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Refractive index profiling of multimode specialty optical fibers by absorption contrast X-ray computed microtomography

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Abstract. We report on successful refractive index profiling of commercially available step-index and in-house made graded-index multimode specialty optical fibers by means of X-ray computed microtomography. Our results demonstrate that the latter is an advantageous technique for characterizing large core optical fibers, which allows for retrieving information about the refractive index at optical frequencies by exploiting the absorption coefficient of X-rays.

1 Introduction

Multimode optical fibers (MMF) have been attracting considerable attention in the recent years. This is mostly because, owing to their large core size, MMF provide several advantages for technological applications with respect to their singlemode counterparts [1]. For instance, MMF allow for guiding and delivering optical beams with higher energy than singlemode fibers. As such, the use of MMF permit to scale-up the power of state-of-the-art fiber lasers. Moreover, the degree of freedom provided by multimodality is pivotal for developing telecommunication systems based on the so-called spatial-division-multiplexing [1], as well as for laser beam delivery for multimode imaging devices, based on nonlinear optical effects [2]. To date, MMF are mostly used for applications whose operating wavelengths are either in the visible or in the near-infrared spectral range, i.e., where silica, the material of which standard MMF are made, has minimum absorption [1].

In the recent past, however, MMF have been targeted for applications in the mid-infrared spectral domain as well, e.g., for molecular fingerprinting, medical diagnostics, gas monitoring, and LIDAR technologies [3]. Working at such long wavelengths requires using specialty optical fibers (SOF), made of non-silica materials, e.g., flouride and germanate glasses, which are generally doped with high atomic number (Z) elements, such as Te and Pb. To date, virtually all of the specialty MMF which are commercially available are step-index fibers. Nonetheless, recent studies have proposed employing nanofabrication techniques for engineering the optical properties of SOF. This made it possible to manufacture specialty graded-index (GRIN) fibers [4].

In this work, we report on an efficient technique for profiling the core refractive index of SOF, i.e., absorption contrast X-ray computed microtomography (XCT). Indeed, as the X-ray absorption nonlinearly scales with Z, the characterization of SOF via XCT is particularly suited. In this regard, it has to be mentioned that the validity of XCT for the refractive index profiling of optical fibers has been demonstrated for standard MMF, whose refractive index contrast between core and cladding is achieved by doping with relatively low Z elements, such as Ge and F [5]. Nonetheless, XCT has proven to be so effective, that the analysis of tomographic images allowed for spotting the presence of micron-size laser-induced damages in the fiber core [6].

2 Principle of operation

Regardless of the manufacturing techniques, the refractive index difference between the core and the cladding (Δn) of MMF is due to the variation concentration of one or more doping elements ($\Delta[X]$) between these regions. In all cases, the material doping is used for increasing the refractive index of the core with respect to that of the cladding, i.e.,

$$\Delta n \sim \Delta[X]. \qquad (1)$$

Now, the variation of doping concentration provides an absorption contrast at X-ray frequencies, which can be visualized using XCT. As a matter of fact, the XCT

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intensity provides a 3D map of the fiber material density, which is proportional to the absorption coefficient μ. In a simple formula, one can write

$$\Delta[X] \sim \Delta\mu. \qquad (2)$$

Note that in both (1) and (2), the sign of the proportionality constants can be either positive or negative. For instance, depending on the fiber manufacturing process, doping elements in the fiber core may have either a higher or a lower atomic number with respect to cladding elements. Therefore, the X-ray absorption coefficient might be either higher or lower in the core than in the cladding. In any case, the following proportionality relation holds

$$\Delta n \sim \Delta\mu, \qquad (3)$$

which is what only matters for refractive index profiling purposes. Note that by exploiting (3), one can retrieve information about the refractive index at optical frequencies by exploiting the absorption coefficient of X-rays, i.e., at several orders of magnitude shorter wavelengths. Interestingly, (3) is not only limited to the core/cladding refractive index difference. Indeed, (3) can be generalized to any refractive index shape. For instance, in the case of GRIN fibers, one can evaluate the convexity factor of the refractive index [5].

3 Results

We applied XCT to two SOF, a commercial ZBLAN step-index fiber and an in-house developed soft glass parabolic GRIN fibers. The experimental setup and conditions were the same as in [5], which provide a spatial resolution of 5 μm. The peculiarities of each sample can be visually appreciated from their tomographic 3D renderings, shown in Fig. 1a,b, respectively. In particular, in Fig. 1a, one may clearly appreciate that the XCT intensity is quite homogeneous inside the core of the step-index fiber (cfr. the blue zone at the center of the fiber facet in Fig. 1a). Whereas, the XCT intensity gradually varies when moving from the axis toward the periphery of the GRIN fiber (see the color change at the center of the fiber facet in Fig. 1b). A more quantitative information is given in Fig. 1c,d, where we trace the XCT intensity profile along the radius (*r*) of a fiber section.

Here we are relying on the fact that XCT intensity is proportional to μ, i.e., we are neglecting the contribution of X-ray refraction. We emphasize that such an assumption is strictly valid in the proximity of the fiber axis, i.e., far from material discontinuities, such as that between cladding and air. As it can be seen, we found a flat profile of μ at the center of the step-index fiber, which is highlighted by a dashed line in Fig. 1c. Whereas, as shown in Fig. 1d, the XCT intensity of the GRIN fiber vs. *r* has a parabolic trend, as indicated by its fit (red curve in Fig. 1d). The agreement between the experimentally measured XCT intensity and the expected shape of the core refractive index of both step-index and GRIN fibers confirms the validity of our method. Finally, it is worth mentioning that, for both step-index and GRIN fibers, the XCT intensity profile was found to be rather uniform along the z direction (not shown here), which demonstrates the high quality of the fiber manufacturing processes.

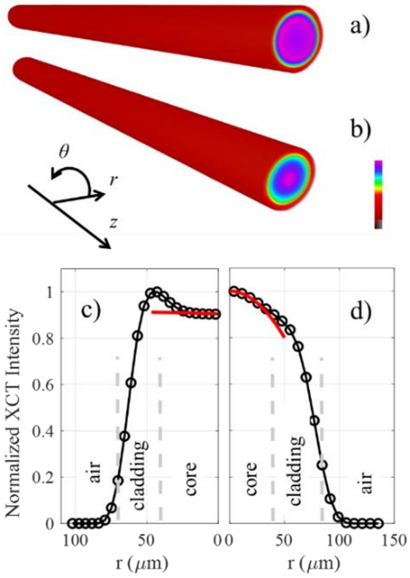

Fig. 1. XCT of SOF. (a,b) Tomographic 3D rendering of a step-index fiber (a) and a GRIN fiber (b). (c,d) XCT intensity profile (or absorption coefficient μ) of the fiber section in (a) and (b), respectively, as a function of the radial coordinate *r*.

4 Conclusion

To conclude, we successfully characterized both commercially available and in-house made MMF for mid-infrared applications. Our results showed that XCT makes it possible to determine the refractive index profile of large core SOF, either step-index or GRIN fiber, with several advantages with respect to the most conventional characterization methods, such as electron spectroscopy and optical tomography. Specifically, XCT is unaffected by fiber bending, and it does not require operating in a vacuum environment. Moreover, XCT permits to scan long samples at once, providing a 3D map of the absorption coefficient, i.e., of the refractive index, even in the presence of fiber coating, which has a low absorption at X-ray frequencies. This task would not be possible with optical characterization techniques.

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