Refractive index profiling of direct laser written waveguides: tomographic phase imaging

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Abstract: We present a technique to measure the refractive index profile of direct laser written waveguides. This method has the potential for straightforward implementation in an existing laser fabrication system. Quantitative phase microscopy, based on the Transfer of Intensity equation, is used to analyse waveguides fabricated with an ultrashort pulsed laser embedded several hundred micron below the surface of fused silica. It is shown that the cumulative phase change induced by the waveguide perpendicular to its axis may be monitored in real-time during the fabrication process. Results are verified through comparison with interferometry. Tomographic measurements using illumination from a high numerical aperture condenser lens are used to infer the waveguide cross-section. Results are compared with measurements of the waveguide cross-section from a third harmonic generation microscope.

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References and links


1. Introduction

Direct laser writing (DLW) with ultrashort pulsed lasers is emerging as a useful tool for machining a variety of structures inside transparent substrates [1]. A particularly interesting application involves translation of the sample relative to the fabrication beam to create an optical waveguide [2, 3]. Knowledge of the refractive index change $\delta n$ induced by the laser is invaluable in understanding the properties of the waveguide, but there still remains to be a well established measurement method. Previously the $\delta n$ has been measured at the output facet of the sample using a range of techniques, including a refractive index profilometer [4,5], microreflectivity [6] or from analysis of the near field intensity pattern for guided light [7, 8]. Since these methods are only sensitive to the refractive index profile at the edges of the sample, they are not adequate for the analysis of more complex circuits where it would be useful to map $\delta n$ throughout. Some elegant schemes, such as optical coherence tomography (OCT) [9] and digital holographic microscopy (DHM) [10], have been demonstrated that can deliver this information, although they involve complicated experimental systems and heavy data analysis.

Here, drawing inspiration from a technique previously applied to optical fibres [11], we use quantitative phase microscopy to measure the refractive index profile of DLW waveguides [12–14]. The significance of this technique lies in its optical simplicity, allowing incorporation of the measurement mechanism in an existing laser machining system. Thus, during the fabrication process, we could monitor in real-time the induced refractive index change associated with a waveguides at every point in a photonic circuit. Furthermore, since the cross-section of the waveguides written in a transverse geometry may not be assumed as rotationally symmetric about the guiding direction, we additionally take tomographic measurements to infer the cross-section of the waveguides.

2. Quantitative phase microscopy: Transport of Intensity Equation

Solving the transport of intensity equation (TIE) represents a non-interferometric method for quantitative phase measurements [15–17]. In contrast to interferometric techniques it does not require a phase-stable set-up and the recording of fringe patterns but only two or more intensity images of the object that were taken at different values of defocus. The TIE principle is based upon the fact that phase gradients within a transparent object affect the wavefront of light traveling through it. The altered wavefront shape is in turn reflected by the local propagation directions. From multiple defocused images, one can infer to these local propagation directions and thus the phase topography of the object. The TIE can be derived from the paraxial wave equation and takes, for a one-dimensional object, the following form:

$$\frac{dI(x)}{dz} = -\frac{\lambda_0}{2\pi n} \frac{d}{dx} \left[ I(x) \frac{d\phi(x)}{dx} \right].$$  (1)

Here, $I(x)$ and $\phi(x)$ represent the intensity and phase functions of the object, $\lambda_0$ the light vacuum wavelength and $n$ the refractive index of the specimen. $dI/\,dz$ denotes the gradient of the intensity in axial direction which is in practice approximated by the difference of two slightly defocused images.

The one-dimensional case described by Eq. (1) can be straightforwardly solved and leads to the following expression for $\phi(x)$:

$$\phi(x) = -\frac{2\pi n}{\lambda_0} \int \left( \frac{1}{I(x)} \int \frac{dI(x)}{dz} \, dx \right) \, dx.$$  (2)

The solution is unambiguous except for the two integration constants which define phase offset and average slope in the final phase profile. Both values however can be set to zero for the...
case of inspecting waveguides. We present all our results in terms of the optical path length \( OPL(x) = \phi(x) \cdot \lambda_0 / (2\pi n) \) rather than the phase, which is the “natural” quantity returned by solving the TIE.

