Optical fibers go nano

The manufacture of nanowires from optical fibers provides the longest, most uniform and robust nanowires. Most important, the low optical loss associated to small surface roughness and high homogeneity allows the use of nanowires for optical applications and opens the way to a host of new optical devices for communications, sensing, biology and chemistry. Additionally, optical fiber nanowires are fabricated by adiabatically stretching optical fibers and thus preserve the original optical fiber dimensions at their input and output allowing ready splicing to standard fibers and fiber components. These fiber pigtails have macroscopic dimensions and allow the manipulation of a single nanowire without the expensive instrumentation typical of the nano-world.

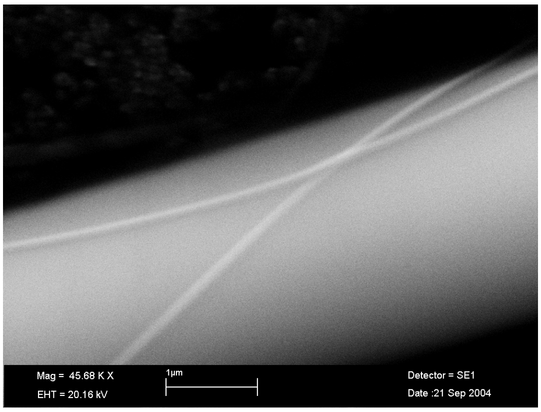

Fig. 1 SEM micrograph of two nanowires with radii of 30nm and 50nm manufactured from standard telecom optical fibres.

In the last decade nanoscience and nanotechnology have attracted much interest because materials exhibit novel different properties when manufactured at nanometer dimensions. In the last two decades nanowires and sub-wavelength wires have been fabricated from a variety of materials using a wide range of techniques, including electron beam lithography, laser ablation, template based, vapor-liquid-solid (VLS) techniques, physical-/chemical-vapor-deposition and sol-gel. Although several nanowires have previously been fabricated from silica, yet most of them exhibited an irregular profile along their length. Surface roughness and length inhomogeneity appear to have limited the loss levels that could be reliably achieved, thus their usefulness for optical applications.

In the last four years the manufacture of nanowires from optical fibers has been established as a methodology to reliably produce structures with a transmission loss low enough to be used for optical devices. Amongst the top-down techniques, the "flame-brushing" technique provides the longest and most uniform nanowires with the lowest measured loss to date. Originally developed for the manufacture of fiber tapers and couplers, "flame brushing" is based on a small flame moving under an optical fiber which is stretched. The control of the flame movement and the fiber stretch can be used to define the taper shape to an extremely high degree of accuracy. Although taper diameters in the range of 1 micron can be easily achieved, the manufacture of nanowires with 30nm radius is challenging engineering and requires an extremely good control of the processing temperature and the air flow around the nanowire. With these procedures researchers at the University of Southampton have used the flame-brushing technique to manufacture the lowest-loss and the longest nanowires from optical fibers. Nanowire fabricated with this technology exhibit an extremely good uniformity, with the nanowire length being millions of times larger than the diameter fluctuations. Nanowires longer than 100mm have been manufactured and record optical losses as small as 1dB/m measured.

Unique properties

Optical nanowires offer a number of enabling optical and mechanical properties, including:

- Excellent flexibility and configurability; because of their relatively high mechanical strength nanowires can easily be manipulated and bent. While telecom optical fibers experiences considerable optical losses for bend radii smaller than 10mm, optical nanowires can have bend radii of few microns with relatively low induced loss, allowing for highly compact devices with complex geometry (figure 2).

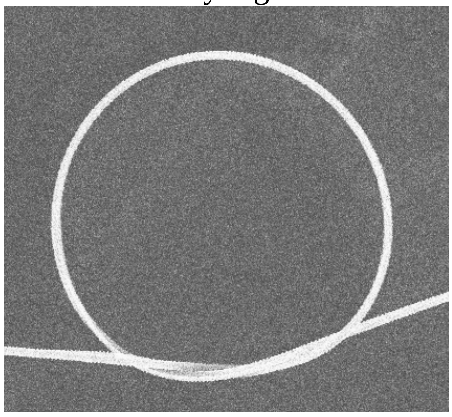

Fig. 2 Optical fiber nanowires can have extremely small bend radii with negligible optical loss; in the microcoil resonator shown above the bending radius is about 45μm, nearly a thousand times smaller that that viable with conventional telecom optical fibers.

