

Development of new practical approach to integrated photonics based on biomimetic molecular self-assembled nanotubes

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The first developments for a new integrated photonics using optical evanescent coupling from organic microstructures to fibres of hybrid nanotubes (NT) are reported. Microstructures are organic discs acting as photon reservoirs, integrated on a photonic chip fabricated by micro-technologic processes. Biomimetic peptidic/silica NT are realised by molecular self-assembly allowing centimetres long fibres of NT. Such heterostructures have been included directly on the organic as an innovative solution based on an NT in situ chip-approach. The latter allowed us to obtain an adequate evanescent coupling localised between micronic-discs and fibrous structures. Highlighted is a specific photonic propagation along various heterostructured-NT-fibres featuring distances beyond the centimetre and losses inferior to 1 dB/cm. It presents an advantageous confinement marked with strong energy localisations between NT.

Introduction: Owing to their noticeably high shape ratio (length/diameter), nanowires and nanotubes (NT) present promising properties for optical components, especially light routing, nano-connections and networks. Thus, sub-wavelength wires and tubes are of great interest for investigation. For example, Mazur and colleagues have developed several specific devices allowing the coupling of light into fused-SiO₂-nanowires from an optical fibre [1]. Moreover, recent research about the understanding and the ability to control mechanisms of molecular self-assembly of sea organisms (biomimetism) has enabled the realisation under ambient conditions of hybrid self-assembled nanostructures [2–4]. In this Letter, we report an original photonic-chip-approach based on the realisation and in situ integration of biomimetic molecular self-assembled peptidic/silica NT-fibres directly into adequate photon micro-disc-reservoirs. This allows the design of hybrid-photonic devices for light routing and directional propagation via an apt optical evanescent coupling between both compound element structures (disc/NT).

Structure of self-assembled NT: Biomimetic self-assembled peptidic templates are mineralised with amorphous silica, forming hybrid bilayered NT with a typical 29 nm diameter (Fig. 1). The template is shaped by way of spontaneous self-assembly into plain water of lanreotide, a dicationic octapeptid, according to five hierarchical steps and multi-scale mechanisms proceeding from nano to macroscopic dimensions. Then, the molecular conformation is subject to the molecular peptidic template, as dimmer arrangements depend on amphiphilic interactions. Both network and formation of NT-bundles rely on electrostatic interaction, lateral interactions of curved NT, considering the growing of hexagonal lattice of columns of NT [3]. The mineralisation of these precisely designed tubes is obtained by bringing into contact a lanreotide gel and a tetraethylorthosilicate (TEOS) solution in water within the confined volume of 1.5 nm-diameter glass capillaries. After a few days, centimetre-long white NT-fibres are formed in the TEOS solution. According to SAXS measurements, the tubes show off internal and external layers of silica, 1.4 nm in thickness, together with a 2 nm peptidic layer. Regarding their thickness, the steadiness of such oxide-walls highlights the perfect hierarchical control of the whole fibrous morphology. As this process yields unusually arranged centimetre-long fibres of thousands of NT in bundles, many advantages such as: easy and cheap fabrication, diameter mono-dispersity and high diameter/length ratio most proper to supra-molecular organisation are to be considered in the design of highly effective devices.

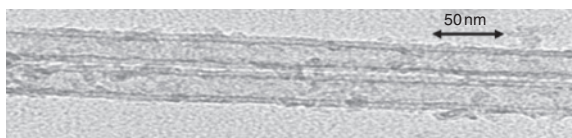


Fig. 1 Transmission electron microscopy (TEM) image of two peptidic/silica bilayered NT

Solutions for injection: The propagation mechanism in nanostructured fibres is investigated by sending light into their core by way of evanescent coupling. We took advantage of a family of disc-reservoir-structures (radius ranging from 100 to 200 μm), allowing the photons to proceed strongly confined on the edge of the disc (whispering gallery mode). While arranging an appropriate way for the NT-fibres in contact with these micro-disc-structures, the bend allows an advantageous stretching of the modal evanescent tail outside the disc that proves to enhance the coupling with the set of NT. We have localised the fibres in contact with the disc reservoirs in two different ways:

- A solution is based on the realisation of organic microstructures by thin-film processes [5]. Then we handle and arrange judiciously the NT-fibres on top of the photonic chip, in contact with the disc reservoirs experimented with.
- The other way goes on direct integration of a set of fibres in the thin-film processes: NT-fibres are dropped on the wafer before photoresist deposition and spin-coating so as to achieve the hybrid moulding of peptidic/silica NT into the organic matrix.

