much broader mode distribution.

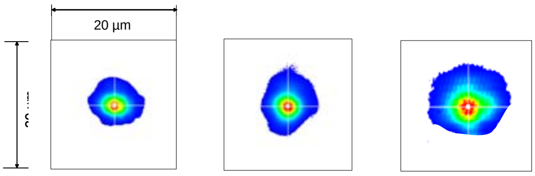

Fig. 9: Measured mode field distributions of surface waveguides for 808 nm / 635 nm and 407 nm wavelengths from left to right.

Fig. 10 shows a CCD picture from a part of the end face of a fabricated buried waveguide package realised with a cladding layer between two polymer substrates. The whole thickness is about 1 mm which can be compared by the scaling of the painted frame. To get this picture, the endface is illuminated from outside by a white light lamp. On the left side near the centre within the frame an arrow marked the light spot of the single mode waveguide. The laser power @ 407nm is reduced (LED mode) for better visibility of the whole picture.

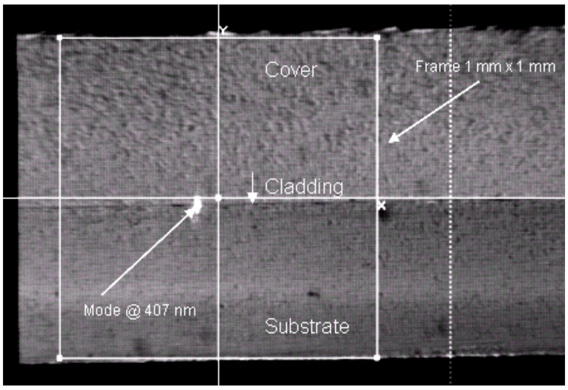

Fig. 10: CCD picture from the end face of a covered substrate with structured single mode waveguides. The light output of a guided mode is marked.

The cladding between substrate (down side) and the cover (top side) is a 10 µm thick layer of glue which looks free from any light propagation. The fine structure over the end face comes from the sawing process.

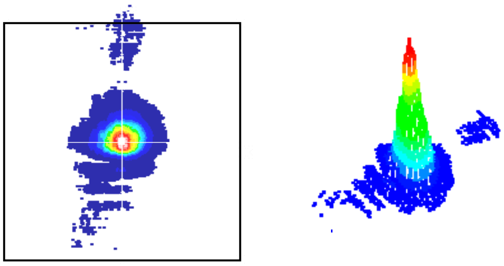

Fig. 11: Measured near field pattern of the light intensity distribution at the end face output of a buried single mode waveguide in a polymer substrate @ 407nm. The frame dimension in the left picture is about 20 x 20 μm^2.

The near field measurement from such a buried single mode waveguide @ 407nm laser wavelength is shown in Fig. 11. At present the fabricated waveguides are with some small imperfections at the adjusted UV exposure dose and the mask slit width. The imaged output intensity distribution in the left side picture of Fig. 11 is in a good agreement with the calculated mode pattern (see Fig. 6) if we consider the opposite orientation (y axis) of the sample in the measurement.

Sometimes, more or less irregularities in the intensity distribution are obtained in the substrate or in the cladding layer. This can be seen in Fig. 12 which gives the intensity distribution along the cross sections of the axis. The x-cut figure is more symmetric than the other and follows approximately a Gaussian curve. The anomaly of a Gauss profile along the (y)-cut profile could have been generated from an index mismatch of the cladding glue. In this example we use a cladding glue with an index difference of $n_{sub} - n_{cla} = 0.0200$. The cursors along the x-profile mark the width of the mask slit and in the y-profile the distance from the intensity maximum to the noise level in direction of the cladding.

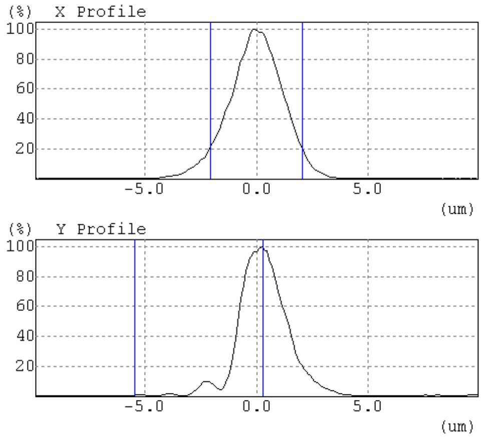

Fig. 12: Measured intensity distribution along the cross sections of the x and y axis.

Conclusions

In this paper we have presented the results of the development of single mode waveguides in a standard polymer substrate for applications in the visible range. The fabrication process for a reasonable index change by a simple UV lithography technique using a metallic evaporated slit mask could be demonstrated resulting in single mode waveguides down to wavelength of 400 nm. The exposure time is on the order of some minutes.

We discussed the wavelengths dependent results for the index change using effective mode index measurements. Based on the results of uncovered multimode film waveguides the index distribution was described by a general equation which can be used to re-calculate the exponential index profiles and the maximum surface index change as a function of the UV exposure dose.

In good agreement between calculated and measured mode profiles we presented results for the intensity distribution of uncovered and covered (buried) single mode waveguides between 400 nm and 635 nm.

In the future we will optimize the single mode propagation of visible light under the aspects of cladding glue index matching, the structure geometry for curved waveguides (S-bands, splitters, couplers), the insertion loss, the polarization depended loss and the optical damage in the case of high power application.

Furthermore the fibre-chip-coupling should be studied under the aspects of the best core diameter, the kind of fibre interface and the long time stability of the hybrid components.

Acknowledgments

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