Characterization of Femtosecond Laser Written Waveguides for Integrated Biochemical Sensing

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Fluorescence detection is known to be one of the most sensitive among the different optical sensing techniques. This work focuses on excitation and detection of fluorescence emitted by DNA strands labeled with fluorescent dye molecules that can be excited at a specific wavelength. Excitation occurs via optical channel waveguides written with femtosecond laser pulses applied coplanar with a microfluidic channel on a glass chip. The waveguides are optically characterized in order to facilitate the design of sensing structures which can be applied for monitoring the spatial separation of biochemical species as a result of capillary electrophoresis.

Introduction

The recent advances in microchip fabrication technologies and microfluidics has enabled the investigation of a large number of biochemical processes in miniaturized lab-on-chip systems. The substitution of conventional bench-top measurement setups with on-chip integrated detectors will lead to a further boost for the development of lab-on-chip systems. In particular, integrated optical detection has emerged as an attractive tool to fulfill the requirements of such an on-chip *in-situ* probing strategy [1]. Current detection schemes mostly depend on the hybrid integration of an existing microfluidic system with external detection optics. This work aims at integrating both functionalities in a single substrate, e.g. a glass. Parallel to the progress in glass-based microfluidics, femtosecond laser writing has emerged as an interesting technique to inscribe optical waveguides in bulk glass substrates [2]. The combination of these two developments to integrate a detection system of optical waveguides written on a glass lab-on-chip with a femtosecond laser beam is a novel approach, forming the key focus of this work [3].

Waveguide fabrication

Femtosecond laser written waveguides are a unique class of waveguides due to the peculiar fabrication process involving material modification, which leads to a graded refractive index distribution unlike many conventional methods of optical waveguide fabrication. Femtosecond laser irradiation leads to localized melting in the focal volume of the femtosecond laser beam and re-solidification upon removal of the writing beam. These non-linear processes accompanied by other thermal effects lead to localized densification and graded refractive index distribution. Waveguiding structures can thus be written by a continuous movement of the substrate with respect to the writing beam.

An important advantage of this technique is the possibility to create 3D waveguide structures by appropriate movement of the substrate during writing [4]. The optical waveguides under investigation were fabricated by means of a femtosecond Ti:Sapphire laser at a repetition rate of 1 kHz, with typical pulse energies of 1 μJ and writing speeds of 100 μm/s, in a fused silica glass chip aimed at bio-sensing applications.

Characterization of modal properties

The application of femtosecond laser written waveguides in optical sensing demands a thorough understanding of their properties, such as refractive index distribution, resulting mode profile, propagation and bend losses for device design purposes. The following paragraphs describe the steps taken in order to experimentally characterize in particular the refractive index distribution *n(x, y)* and propagation loss.

Mono-modality is important for devices such as Mach-Zehnder or Young interferometer based sensors, which depend on the optical interaction of the modal field with the measurand and the interference pattern read out as a result. On the other hand, in case of fluorescence or absorption sensors, the interaction is based on the incident light intensity and multimode waveguides can be used to interact with the contents of the microfluidic channel. In order to determine the modal-field properties of our waveguides, the near-field mode profiles were captured with a highly sensitive linear-gray-scale CCD camera. It was observed that depending on the glass and the production batch to which the specific substrate belongs, different modal propagation features are induced in waveguides written with the same writing parameters. The images in Fig. 1 show a few typical mode profiles that have been obtained. It was also observed that the excited near-field mode profile was dependent on the position of the in-coupling fibre in x-y plane with respect to the waveguide input end face.

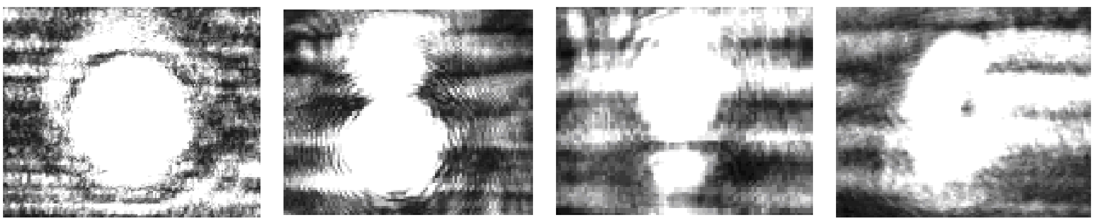


Fig. 1. Near-field mode profiles of fs-laser written waveguides. a) fundamental mode b) 1st order mode, c) 2nd order mode, d) 'donut' mode