From Eq. (2) one may conclude that the acquisition of three images should be sufficient to calculate the phase profile: one image showing the sample in focus (corresponding to \( I(x) \)) and two symmetrically defocused around the sample to estimate the axial intensity gradient. For transparent objects however showing sufficiently smooth phase profiles, the in-focus image can be replaced by a constant, which reduces the number of required images to two. As we will show later, for the specific case of a direct-laser-written waveguide, even the acquisition of only a single image allows one to determine the phase profile with good accuracy, which can enable live quality monitoring during the fabrication process.

3. Results

To confirm the accuracy of the TIE method we performed comparative measurements on DLW waveguides in fused silica using both an interferometric and the TIE approach.

The TIE measurements were done in an epi-illumination microscope with the sample placed on a mirror. The sample was illuminated under high spatial coherence with light from a fibre-coupled green LED (approx. 532 nm wavelength). The microscope objective (Olympus 20×, 0.7 NA) was mounted on a piezo stage which allowed for controlled z-stepping. Each measurement comprised the acquisition of three images: one showing the waveguide in focus and two defocused by ±1.5 μm. Interferometric measurements were performed with a Mach-Zehnder interferometer, using a laser diode (640 nm wavelength) and the same objective lens. The interferometer was set such that the interferograms showed a high fringe density, which allowed for the extraction of the phase information without the need for phase stepping. The results of the TIE and interferometric measurements are summarized in Fig. 1.

Figure 1(a) shows the measured integrated optical path lengths across sections through two different waveguides. The reason for the TIE profiles appearing smoother is explained by the double-integration (see Eq. (2)) which is required to obtain the phase from the measured data. Figure 1(b) compares peak values and widths (1/e2) of Gaussians that were fitted to nine different waveguide profiles. Generally, the data delivered by the interferometry and TIE approaches are in good accordance. The error bars for each data point correspond to the standard deviation of five (TIE) and two (interferometry) independent measurements, respectively.

Choosing a suitable value for the defocus distance \( \Delta z \), i.e. the axial separation between the upper and lower defocused images, represents a trade-off between the signal to noise ratio in the images and the accuracy of the estimated axial intensity gradient. Too small defoci lead to vanishing image contrast whereas too large values lead to an inaccurate approximation of \( dI/dz \). We experimentally determined optimal values for \( \Delta z \) by conducting a series of TIE measurements on a typical waveguide with varying defocus magnitudes. Five subsequent measurements were made for each magnitude to estimate the uncertainty caused by noise. Again, Gaussian fits were performed. The obtained peak- and width- parameters of the fitted curves are shown in Fig. 2. The large error bars in both graphs for low values of \( \Delta z \) indicate the presence of significant noise, whereas the increase of the width parameter for larger \( \Delta z \) values is caused by an imprecise estimate of the axial intensity gradient. From the data, an optimal range for \( \Delta z \) can be defined between two and six micrometers.

The TIE method provides accurate phase measurements as long as the phase gradients within the sample fulfill the requirements set by the defocus distance \( \Delta z \). The value of \( \Delta z \) chosen here is appropriate for smooth waveguide profiles, and it is worth noting that the presence of scattering structures, such as nano gratings [18], within the waveguides would lead to corrupted results. Nevertheless, the TIE method makes no demands on the sample structure in terms of...
its spatial frequency content, and small structures are typically measurable as long as they fall within the general limits of imaging with light. Additionally, it would be possible to measure in-plane birefringence of structures by using polarised light for illumination. It is, however, worth mentioning that there exists a class of phase distributions that cannot be measured with propagation-based techniques such as the TIE method [19]. Such phase distributions are for instance optical vortices.

