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Direct injection in organic SU8 nanowires and nanotubes for waveguiding properties investigation

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ABSTRACT

We report photonic concepts related to injection and sub-wavelength propagation in nanofibers (nanowires and nanotubes). These nanostructures are fabricated by the wetting template method leading to aspect ratio of over 250. At first, injection into nanowires and nanotubes of SU8, a photoresist used for integrated photonics, was successfully achieved by using polymer microlensed fibers with sub-micronic radius of curvature. Theoretical simulation by finite domain time-dependent (FDTD) method was used to determine the sub-wavelength propagation for nanowires and nanotubes and corroborate this coupling phenomena. The original confinement of energy density into SU8 nanotubes is highlighted. Finally, characterisation of propagation losses is reported by using a cut-back method transposed to such nanotubes and determined to range between 1 and 2 dB/mm. Both injection and cut-back method developed here are compatible with any sub-micronic structures. This work on SU8 nanofibers suggests broader perspectives for future nanophotonics.

Keywords: nanophotonics, sub-wavelength propagation, SU8, polymer, wetting-template, nanotube, nanowire, cut-back method

1. INTRODUCTION

Sub-wavelength waveguides are the subject of numerous publications and applications¹ (Mach-Zehnder, add-drop filter, etc...). Due to their sub-wavelength dimensions, 1D-nanostructures are of particular interest in integrated optics by the ability to control their aspect ratio. Effective light waveguiding has been well investigated mainly in silica nanofibers while only few studies have been reported in organic nanofibers. The SU8 polymer was selected, because it is a widely-used epoxy based negative photoresist, and commonly used in integrated photonics, due to its excellent characteristics for micronic waveguides.² SU8 polymer presents large refractive index compared to most organics and polymers. This large refractive index enhances the confinement in light waveguiding. Further, the tubular aspect of nanotube give a new degree of modulation in photonics. In literature, Zhao *et al.*³ have shown that the tubular geometry of nanotube can uniquely confine part of the energy density in the lowest refractive index area, the core of the nanotube. This original confinement allows tuning of light propagation and light-matter interaction. In this present work, we detail keys for: low-cost production of SU8 polymer nanowires and nanotubes by wetting template method, experimental protocol to directly inject light into such nanostructures, numerical analysis of sub-wavelength propagation, and finally characterisation of optical losses for SU8 nanotubes.

2. SYNTHESIS

The wetting template method allows the creation of 1D nanostructures with high aspect ratio, diameter ranging from 50 nm to 250 nm and length up to 100 μ m typically. This method achieves low-cost fabrication, fine control dimensions while providing the possibility of large-scale production. This method is based on the use of a previously nanostructured template, pores with nanometer dimensions, which allows to organise the growth

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of nanomaterials. This link between morphology and nanomaterial template allows control of size, shape and orientation of the nanofibers. In our study, AAO (Anodic Aluminium Oxide) membrane presents perfectly cylindrical pores arranged in the plane perpendicular to the axis of the pores, as visible on figure 1a.

Wetting template method ensures wetting of AAO by the material in a liquid phase due to the surface energy of the alumina. Here, we used the SU8 photoresist in solvent. Additionally, the different viscosities of SU8 available in liquid phase are a central advantage for the template strategy. Elaboration of SU8 nanowires and nanotubes is selected by the difference of surface energy between the polymer in liquid phase and the alumina. High or low viscosity of solution leads to synthesis of nanowires or nanotubes respectively.

Once the in-solution polymer penetrates over the entire thickness, a UV insolation ($\lambda = 365 \text{ nm}$, 200 mJ/cm^2) promotes cross-linking of the SU8 to get quite rigid nanofibers. A selective chemical etching by H_3PO_4 solution, releases SU8 nanofibers from the AAO. Finally, SU8 nanofibers were dispersed into isopropyl alcohol or distilled water. A drop of the suspension of SU8 nanofibers was deposited onto a clean SiO_2 wafer. Figure 1b and 1c displays scanning electron microscopy (SEM) images of SU8 nanotubes and SU8 nanowires respectively after partial release from the AAO membrane. No residual material and a smooth surface confirm fabrication process and purification protocols. SU8 nanofibers present regular and hollow endfacets. External diameter of 240 nm was extrapolated for nanowires and nanotubes (for an average inner diameter of 120 nm).

