Optical Materials 75 (2018) 230–235

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

# Two-dimensional interferometric characterization of laser-induced refractive index profiles in bulk Topas polymer

Steffen Hessler [a,*], Manuel Rosenberger [a], Bernhard Schmauss [b], Ralf Hellmann [a]

[a] Applied Laser and Photonics Group, University of Applied Sciences Aschaffenburg, Würzburger Straße 45, 63743 Aschaffenburg, Germany
[b] Institute of Microwaves and Photonics, University of Erlangen-Nuremberg, Cauerstraße 9, 91058 Erlangen, Germany

ARTICLE INFO

*Article history:*
Received 13 July 2017
Received in revised form
7 September 2017
Accepted 21 October 2017

*Keywords:*
Polymer waveguides
Interferometry
Cyclic olefin copolymer

ABSTRACT

In this paper we precisely determine laser-induced refractive index profiles created in cyclic olefin copolymer Topas 6017 employing a sophisticated phase shifting Mach-Zehnder interferometry approach. Beyond the usual one-dimensional modification depth measurement we highlight that for straight waveguide structures also a two-dimensional refractive index distribution can be directly obtained providing full information of a waveguide's exact cross section and its gradient refractive index contrast. Deployed as direct data input in optical waveguide simulation, the evaluated 2D refractive index profiles permit a detailed calculation of the waveguides' actual mode profiles. Furthermore, conventional one-dimensional interferometric measurements for refractive index depth profiles with varying total imposed laser fluence of a 248 nm KrF excimer laser are included to investigate the effect on refractive index modification depth. Maximum surface refractive index increase turns out to attain up to $1.86 \cdot 10^{-3}$ enabling laser-written optical waveguide channels. Additionally, a comprehensive optical material characterization in terms of dispersion, thermo-optic coefficient and absorption measurement of un-modified and UV-modified Topas 6017 is carried out.



## 1. Introduction

Polymer materials play an ever increasing role in manufacturing versatile integrated optical devices. Since defining the fabrication methods as well as the final application capabilities a proper polymer choice is of decisive importance especially for polymer optical waveguide design [1]. Beside lithographic, embossing and imprint technologies direct writing of polymer waveguides using UV irradiation offers rapid and low-cost fabrication processes of optical integrated circuit (OIC) devices [2–6]. Therefore, a thorough knowledge and control of the UV-induced refractive index (RI) modification is of fundamental importance as it determines the waveguide's properties such as mode field distribution and attenuation.

With Topas®, a cyclic olefin copolymer (COC), a new amorphous polymer class with exceptional promising features for integrated optics has been introduced and extensively applied since then. Topas materials exhibit high glass transition temperatures up to 170 °C, a pronounced chemical resistance, low birefringence and a very low water absorption behavior ( < 0.01%) being superior to standard optical polymer materials like PMMA or PC [7–10]. Using different fabrication methods, various optical waveguide designs have been developed with the use of Topas polymers [11–16]. In particular, direct excimer laser written waveguides in bulk Topas material have been successfully demonstrated and comprehensively investigated by the authors [17–19].

When employing the UV direct writing method, the local polymer modifications characteristically result in gradient refractive index profiles due to a combination of UV beam shape, material absorption and UV-triggered chemical reactions. In order to quantitatively determine a gradient refractive index distribution of this type, Shams El-Din et al. demonstrated a phase shifting Mach-Zehnder interferometer (MZI) setup [20,21]. By this means direct excimer laser written waveguides in a commercial grade PMMA as well as their long-term stability [22] have been characterized in a precise manner. Based on these works, a comparison between waveguides in different PMMA grades with slightly different chemical composition but strong effect on waveguide formation was conducted by the authors in a previous study [23].

However, all this published research so far is limited to PMMA materials only, which exhibit a comparatively high UV-induced surface refractive index increase (up to $8 \cdot 10^{-3}$). Moreover, all the

* Corresponding author.
*E-mail address:* steffen.hessler@h-ab.de (S. Hessler).

https://doi.org/10.1016/j.optmat.2017.10.029

previous investigations using the phase shifting interferometry (PSI) technique on laser-written waveguides assume an ideal rectangle waveguide profile in order to facilitate the extraction of a one-dimensional refractive index depth profile.

In this publication we comprehensively employ phase shifting Mach-Zehnder interferometry on excimer laser irradiated cyclic olefin copolymer Topas 6017 for the first time. Beside the hitherto acquisition of one-dimensional refractive index depth profiles we introduce a novel two-dimensional measurement scheme of a laser-written waveguide's whole refractive index cross-section. Furthermore, the measured 2D refractive index profile is directly fed into a beam propagation simulation (Synopsys RSoft) to investigate the structure's waveguiding properties. Additional absorption measurements on the Topas polymer material corroborate the evolving surface refractive index modifications. Beyond that, a full Abbe refractometry characterization of the unmodified Topas material is undertaken.

## 2. Experimental setup

### 2.1. Material characterization

In this study, Topas 6017 sheets (Topas Advanced Polymers GmbH) with 1 mm thickness are deployed in all experiments. The sheets are cut to sample size by means of a mechanical precision saw (Struers Secotom 15) and the sample edges are grinded and polished by a semi-automatic polishing machine (Struers Tegramin 20).