4. Live acquisition of phase profiles during fabrication

From an engineering perspective, it would be extremely useful to acquire an estimate of the local refractive index contrast for the fabricated waveguides at each point in the network, live during the machining process. This would aid quality control during fabrication, allowing monitoring to ensure uniformity of the waveguides throughout the chip. This is particularly important when manufacturing three dimensional photonic circuits as depth dependent aberrations can affect the focal intensity distribution of the fabrication beam [20–22]. It would also enable online adjustment of the fabrication procedure to ensure that the waveguide network may display cer-
tain desired properties. For example, this would be advantageous when machining evanescent couplers, since additional passes of the fabrication beam could be executed or other parameters adjusted to modify the waveguide index contrast until the appropriate coupling ratios are predicted.

Calculation of a phase profile via the TIE relies on our knowledge of the axial intensity gradient, requiring at least two images at different defocus planes. However, for weak phase objects like the DLW waveguides considered here, an in-focus image may be approximated by a uniform intensity distribution. Then a single image from a defocus plane allows us to estimate the axial intensity gradient and hence the transverse phase profile. This can be easily incorporated into the experimental system for waveguide fabrication, as shown in Fig. 3(a). Since the TIE computation can be done much quicker than the camera frame acquisition, it is possible to obtain a “live” value for the induced index contrast immediately behind the fabrication focus. Köhler epi-illumination is set up using an LED source and coupled through the same objective lens used for the fabrication by a dichroic mirror. A mirror placed beneath the sample ensures uniform illumination as the sample is scanned. The reflected light is imaged onto a CCD through a 50:50 beamsplitter, with the tube lens (f = 300 mm) translated axially a small amount such that the image recorded is defocused by a defined amount Δz with respect to the waveguide axis.

Figure 3(b) and 3(c) show typical images for a DLW waveguide defocussed by Δz = 3µm, and in focus. By inspection of Fig. 3(c) it can be seen that the approximation to a uniform intensity for estimation of the axial intensity gradient is reasonable. Indeed when results are compared for phase profiles derived from the TIE using a single defocus image as opposed to two images at defocus plane ±Δz, the residual RMS error is less than 4%. The “live” acquisition of phase profiles in this manner allows us, for example, to observe the accumulation of refractive index contrast in the waveguide with multiple passes of the fabrication focus along the same track, Fig. 3(e).

5. Tomographic imaging of the phase profile

In the preceding section, we measured the accumulated OPL through a waveguide structure. Previously it has been shown that this may be mapped to a radial refractive index distribution for the waveguide using an inverse Abel transform, on the base assumption that the waveguide
Fig. 3. (a) Experimental setup allowing online acquisition of waveguide phase profiles during fabrication. (b) An example defocus image captured for the waveguide and, for comparison, an in focus image (c). Approximating the intensity distribution in (c) as a constant, the phase profile of the waveguide may be estimated (d). The increase in optical path length for the waveguide structure with multiple passes of the fabrication focus (e).

is radially symmetric [11, 13]. However, for DLW waveguides there is a strong chance of asymmetry, particularly for those written in the transverse geometry where the sample is translated perpendicular to the optic axis to trace out a guide. This is related to the natural elongation of the focal intensity distribution parallel to the optic axis when focussing with lenses of limited numerical aperture. Optical techniques such as astigmatic focussing [23], spatio-temporal focussing [24] or slit beam shaping [25–27] may be used to control the waveguide cross-section, although these are still not guaranteed to generate axially symmetric guides due to the potential for optical aberrations induced by focussing through a refractive index boundary [28]. Additionally, there are certain scenarios where asymmetry in the refractive index profile is desired; for example in generating form birefringence [29, 30]. Thus we should develop a method for estimation of the refractive index distribution for non-symmetric waveguides.