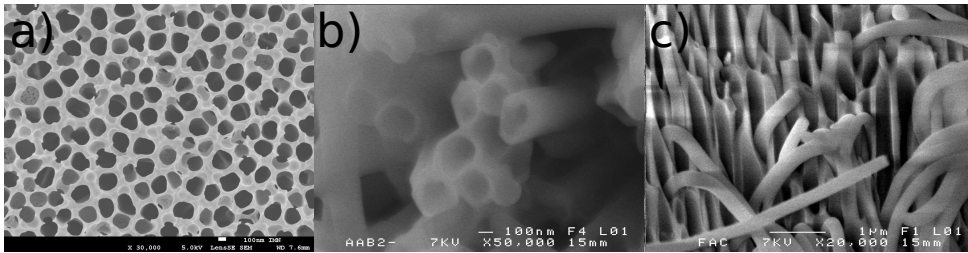


Figure 1. a) SEM top-view image of AAO membrane with cylindrical nanopores. SEM image of b) SU8 nanotubes and c) SU8 nanowires elaborated by the wetting template method after the partial release from the AAO membrane.

3. EXPERIMENTAL SET-UP

In literature, the injection in light-guiding sub-micronic structures is based on two different mechanisms : by grating side couplers⁴ or through evanescent coupling between two photonic structures.¹ However, these approaches require micronic coupling distances and do not allow to fully optimise the quality of the injection in nanostructures nanoscale. In previous publications,^{5,6} we have reported the single-mode behavior hybrid mode HE_{11} of SU8 polymer nanowires and nanotubes by theoretical and experimental approach. Light injection was accomplished by evanescent coupling with SU8 sub-micronic structures.⁵

Here, an innovative way to inject light into 1D nanostructures has been developed by using polymer microlens. The injection of the light is provided by single-mode (@630 nm) microlensed polymer fiber (Lovalite). In addition, microlens fibers are positioned by piezo-electric nano-positionner (Pi-611-SF) in order to precisely control their positioning with 10 nm step in the three directions and optimise light injection inside nanostructures. A top-view display system, figure 2, consisting of a monochrome CCD camera (AVT GX1920), with pixels size of $4.54 \mu\text{m}$ associated with x40 and x100 optical lenses (numerical aperture 0.90, working distance 1 mm) permits the simultaneous control and optimisation of the light injection in nanostructures. A beam-splitter element on optical path allows the spectral detection of nanostructures by spectrometer (OCEAN Optics USB2000).

4. SUB-WAVELENGTH PROPAGATION

Figure 3a displays a SEM image of a microlensed fiber which present at their end a curvature radius of 500 nm. The cylindrical geometry of the microlens has been chosen to coincide with the tubular symmetry of SU8 nanofibers. Thereby, the energy overlap integral between the injecting microlens and the SU8 nanofibers is maximised. Under laser excitation (675 nm), microlens polymer fibers exhibit a light lobe typically of a few micrometers in diameter. Figure 3b presents the approach phase of the microlensed fiber near the SU8 nanotube

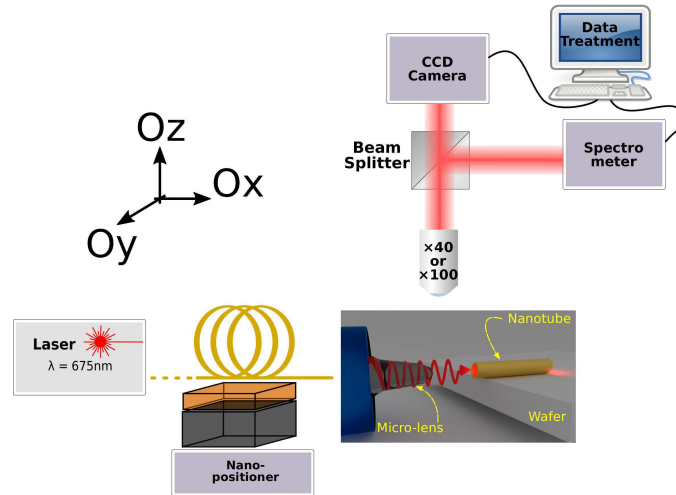


Figure 2. Sketch of top-view display system to control and optimise the direct light injection into 1D nanostructures. A microlensed fiber is mounted on piezo-electric nano-positionner. CCD Camera or spectrometer allow optical analysis of coupling phenomena.