A detailed optical characterization of the unmodified cyclic olefin copolymer in terms of dispersion characteristics and thermo-optic coefficient (TOC) is performed by employing multi-wavelength white light Abbe refractometry equipped with a thermostat circulator unit (Atago DR-M2/1550, refractive index precision $\Delta n = \pm 0.0001$). The measurement temperature is varied between 10 °C–70 °C in steps of 10 °C. In addition, the influence of UV-modification on Topas 6017 irradiated with 150 J/cm$^2$ KrF excimer laser flood exposure is also investigated.

Moreover, the spectral dependence of the material absorption is determined by carrying out transmission measurements (T) using a spectro-radiometer (Instrument Systems, transmission measurement accuracy $\Delta T = \pm 0.1\%$). Topas samples are flood exposed to KrF excimer laser (Coherent BraggStar) irradiation with an emission wavelength $\lambda$ of 248 nm. Transmission spectra for the UV modified Topas 6017 samples with total excimer laser fluences of 50 J/cm$^2$, 100 J/cm$^2$, 150 J/cm$^2$ and 200 J/cm$^2$ are compared to the unmodified transmission spectrum.

### 2.2. Interferometric refractive index profiling

In order to determine UV-induced refractive index alterations at the laser-irradiated COC areas, a phase shifting interferometer in Mach-Zehnder configuration is employed which is based on the pioneering works on 1D refractive index depth profiles by Shams El-Din et al. A detailed description of the interferometer setup and interferogram analysis can be found in previous publications either by Shams El-Din [20–22] or by the authors [23].

An expanded beam of a HeNe laser ($\lambda = 632.8$ nm) is split into object and reference beam by a cube beam splitter. The object beam travels through the Topas sample incorporating a Krf excimer laser-written waveguide area which alters the phase of the object beam relative to that of the reference beam. The Topas sample is placed inside an optical glass cuvette filled with an immersion liquid (methyl salicylate) matching the refractive index of the unmodified COC substrate. This immersion oil with known refractive index of 1.5293±0.00006 serves as reference for the measured phase values and provides continuous interference fringes by minimizing the influence of sample surface roughness. Two 10x microscope objectives enlarge the beam paths such that the viewed waveguide area is magnified and the reference wavefront matches the object wavefront. After superposition of the two interferometer beams the resulting forms of the interference fringes contain the whole phase information and thus resemble the refractive index distribution of the sample. The resulting interferogram at the interferometer output is recorded by a monochromatic CCD camera (Allied Vision Marlin, 1392 × 1040 pixels, pixel width 4.65 μm). For the determination of the phase difference values between object and reference arm, Phase Shifting Interferometry (PSI) using a piezo-mounted mirror in the reference arm is applied. The recorded interferograms are processed by the software Fringe Processor (BIAS GmbH). The actual scale of the interferogram is calculated using the camera's pixel width and taking into account the interferometer beam magnification at detector distance. After phase unwrapping and normalization the obtained phase difference values are converted pixelwise into refractive index values following [21,23].

Integrated waveguides in COC substrates are usually written by irradiating the planar surface with a KrF excimer laser at 248 nm [17]. However, for the measurement of the refractive index profiles with the Mach-Zehnder interferometer the waveguides are generated in an optically polished edge of the 1 mm thick Topas substrate. This approach limits the overall optical path length of the lateral measurement beam through the COC samples, which enables detectable phase differences allowing the use of interferometry and permits the application of the rectangular multi-layer waveguide model according to [20].

For the conventional measurement of one-dimensional refractive index depth profiles the straight Topas waveguides are laser-written lengthwise into the sample edge through an amplitude mask with a width of 150 μm in contact exposure mode. In this configuration, the interferometric measurement beam traverses the modified area laterally and the RI depth profile is extracted by assuming an ideal rectangular waveguide profile. Fig. 1 (a) depicts the sample layout for refractive index depth profiling together with an exemplary resulting phase difference map clearly showing the surface and the RI depth profile information of the modified area.

However, in order to directly measure the whole two-dimensional refractive index distribution in a novel approach, the waveguide is laser-written orthogonally over the polished Topas edge. In this layout the measurement beam illuminates the modified area in waveguide axis direction and therefore encompasses the exact waveguide shape without the necessity of assuming ideal waveguide forms. Fig. 1 (b) shows the special sample design and a corresponding exemplary phase difference map containing the full information of the waveguide's 2D refractive index profile.

According to our previous works on polymer waveguides in Topas material, channel waveguides are written using the following excimer laser parameters: single pulse fluence 10 mJ/cm$^2$ and pulse frequency 200 Hz [17,19]. The number of pulses N is varied between 5000 and 40,000. To increase the speed of occurring light-induced chemical reactions and to stabilize the refractive index modification, the samples are tempered on a hotplate for 2 h at 120 °C after UV irradiation.

## 3. Results

### 3.1. Material characterization

In Fig. 2 the results of the comprehensive Abbe refractometry measurements on Topas 6017 are summarized. Fig. 2 (a) shows the dispersion curves at different temperatures. The averaged Abbe