Design of composite nanofibers for new all-solid state Raman wavelength converters

Maha Bouhadida[1], *Abderrahim* Azzoune[2], *Théo* Dampt[3], *Laurent* Divay[3], *Mathieu* Fauvel[3], *Christian* Larat[3], *Jean-Charles* Beugnot[4], and *Sylvie* Lebrun[1,*]

[1]*Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127, Palaiseau, France*
[2]*Ecole Militaire Polytechnique, Laboratoire Systèmes Lasers, BP17, 16111, Bordj-El-Bahri, Algiers, Algeria*
[3]*Thales Research and Technology, 91767, Palaiseau Cedex, France*
[4]*Institut Femto-ST, CNRS, Université Bourgogne, Franche-Comté, 25030 Besançon, France*

Abstract: We present the design of composite optical nanofibers coated with different nonlinear materials (PMMA and TiO_2) for the realization of new all-solid state Raman wavelength converters. Two coating processes, multilayer dip-coating and atomic layer deposition, have been successfully developed and optimized for the functionalization, inducing only relatively low losses comprised between 0.5 dB and 1.76 dB on 2 cm. Encapsulation has also been demonstrated. The Raman modal gain coefficients have been calculated to lie between 0.3 and 0.4 $m^{-1}W^{-1}$. Based on our previous results obtained with nanofibers immersed in different liquids, Raman threshold in the ns second regime should be obtained with few cm long nanofibers. This work opens the way to a new family of composite nanofibers for different applications in nonlinear optics.

1. Introduction

Optical nanofiber (ONF – fig. 1), i.e., the homogeneous section of a stretched and tapered silica optical fiber (sub micrometer or micrometer diameter on length of up to more than 10 cm) between two tapered transitions, has been presented a widespread use in science and engineering applications since more than thirty years as an elementary optical component easily integrated by its nature in an all-fibered network. The expanding use of ONF is due to its physical properties. The optical modes guided by the ONF have large intensities due to their strong transverse confinement, present very low losses (below 0.005 dB/cm, far beyond other micro/nano waveguides) and exhibit an evanescent part outside the ONF and therefore in interaction with the external medium.

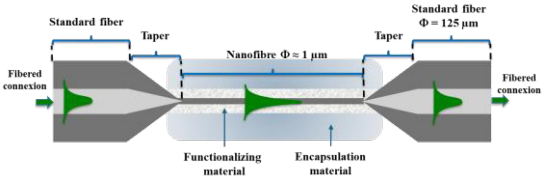

Figure 1 Principle of a functionalized and encapsulated ONF

Due to these intrinsic properties, ONF-based technologies have addressed a large versatility of domains from fundamental to applications such as quantum information devices, nonlinear optics and remote sensor devices for the most active ones. We have already performed several experimental demonstrations in nonlinear optics using ONF. Among them we realized highly efficient wavelength converters based on Stimulated Raman Scattering in the evanescent field of ONF immersed in liquids with conversion efficiencies from the pump source emitting at 532 nm to the first Stokes order of ethanol at 630 nm as high as 60% [1]. We also experimentally demonstrated the emission of photon pairs by four wave-mixing in a bare ONF with high Coincidence to Accidental Ratio [2] and proposed the design of sources of photon pair by Spontaneous Parametric Down Conversion (SPDC) [3].
In this work, we investigate the possibility to add a new degree of freedom to silica ONF by its functionalization with a nonlinear material coating, such as a polymer or other material of interest such as TiO_2. We show that optical nonlinearities can be obtained and even enhanced in such composite ONF by studying the design of new all-solid Raman converters. The encapsulation of ONF, bare or functionalized, is also studied, as this is a critical point for the protection and manipulation of an ONF-based component (see fig. 1).

2. Design of all-solid state Raman wavelength converters

In these converters, the Stokes photons are generated in the functionalizing material of thickness e and refractive index n_g by the Raman scattering of the pump photons present in the evanescent field. These Stokes photons then couple to a guided mode of the composite ONF.

We have studied two functionalizing materials, PMMA, whose strong adhesion to silica surfaces makes it an attractive coating material for silica ONF, and TiO_2, which presents a high Raman gain. In the first configuration the ONF with PMMA coating is

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*Corresponding author: sylvie.lebrun@institutoptique.fr encapsulated in silicone for protection ($n_{silicone}$ = 1.39). We performed simulations on the propagating modes using a three-layer modelling (see fig. 2 for a calculated spatial mode example).