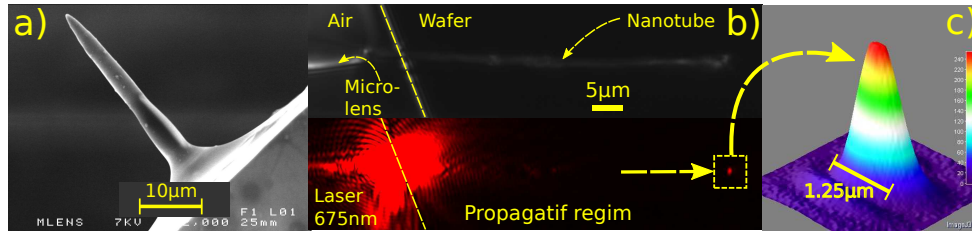


Figure 3. a) SEM image of the microlensed polymer fiber for direct injection into nanotube. b) Top-view image of the approach phase of the microlensed fiber near the SU8 nanotube under visible light and under laser excitation (675 nm). c) 3D-view of output propagative spot at the end of the SU8 nanotube.

under visible light. After an adequate protocol of positioning optimised by the top-view display system, the microlens is brought thanks to the piezo control at few micrometers of the nanotube. On the figure 3b, when the microlens is located close to the SU8 nanotube, under laser excitation at 675 nm, a spot at the opposite end of the nanotube is visible. The presence of this spot, highlighted by 3D-view on figure 3c, is the proof of a significant injection into the SU8 nanotube. The absence of light scattering along the organic SU8 nanotube is an indicator of low roughness of the surface of the nanotube and the absence of morphological defects. An identical behavior has been determined for SU8 nanowires.

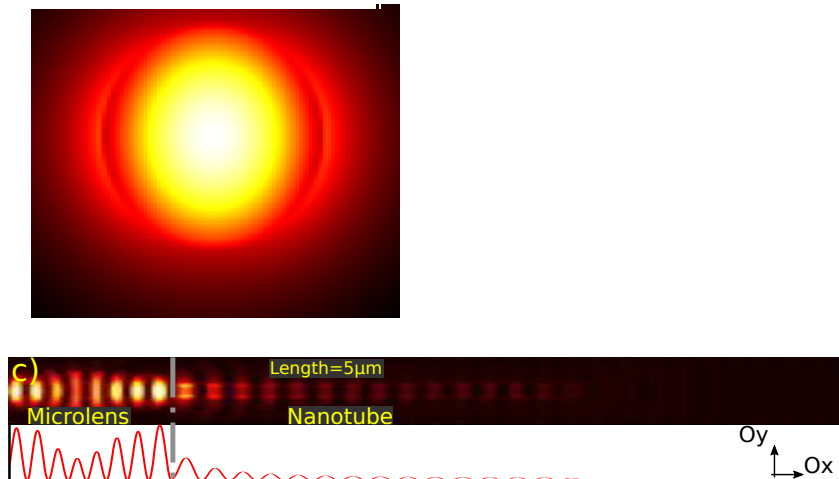
5. FDTD MODELISATION

The sub-wavelength propagation of nanowires and nanotubes has been investigated by a numerical 3D finite domain time-dependent (*FDTD*) simulation and performed by Meep freeware.⁷ *FDTD* simulation has already proved accuracy to study optical sub-wavelength propagation in nanostructures.^{8,9} As determined by figure 1b,c in section 2, geometrical parameters of SU8 nanowires are set as an external diameter of 240 nm for SU8 nanowires and nanotubes, and an inner diameter of 120 nm for nanotubes. The model contains an *Oy*-polarised laser source at 675 nm (FWHM = 12nm) launched inside nanowires and nanotubes with refractive index of $n_{SU8} = 1.56$.

