



**HAL**  
open science

## X-ray tomography for the refractive index profiling of standard glass optical fibers

Maria Caterina Crocco, Mario Ferraro, Fabio Mangini, Maxime Jonard, Francesco Sangiovanni, Mario Zitelli, Raffaele Filosa, Joseph Beltrano, Antonio de Luca, Riccardo Barberi, et al.

### ► To cite this version:

Maria Caterina Crocco, Mario Ferraro, Fabio Mangini, Maxime Jonard, Francesco Sangiovanni, et al.. X-ray tomography for the refractive index profiling of standard glass optical fibers. 2022 Advanced Photonics Congress, Jul 2022, Maastricht, Netherlands. pp.SoTh3G.2, 10.1364/SOF.2022.SoTh3G.2 . hal-04670701

**HAL Id: hal-04670701**

**<https://hal.science/hal-04670701v1>**

Submitted on 12 Aug 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# X-ray tomography for the refractive index profiling of standard glass optical fibers

Maria C. Crocco<sup>1,2</sup>, Mario Ferraro<sup>1,3,\*</sup>, Fabio Mangini<sup>3</sup>, Maxime Jonard<sup>4</sup>,  
Francesco Sangiovanni<sup>1</sup>, Mario Zitelli<sup>3</sup>, Raffaele Filosa<sup>1,2</sup>, Joseph J. Beltrano<sup>1,2</sup>,  
Antonio De Luca<sup>2</sup>, Riccardo C. Barberi<sup>1,2</sup>, Raffaele G. Agostino<sup>1,2</sup>,  
Vincent Couderc<sup>4</sup>, Stefan Wabnitz<sup>3,5</sup>, and Vincenzo Formoso<sup>1,2</sup>

<sup>1</sup>STAR IR, Università della Calabria, Via Tito Flavio, 87036 Rende (CS), Italy

<sup>2</sup>Physics Department, Università della Calabria, Via Pietro Bucci, 87036 Rende (CS), Italy

<sup>3</sup>Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy

<sup>4</sup>Université de Limoges, XLIM, UMR CNRS 7252, 123 Avenue A. Thomas, 87060 Limoges, France

<sup>5</sup>CNR-INO, Istituto Nazionale di Ottica, Via Campi Flegrei 34, 80078 Pozzuoli (NA), Italy

mario.ferraro92@unical.it

**Abstract:** By exploiting the absorption contrast provided by the doping of silica, we demonstrate that X-ray microtomography is capable of retrieving the 3D spatial profile of standard multimode glass optical fibers. © 2022 The Author(s)

## 1. Introduction

Glass optical fibers are conventionally characterized by means of all-optical techniques [1]. Besides the measurement of residual-stress, the characterization of optical fibers mainly consists of determining the value of the refractive index inside their entire volume. In particular, the refractive index profiling along the fiber axis is achieved by means of optical tomography techniques [2]. In the spite of their effectiveness, these techniques only work in the absence of plastic coating. This is because the latter absorbs optical radiation, thus preventing light to reach the glass fiber, hence its characterization. This is a major drawback, since the coating and the jacket are essential for providing to fiber devices the necessary flexibility and shielding from external perturbations.

In this context, X-ray computed micromotography ( $\mu$ CT) has been recently proposed as a novel, noninvasive method for characterizing optical fibers, even in the presence of coating. In particular, Sandoghchi et al. reported the  $\mu$ CT analysis of photonics crystal fibers, by exploiting the X-ray absorption contrast between glass and air [3].

Here, we perform a  $\mu$ CT study of standard optical fibers, whose refractive index profile is provided by either Ge or F doping. Specifically, we apply  $\mu$ CT to both step-index fibers (SIFs) and graded-index fibers (GIFs). Because of the limited spatial resolution of our experimental setup, we consider multimode fibers (MMFs), because of their relatively wide transverse cross-section. MMFs are both timely and relevant for several emerging fiber-based technologies, such as high-power beam delivery, space-division-multiplexed telecommunication, and biomedical imaging or endoscopy [4, 5]. However, we underline that  $\mu$ CT can also be applied to: singlemode glass optical fibers, specialty optical fibers (e.g., microstructured and multimaterial fibers), and plastic optical fibers. For GIFs, we validate our method by comparing the results of  $\mu$ CT with that provided by the analysis of doping luminescence.

## 2. Results

We carried out absorption contrast  $\mu$ CT of several SIFs and GIFs, whose typical 3D rendering is shown in Fig. 1a and b, respectively. In particular, we analysed both silica SIFs, whose core is undoped, while the cladding is doped by F, and GIFs, whose cladding is made of pure silica, whereas the core is doped by Ge. Here the Ge doping is spatially nonuniform, for imparting a parabolic profile to the core refractive index. The differences between the  $\mu$ CT of SIFs and GIFs can be better appreciated by examining their single tomographic slices, which are shown in Fig. 1c and d, respectively. The  $\mu$ CT intensity profile along the slice diameter is shown in Fig. 1e and f for a 50/125 SIF or a 50/125 GIF, respectively. As it can be seen, the  $\mu$ CT intensity mimics the doping concentration. Indeed, for SIFs, the  $\mu$ CT intensity has a peak inside the cladding, and it is flat inside the core. To the contrary, for GIFs the  $\mu$ CT intensity profile is rather flat in the cladding (besides the zone close to the interface with air), and exhibits a parabolic profile in the core (cfr. the parabolic fit, shown by a red curve in Fig. 1f).