- Large evanescent fields; on the contrary of optical fibers, where all the light is confined in the core/cladding glass structure, in optical nanowires a considerable fraction of the transmitted power can propagate in the evanescent field outside the nanowire physical boundary.
- High nonlinearity; nonlinear processes are strongly intensity dependent and high intensity can be achieved either by high power sources or small waveguides. With respect to conventional telecom optical fibers, in optical nanowires light can be confined to an area 100 times smaller over relatively long device lengths, allowing the ready observation of nonlinear interactions such as supercontinuum generation at relatively modest power levels.

Amongst these properties, the large evanescent field is almost certainly the most appealing for the realization of sensors and devices. While in a conventional telecom fiber light is propagating in the core, for smaller diameters light is confined by the cladding and its spot size decreases with decreasing diameters. In the sub-micrometer regime the fiber diameter becomes smaller than the wavelength of light propagating in it and because of diffraction, light cannot be confined into the fiber. A considerable fraction of the power propagates outside the physical fiber boundary (figure 3): when the fiber radius approaches 100nm, light with wavelength of 1.55μm is highly diffracted and its spot size is 100 times bigger than the fiber

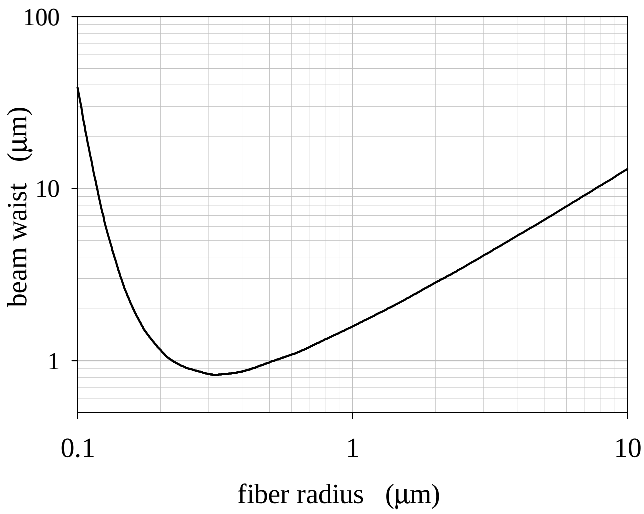

Fig. 3 Relation between beam and fiber sizes. In conventional silica fibers for decreasing fibre diameters the beam waist decreases until it reaches a minimum and then increases again. For fiber sub-micron radii, the beam waist can be hundreds of times larger than the fiber.

physical dimension. More than 99% of the power is propagating outside the fiber! The evanescent field propagates in the surrounding medium and it can be promptly used as a chemical sensor. A straightforward Pd-coating can provide an excellent hydrogen sensor with fast response (less than 10s). Still, the interaction length is limited to the optical nanowire length, which is usually just few millimeters long. By coiling the optical nanowire on itself (fig. 2), light is trapped in the microcoil and it can make several thousand loops before reaching the output pigtail. This extends the "effective" length of the device which has therefore a much longer interaction with the chemical components to sense: a simple coil with sub-millimeter diameter can have an interaction length greater than 1m. Compared to other high-Q resonators which experience considerable input/output coupling problems, the microcoil has the great advantage of an easy connection to other fiberised components because it has standard fibers at the pigtailed extremities.

A bio/chemical sensor

The fiber microcoil resonator is of great interest because it has very narrow resonances, as small as few pm at telecom wavelengths, allowing for the manufacture of narrowband filters and high-sensitivity refractometric sensors. Refractometric sensors are chemical/biological sensors which rely on a change in the refractive index to measure the concentration of a specific chemical/biological compound. In these sensors, high Q-factors (or small bandwidths) relate to a low detection limit (minimum detectable amount of analyte) and large evanescent field to high sensitivities (shift of resonance wavelength as a consequence of a unit change in the refractive index). For this type of sensor, small size, high sensitivity and low detection limit are the most important criteria. Optical nanowires are ideally suited for this application when embedded in a low-refractive-index material as shown in figure 4. Most of the area inside the resonator coils is empty, which constitutes an intrinsic fluidic channel to deliver samples to the sensor, unlike most of the ring- or microsphere-resonators which require an additional channel for this purpose. The nanowire microcoil sensor can be easily manufactured by coiling the optical nanowire on a disposable rod, coating it with a low refractive index polymer and then removing the rod. The sensitivity of this sensor has been evaluated for different optical nanowire sizes and coating thicknesses and it has been found that for nanowire sizes of 200nm and/or coating thicknesses of tens of nanometers a detection limit as low as 10^{-7} has been achieved, meaning that it is possible to recognize a molecule of analyte in 10 millions molecules of solvent. This is more than ten times larger than any sensor previously proposed.