Figures 4a and 4b present orthogonal views (*i.e.* : along *Oyz* plan) of the optical power mode HE_{11} inside the SU8 nanowires and nanotubes. It highlights the separate behavior of density energy confinement of both nanostructures. In case of nanowires, the maximum of light is confined into the SU8 nanofibers. In case of nanotubes, the tubular geometry allows a significant confinement of density power inside the hollow region, the

maximum of light propagating in the wall of the nanotube with a extension of the density power of 50 nm in air. This makes nanotubes based devices sensitive to surface modification and offers great opportunities for near-field sensors.

In such sub-wavelength propagation regime, the optical coupling between the microlensed fiber and the SU8 nanofibers is critical and deserves a specific study. Figure 4c is a top-view of the power density of the microlensed fiber aligned in direction of free-standing SU8 nanotube. The presence of standing wave patterns along the axis of nanotube attest the coupling phenomena between SU8 nanotube and microlensed fibers. They are due to interference between propagating light and reflection at the output endfacet. This phenomena has been already established on waveguiding silica nanowires.¹⁰ Projection of power density inside the nanotube along Ox on figure 4a corroborates the period of standing waves : $P = \frac{\lambda}{2n_{eff}} \cong 332 \text{ nm}$ from our previous theoretical work.⁶



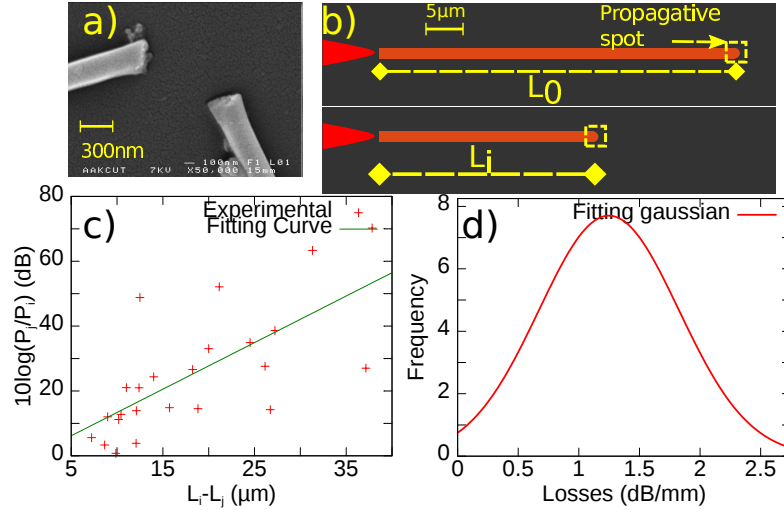


Figure 5. a) SEM image of a clean cleaved endface of SU8 nanotube, b) top-views of images during waveguiding of laser light at different lengths. c) Intensity of propagative spot for different propagation distances and d) distribution of losses determined to range between 1 and 2 dB/mm.

dispersion of attenuation coefficient summarised on figure 5d, determined to range between 1 and 2 dB/mm. For comparison, SU8 microstructures exhibit losses of 17 dB/mm.¹¹ It can be noted that plasmon nanowaveguides much investigated for sub-wavelength photonics present losses of 4000 dB/mm.¹² In previous work,⁵ scattering losses of SU8 nanotubes had been estimated around 150 dB/mm. This higher value was allocated to the measurement process (*i.e.* : scattering), to a synthesis process not optimised, and to a different injection process of light inside SU8 nanotubes (evanescent coupling with microstructures).

7. CONCLUSION

In summary, direct injection into organic nanofibers (nanowires and nanotubes) has been demonstrated and confirmed their efficient waveguiding properties. A derivated cut-back method is proposed for attenuation coefficient estimation in such sub-micronic structures. In SU8 nanotubes, the attenuation coefficient is determined to range between 1 and 2 dB/mm. The sub-wavelength regime propagation in such SU8 nanotubes highlight the modulation of guiding light provided by tubular geometries in nanostructures. This study allows perspectives for SU8 nanotubes as building blocks in more complex systems or sub-wavelength optical probes for near-field interactions. This feature makes polymer SU8 nanotubes a good candidate as the basic element of highly integrated nanophotonics and sub-wavelength optical probes.

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