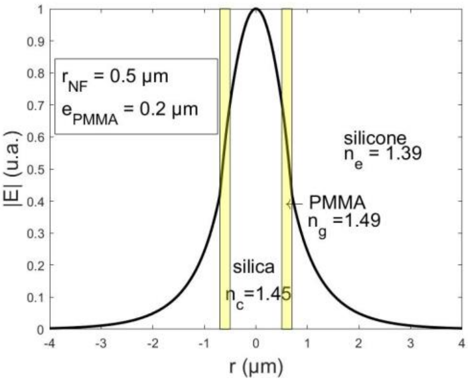

Figure 2 Mode propagating in an ONF having a radius of 500 nm, functionalized by a 200 nm thick layer of PMMA and encapsulated in silicone.

The parameters used in our simulations are summarized in Table 1. The chosen ONF radius is 0.5 µm. Based on our previous results on ethanol Raman ONF converters [1] we believe that the modal Raman gains in both configurations should enable to reach Raman threshold by using a pulsed pump in the ns second regime.

	λ_p (µm) pump	λ_s (µm) Stokes	e (nm)	n_g	Raman modal gain ($m^{-1}W^{-1}$)
PMMA + silicon	1	1.42	200	1.49	0.3
TiO_2 + air	1.30	1.32	60	2.238	0.4

Table 1 Parameters used for the calculation of the modal Raman gains in ONF coated with PMMA and TiO_2.

3. Fabrication of the functionalized nanofibers

ONF were fabricated following the classical "pull and brush" technique to create the tapers and the uniform part [1]. We have developped a process to coat the ONF with PMMA based on multilayer dip-coating to obtain thicknesses of a few hundreds of nm (see fig. 3). We also performed the encapsulation of a PMMA coated ONF with silicone. We measured relatively low additional losses of 1.76 dB after the 2 processes, decreasing from 57% to 38%. For the coating with TiO_2, we have used Atomic Layer Deposition technique (see fig. 4). The additional losses are only 0.5 dB on 2 cm.

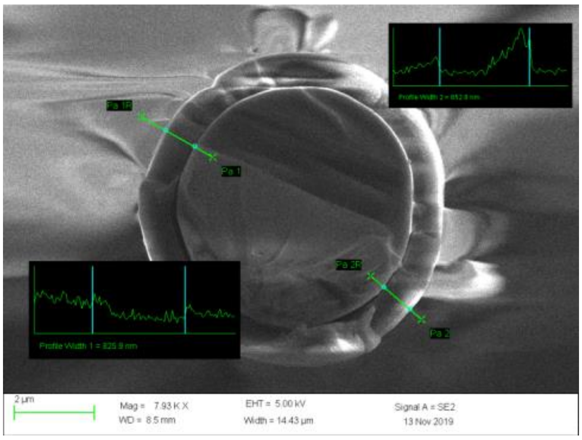

Figure 3 MEB cross-section in a taper of an ONF coated with PMMA (e = 850 nm).

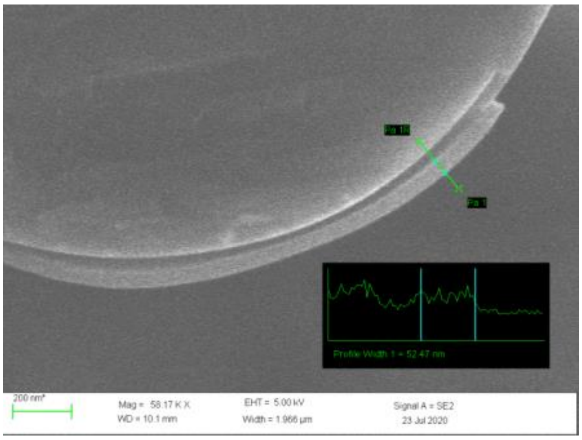

Figure 4 MEB cross-section of an ONF coated with TiO_2 (e = 48 nm). TiO2 thickness can be accurately measured thanks to the partial delamination of the thin film during fiber cleaving.

4. Conclusions and perspectives

The preliminary results presented in this study open the way to a new family of composite ONF for different applications in nonlinear optics. We have studied as an example the realization of all-solid state Raman converters. Many other experiments can be imagined thanks to the wide range of possible materials for coatings.

References

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*Corresponding author: sylvie.lebrun@institutoptique.fr