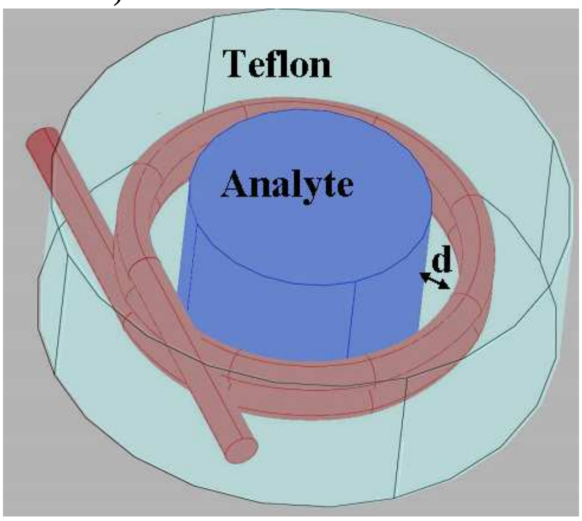

Fig. 4 A diagram of the optical nanowire sensor. The analyte is flowing in the vertical channel and interacts with the optical nanowire evanescent field. The analyte concentration is detected by the change in the fiber optical output.

Optical Manipulation

The manipulation of particles/cells at the nanowire surface is another application for which the large evanescent field is advantageous. Light gradients have been shown to be extremely useful to trap particles with optical tweezers. In the most recent years, there has been an increasing interest in optical manipulation at surfaces, because of the possibility to continuously handle a great number of particles at the same time. This technique can be particularly advantageous in the sorting of a great number of cells in a sterile environment, as it is often required in biomedical research. Propulsion along waveguides manufactures in glass or in Silicon nitride has been demonstrated in the last coupler of years. However, because of their intrinsic nature, planar waveguides are limited to two dimensions, have a small fraction of the light propagating outside the waveguide and present high insertion losses. In contrast, optical nanowires offer the advantage of a greater evanescent field, a 3D flexibility and low insertion/extraction losses. Figure 5 shows pictures of 3μm microspheres propelled along an optical nanowire taken at 1 second intervals. Letters a-c point to particles trapped at the nanowire surface and propelled by the nanowire evanescent field at an average speed of 9μm/s. Optical propulsion may be explained in terms of the contribution of several optical forces: a gradient force drives particles up an intensity gradient and locks them to the waveguide while absorption and scattering forces accelerate particles in the direction of the propagating field. The viscous drag force of the surrounding medium opposes the propulsion forces and provides a limitation to continuous acceleration. The optical force experienced by the particles is proportional to the light optical intensity at their surface, thus the optical nanowire large evanescent field and its good source/waveguide coupling make it an excellent tool for the manipulation and sorting of particles, cells and bio-molecules.

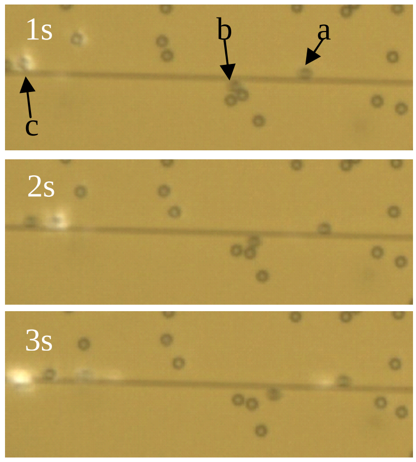

Fig. 5 Optical nanowires are used to manipulate microspheres at their surface. 3μm polystyrene particles (labelled with a,b,c) are propelled along an optical nanowire by few hundreds mW of optical power.

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