The biphenol A ether glycidyl polymer photoresist (SU8) proved to be most convenient to realise the microstructures: the SU8 is spin-coated on a silicon wafer covered by a 1 μm layer of thermal silica acting as lower cladding. Then, waveguide patterns are shaped in the polymer by UV lithography. After development and classical thermal processes, we obtain a photonic chip with 6 μm large rib waveguides leading to the previously mentioned disc reservoirs with radius ranging from 100 to 200 μm (Fig. 2a). Regarding direct integration of a given fibre into the SU8 matrix, for UV lithography we arrange the mask in such a way that the fibre will be included in a disc reservoir (Fig. 2b).

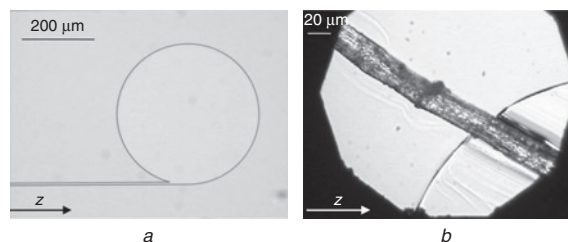


Fig. 2 Optical images of photonic chips

a 6 μm -large rib waveguide leading to disc reservoir (200 μm radius), before positioning of fibre (first configuration)
b 20 μm -diameter fibre embedded in SU8 matrix and crossing 200 μm radius disc reservoir (second configuration)
z-axis indicates direction of propagation

Results: Both methods allow us to achieve evanescent coupling from microstructures to nanostructured fibres, the propagation in NT verified over a distance greater than a centimetre. Fig. 3 shows a configuration obtained using the first way: a 6 μm -diameter fibre is placed in contact with a disc reservoir (200 μm radius) after thin-film processes. A laser light (670 nm wavelength) is injected from the left side into the rib waveguide and propagates through the z-axis to the disc reservoir where a significant evanescent coupling is proved to occur. Then, light proceeds in the NT-fibre in both directions over a whole distance of 2 cm. We obtained the same results with the second method involving fibre diameters ranging from 4 to 20 μm .



Fig. 3 6 μm -diameter NT-fibre placed in contact with disc reservoir (200 μm radius)

Light (670 nm wavelength) is injected into rib waveguide (6 μm in width) and propagates to disc reservoir where evanescent coupling is achieved. Then light propagates in fibre over distance of 2 cm
z-axis indicates direction of propagation

The most effective evanescent coupling and propagation observed in the NT-fibres is due, respectively, to the adequate disc reservoir configuration and certainly to the strong energy localisation inherent in hollow leaky-mode waveguides: the latter enhance and confine light in

nanometre-wide voids or low-permittivity materials [6]. Moreover, according to the symmetrical disc-reservoir structure, such results remain consistent with any orientation of the fibre with respect to the disc (Fig. 2b). By imaging and measuring (Newport Micro-Beam-Profiler Series and software) the optical intensity over the NT-propagation (Fig. 3) while considering the classical Beer-Lambert law, we estimate that propagation losses in such heterostructured-NT-fibres are less than 1 dB/cm.

Conclusions: We have validated several hybrid thin layer processes to include biomimetic NT into organic optical materials, so as to realise and to achieve effective optical evanescent coupling. Propagation features losses less than 1 dB/cm in NT-fibres with distances greater than the centimetre with strong light confinement. This is a promising intermediate result for development of new integrated photonics based on biomimetic molecular self-assembly methods. Such an approach is advantageous to realise centimetre-long fibres with gaps, as the gap pattern can be fixed at nanometric scale by the nature of the template. Moreover, photon reservoirs with disc symmetry coupled to NT-fibres come up as an original and interesting solution for nano-connections and optical routing allowing new shapes for star couplers (1 disc reservoir connected to n NT-fibrous).

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