Quantitative Phase Tomography allows for the measurement of three dimensional phase information, through acquiring a series of images of a sample with light propagating in different directions. It has previously been applied to the measurement of refractive index contrast in optical fibres, where it is straightforward to change the orientation of the sample in the microscope [31]. With DLW waveguides in bulk substrates, it is impossible to rotate the sample, but we may vary the angle of light propagation through selective illumination of a high numerical aperture condenser. The experimental scheme is shown in Fig. 4(a). The LED illumination is focussed with a tube lens (f=120 mm) onto the back aperture of a 1.4 NA oil immersion condenser lens. A rotatable mirror in the back focal plane controls the position of the focus at the condenser back aperture and, hence, the angle of the illumination through the specimen. The light is collected by an objective (Zeiss 1.3 NA 40x oil immersion) and imaged onto a CCD.
Phase profiles for the waveguides are accumulated, using the TIE approach, at a series of illumination angles oblique to the waveguide axis. The waveguide cross-section can be estimated by fitting an appropriate model to the obtained data. If the refractive index profile of a waveguide is assumed to be Gaussian, the peak OPL as a function of the illumination angle should be proportional to the radius of an ellipse, i.e., $\text{OPL}(\theta, e) \propto 1/\sqrt{\cos(\theta)^2 + e^2\sin(\theta)^2}$, where $\theta$ denotes the illumination angle and $e$ the ellipticity of the guide, i.e. the ratio between the long and short axes. Likewise, the width of the measured projection should be proportional to the inverse ellipse radius. This can be shown using the Fourier projection-slice theorem, which states that the one-dimensional Fourier transform of a projection is equal to a slice (taken perpendicular to the projection direction) through the two-dimensional Fourier transform of the profile. It is worth noting that these models are relatively robust against variations in the exact profile shape as long as the ellipticity is maintained. For instance, numerical simulations showed that Gaussian and flat-top profiles with the same ellipticity are not distinguishable from the estimates delivered by the fits. Whilst this is advantageous if one is only interested in producing waveguides with a certain axis ratio, it also means that the method is not suitable for reconstructing quantitative refractive index profiles of waveguides. This task would require more elaborate data analysis as for instance used in X-ray computed tomography.

![Fig. 4.](image)

(a) Experimental schematic for tomographic phase imaging of DLW waveguides. (b) Sample retrieved plots of the OPL for waveguides A and B for illumination at different incident angles. Measurements of the characteristic waveguide width $\sigma$ (c) and peak OPL (d) as a function of the illumination direction. Fits to the data are shown as dashed red curves providing a measure of waveguide ellipticity $e$ (as denoted in the caption). (e) The waveguide cross-sections estimated from the tomographic measurements and measured using a third harmonic generation (THG) microscope.

DLW Waveguides were fabricated in a transverse geometry in fused silica using an amplified Ti:Sapphire laser ($\lambda = 790$ nm and pulse repetition rate 1 kHz). An adaptive slit beam shaping method [27] was used to control the cross-section of the waveguide by varying both the width and length of the slit illumination in the back aperture of the fabrication objective. The slit width governs the broadening of the intensity distribution within the focal plane, while the length of the slit essentially controls the numerical aperture (NA) of the objective and, hence, the depth of focus. Two differing waveguides were written with slit width $w$ and effective numerical
aperture $\text{NA}_{\text{eff}}$. Guide A was designed to have circular cross-section with $w = 0.9$ mm and $\text{NA}_{\text{eff}} = 0.5$. The parameters used for Guide B were chosen to generate an elliptical cross-section by decreasing the numerical aperture $\text{NA}_{\text{eff}} = 0.4$ to stretch the structure along the fabrication optical axis and widening the slit $w = 1.6$ mm to reduce the transverse dimension.

Measurements of the three dimensional structural properties of the two waveguides were made by Quantitative Phase Tomography. Defocus images were taken for a range of illumination angles up to $36^\circ$. Images at higher illumination angles became too highly distorted by off-axis aberrations in the system to be included. Five measurements were taken for each illumination angle. Care needs to be taken in estimating the axial intensity gradient from the defocus images, since the off-axis illumination introduces an additional lateral translation of the image with defocus. The results are shown in Fig. 4(b), where we display for the two waveguides some examples of the calculated OPL for different incident illumination angles. These results are quantified in Figs. 4(c) and 4(d), where we display for the two waveguides a characteristic width $\sigma$ and the peak OPL from the measured phase profiles. Error bars take into account differences between measurements and uncertainty arising from the data processing.