Therefore, we may infer that, along the fiber cross-section, the  $\mu$ CT intensity profile takes the shape of the refractive index at optical frequencies. This means that  $\mu$ CT permits to estimate (within a multiplicative constant) the refractive index profile of the fiber. For instance, one may determine the grading factor, say  $g$ , of GIFs.

To verify the validity of this method, we compared values of  $g$  obtained by fitting the  $\mu$ CT intensity, say  $g_\mu$ , with values, say  $g_L$ , from the analysis of fiber defect luminescence due to Ge inclusions. The latter are calculated by starting from the measurements of the period ( $\Gamma$ ) of the luminescence that is generated from the multiphoton absorption of intense femtosecond laser pulses propagating into the fiber core [6] (see Fig. 1g). The relationship between  $\Gamma$  and  $g_L$  is discussed in [7]. In Fig. 1h, we plot the measured values of  $g_\mu$  and  $g_L$  for four different GIFs, made by different manufacturers and with different core sizes. As it can be seen, a direct proportionality holds between those two quantities. In particular, we found a linear correlation coefficient  $r^2 = 0.94$ .

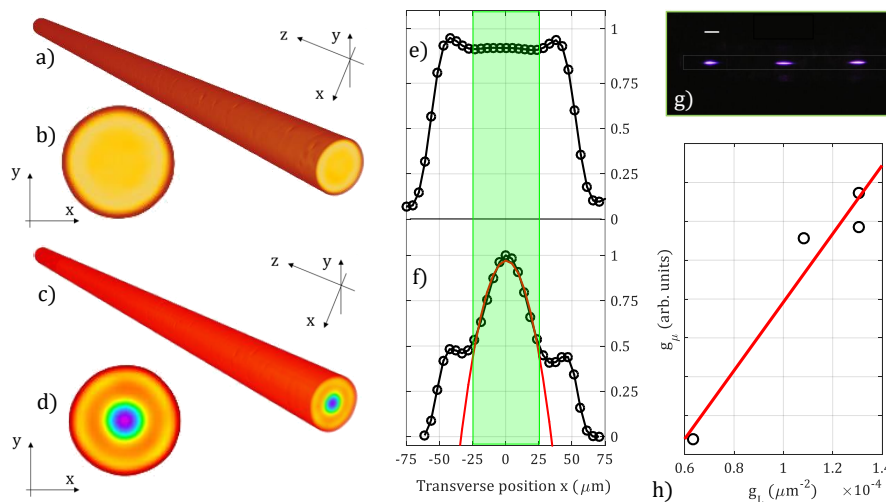


Fig. 1. a,b) 3D rendering of  $\mu$ CT of SIFs (a) and GIFs (b). c,d) Single  $\mu$ CT slice of the reconstruction in (a) and (b), respectively. e,f)  $\mu$ CT intensity profile along the dashed lines in (c) and (d), respectively. The red solid line in (f) is a parabolic fit. The core region is highlighted in green. g) Luminescence pattern of a GIF due to the excitation of Ge-related defects. The white bar is  $100 \mu\text{m}$  long. h) Correspondence between the values of  $g_\mu$  and  $g_L$  for four different GIFs.

### 3. Conclusion

$\mu$ CT candidates as a powerful tool for refractive index profiling of optical fibers. Here, we successfully characterized the index profile of standard glass multimode fibers. The method was validated for GIFs, by comparing the results of  $\mu$ CT with the analysis of fiber defect luminescence. Further confirmations were obtained by comparing the spatial profile of  $\mu$ CT intensity with that of energy dispersed X-ray spectroscopy. These are not shown here and will be discussed in the presentation.

We acknowledge financial support from: Ministero dell'Istruzione, dell'Università e della Ricerca (PIR01-00008, R18SPB8227); European Research Council (740355); Agence Nationale de la Recherche (ANR-18-CE080016-01, ANR-10-LABX-0074-01).

### References

1. W. Stewart, "Optical fiber and preform profiling technology," *IEEE Transactions on Microw. Theory Tech.* **30**, 1439–1454 (1982).
2. R. Hui and M. O'Sullivan, *Fiber optic measurement techniques* (Academic Press, 2009).
3. S. Sandoghchi, G. Jasion, N. Wheeler, S. Jain, Z. Lian, J. Wooler, R. Boardman, N. Baddela, Y. Chen, J. Hayes *et al.*, "X-ray tomography for structural analysis of microstructured and multimaterial optical fibers and preforms," *Opt. express* **22**, 26181–26192 (2014).
4. K. Krupa, A. Tonello, A. Barthélémy, T. Mansuryan, V. Couderc, G. Millot, P. Grelu, D. Modotto, S. A. Babin, and S. Wabnitz, "Multimode nonlinear fiber optics, a spatiotemporal avenue," *APL Photonics* **4**, 110901 (2019).
5. N. O. Moussa, T. Mansuryan, C.-H. Hage, M. Fabert, K. Krupa, A. Tonello *et al.*, "Spatiotemporal beam self-cleaning for high-resolution nonlinear fluorescence imaging with multimode fiber," *Sci. Reports* **11**, 1–8 (2021).
6. F. Mangini, M. Ferraro, M. Zitelli, A. Niang, A. Tonello, V. Couderc, and S. Wabnitz, "Multiphoton-absorption-excited up-conversion luminescence in optical fibers," *Phys. Rev. Appl.* **14**, 054063 (2020).
7. T. Hansson, A. Tonello, T. Mansuryan, F. Mangini, M. Zitelli, M. Ferraro, A. Niang, R. Crescenzi, S. Wabnitz, and V. Couderc, "Nonlinear beam self-imaging and self-focusing dynamics in a grin multimode optical fiber: theory and experiments," *Opt. Express* **28**, 24005–24021 (2020).