The process of material modification during femtosecond laser writing and resulting refractive index distribution is highly dependent on the substrate as well as the writing laser beam. It is, therefore, important to characterize it for each new combination of glass substrate and inscribing laser beam. The technique described in this work utilizes a back-calculation algorithm based on the near-field profile of the first-order mode propagating in a low-index-contrast, weakly guiding, single-mode waveguide [5]. Capturing the near-field profile by a CCD camera restricts the resolution of the image depending on the camera being used. In order to attain higher resolutions, the near field is scanned with a fiber tip, such that the effective spatial resolution is essentially dependent on the diameter of the fiber tip and on the scan resolution (down to 25 nm is achievable using SNOM tips and automated 3D motion stages). The scalar eigen-value equation for the modal field can be expressed as

$$\nabla_T^2 \Psi(x,y) + (k_0^2 n^2(x,y) - \beta^2)\Psi(x,y) = 0,$$

where $\Psi(x,y)$ is the modal field, β is the propagation constant, and $n(x,y)$ is the refractive index profile to be determined. Rearranging the above equation, we obtain

$$n^2(x,y) = \left(\frac{\beta^2}{k_0^2}\right) - \frac{\nabla_T^2 \Psi(x,y)}{k_0^2 \Psi(x,y)}.$$

Substituting the modal field intensity $I(x,y) = \Psi^2(x,y)$ and $n(x,y) = n_B + \Delta n(x,y)$, where n_B is the refractive index of the bulk material, we obtain

$$\Delta n(x,y) = \frac{\beta^2}{2 n_B k_0^2} - \frac{n_B}{2} - \frac{\nabla_T^2 \sqrt{I(x,y)}}{2 n_B k_0^2 \sqrt{I(x,y)}}.$$

The above algorithm was implemented in an in-house developed software tool, and the refractive index changes were evaluated. The peak refractive index contrast of ~ 1×10^{-3} was found to be in good agreement with the results of refractive index profile measurements carried out with a commercial instrument (Rinck Elektronik GmbH).

Characterization of propagation losses

Another parameter that plays an important role in the efficiency of any integrated optical sensing device is the propagation loss. It is conventionally evaluated using the cut-back method, which is a destructive method. Alternatively, a streak-of-scattering measurement along the waveguide can be performed. The waveguides studied during this work did not show any scattering at any of the wavelengths investigated, which already gave an indication of their good quality. Therefore, the propagation losses due to absorption were evaluated based on the fact that during the writing process colour centres are created [6]. The spectral dependence of waveguide insertion losses was evaluated experimentally. The results were normalized with respect to the coupling losses, and thus the losses induced by colour centres were plotted as a function of wavelength, see Fig. 2.

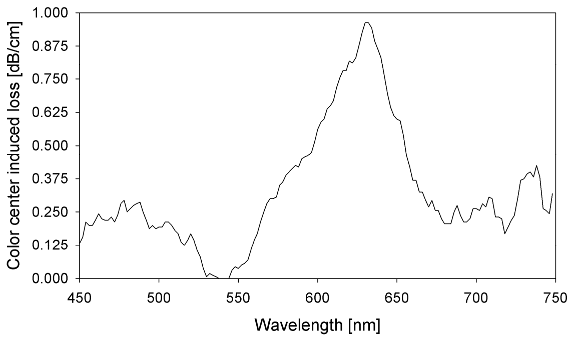
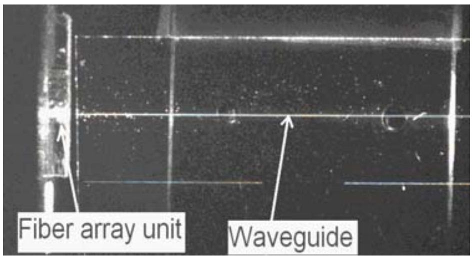


Fig. 2. Color-center induced loss spectrum of a fs-laser written waveguide

The illumination of these waveguides with an end-coupled He-Ne laser at 633 nm excited these colour centres resulting in photoluminescence which was imaged from the top with a linear CCD camera, as shown in Fig. 3(a). The variation in the pixel intensity along the waveguide was captured and plotted as a function of waveguide length. The effective slope of the fitted curve corresponds to the propagation loss along the waveguide. Figure 3(b) shows a typical loss evaluation curve.



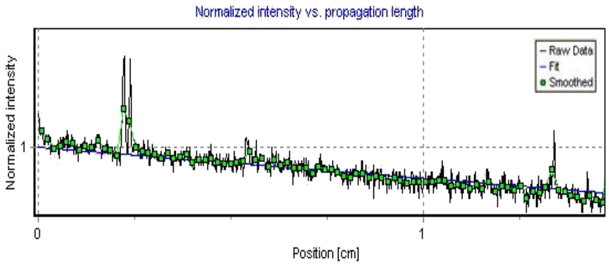


Fig. 3. a) Top view of photoluminescence in a waveguide operating at 633 nm. b) Propagation loss evaluation based on decay of photoluminescence

The losses were measured to be 0.5 – 0.9 dB/cm at 633 nm and were found to be in good agreement with cut-back measurements performed independently. These propagation losses are comparable to those obtained by conventional waveguide fabrication techniques and acceptable in optical sensing applications.

Conclusions

We have characterized optical waveguides fabricated by irradiation of a glass substrate with femtosecond laser pulses and their potential application to integrate on-chip optical detection with glass-based lab-on-chip systems. A number of properties critical for the application of these waveguides in optical sensing were characterized. The results indicate that such integration is indeed feasible. The thorough understanding of the waveguide properties provides an important input for the design of integrated sensing devices on a commercial lab-on-chip system for exploitation of these two glass-based technologies.

Acknowledgements

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