With incident illumination normal to the substrate our results predict the waveguides to be similar in transverse dimension but that Guide B has a significantly greater OPL. As the illumination angle is increased, both the OPL and transverse size remain approximately constant for Guide A as to be expected for a circular waveguide cross-section. In contrast, the OPL drops steadily and the transverse dimension increases for Guide B at higher illumination angles, consistent with a highly elliptical waveguide cross-section. The red dashed lines in Figs. 4(c) and 4(d) are the fitted curves for the data. By assuming an elliptical description of the waveguide cross-section, the fit to the tomographic width data (Fig. 4(c)) provides estimated ellipticities of $2.04 \pm 0.14$ and $3.85 \pm 0.10$ for guides A and B, respectively. The corresponding estimates from fitting the peak OPL data (Fig. 4(d)) are $0.62 \pm 0.17$ and $3.04 \pm 0.30$. Both fits reveal waveguide B to be significantly more elliptic than waveguide A, although the ellipticity estimates from the width data generally show higher values than those from the peak OPL data. This discrepancy is probably caused by the afore-mentioned image distortions at high illumination angles, which effectively broaden the image (and hence increase the width) of the waveguide. An initial calibration measurement [32], done with a waveguide of known circular cross-section, might allow the derivation of more accurate predictions from the tomographic data.

Sketches of the waveguide profiles estimated from the tomographic measurements are shown in Fig. 4(e) (dashed lines indicate the one sigma confidence intervals). The sketches highlight the discrepancy in the expected profiles obtained from the different fits to the tomographic data. This discrepancy is particularly pronounced for waveguide A, where the expected ellipticity is reversed dependent on whether we use the peak OPL data or the characteristic width of the OPL measurement. In order to ascertain the true nature of the waveguide cross-sections, we imaged the sample in a third harmonic generation (THG) microscope [33]. The THG microscope is sensitive to non-uniformity in the third order susceptibility ($\chi^{(3)}$), which typically coincides with regions where there is a gradient in the local refractive index. The nature of the THG process dictates that the signal is only generated at the focus of the excitation beam, and hence gives a direct measurement of the waveguide structure with three dimensional resolution.

The cross section images obtained with the THG microscope for waveguides A and B are shown in Fig. 4(e), in addition to the cross-sections inferred by tomography. The THG cross-section for both waveguides is hollow, indicating that the refractive index change has a step nature, with a vanishing gradient in the middle of the guide. The THG data confirms our conclusions from the tomographic data that waveguide B is more elliptical than waveguide A. The ellipticity of the measured THG cross-sections are also found to coincide well with the waveguide profiles estimated from the characteristic width in the retrieved tomographic OPL
measurements. However, it should be noted that due to the diffraction limited shape of the probing laser spot, the PSF of the THG microscope is elongated along the optic axis. This causes asymmetric blurring of the image and the appearance of greater elongation along the optic axis, which is particularly apparent at the small length scales considered here. As a consequence, the waveguide ellipticity displayed by the THG microscope corresponds more closely to an average of the ellipticities predicted from the two tomographic fits.

6. Summary

The extraction of the refractive index (RI) profile for DLW waveguides represents a difficult task, yet is incredibly important for a clear understanding the properties of photonic circuits. We use quantitative phase microscopy, via the TIE method, as an optically simple approach to gain indirect information about the waveguide RI. The technique requires no specialist equipment, can be easily performed at any point within a 3D waveguide network and is not computationally expensive. An obvious engineering advantage is gained from the incorporation of the TIE measurement into a laser machining system to allow real-time monitoring of a waveguide RI during fabrication. However, since waveguides formed by DLW are not guaranteed to be rotationally symmetric about the guiding axis, for the TIE measurement to provide an accurate inference of the waveguide properties, we require some further information about the waveguide cross-section. A tomographic implementation of the TIE method, as demonstrated here, is useful in gaining an estimate of the waveguide ellipticity and is also simple enough to potentially be included within the fabrication experimental system. It is apparent that some of the estimates of individual waveguide characteristics, such as the cross-section profile, based upon TIE measurements are subject to large uncertainties. However, the combination of such measurements with a priori information about the expected waveguide properties would lead to more accurate estimates. Such in situ measurement will be a valuable addition to the technology of DLW waveguide fabrication.

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