Optical Fibre Nanowire Technology and Applications

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Abstract - A review of optical fibre nanowires and their applications is presented.

Introduction

Optical fibres with sub-micrometric diameters are commonly called photonic or optical fibre nanowires (OFN). Although OFN were firstly manufactured in 1987 [1], they have attracted much attention only after 2003, when it was demonstrated that low-loss structures can be reliably fabricated [2-7]. Previously, surface roughness and inhomogeneity appear to have limited the use of OFNs for optical applications [8].

OFN and sub-wavelength wires have the potential to become building blocks in future micro- and nano-photonic devices since they offer a number of unique optical and mechanical properties, including:

1) Large evanescent fields: a considerable fraction of the power can propagate in the evanescent field outside the physical boundary of an OFN [3]. This allows the fabrication of atom guides [9], sensors [10-15], high-Q resonators [7,16-21] and particle handling [22].

2) High nonlinearity: Light can be confined to a very small area over long device lengths allowing the ready observation of nonlinear interactions [23], such as supercontinuum generation [4], at relatively modest power levels.

3) Extreme flexibility and configurability: OFNs show an extraordinary mechanical strength and can easily be bent and manipulated. Bend radii of the order of a few microns can be readily achieved with relatively low induced bend loss [2, 24] allowing for highly compact devices with complex geometry e.g. 3D multi-ring resonators [16-20].

4) Low-loss interconnection to other optical fibres and fiberised components: OFNs are fabricated by adiabatically stretching optical fibres and thus preserve the original dimensions of the optical fibre at their input and output allowing ready splicing to standard fibres. This allows for an efficient confinement of power [25] and represents a significant advantage when compared to small-core microstructured fibres that always present significant insertion/extraction losses. Moreover, these fibre pigtails have macroscopic dimensions and allow the manipulation of a single nanowire without the expensive instrumentation typical of the nanoscience and nanotechnology worlds.

For the manufacture of sensors and devices the most attractive of the OFN properties is the large evanescent field. When the fibre diameter becomes smaller than the wavelength of the light propagating in it, diffraction dominates and a considerable fraction of the power propagates outside the physical fibre boundary.

Fabrication

To date, OFNs have been manufactured from a variety of materials including silica [2-25], bismuth-silicate [26] lead-silicate [26] and chalcogenide [27] fibres. OFN have also been manufactured from telluride glasses [28] directly from bulk glasses, but their poor uniformity and the lack of fiberised pigtails have limited their use for devices/applications.

While the manufacture of micrometric tapers is well established, the fabrication of 100nm OFNs represents a considerable challenge. In the last 5 years three top-down techniques have been developed to manufacture OFNs: a two-step process [2], the “flame-brushing” technique [3-6] and a sapphire tube heated by a CO_2 laser.

In the two-step process a micrometric taper is broken and wrapped around a hot sapphire tip which is used to draw the OFNs. Although this technique has shown the capability to manufacture OFN with radii of ~10nm, because of the intrinsic nature of the process it also provides high losses and only one fibre pigtail.

In the “flame brushing” technique a small flame moves under an optical fibre which is being stretched. The flame brushing process provides the longest and most uniform OFNs [6] with the lowest measured loss [4-6] and highest strength [6]. Moreover, this technique has the benefit of maintaining the OFN intact and fibre pigtails at both OFN ends allowing a prompt connection to fiberised components. These technique still provides a propagation loss close to the theoretical minimum [29,30]. A modified version of the “flame brushing” technique has been used for the manufacture of OFNs with low processing temperature by replacing the flame with a microheater [26,27].

The third manufacturing method uses a sapphire tube heated by a CO_2 laser [7] and provides short OFNs with similar quality to the “flame brushing” technique.

Mode confinement

When the OFN diameter becomes smaller than the wavelength of the light propagating in it the field distribution spreads significantly outside the OFN physical boundary [3]. The maximum confinement occurs for V-numbers around 1, where V is defined as $V=2\pi\cdot r\cdot NA/\lambda$ (r is the OFN radius, NA its numerical aperture and λ the wavelength of light propagating in it). Losses of 10^{-3} dB/mm have been reported in this regime [4-6]. “Soft” glasses like telluride, bismuthate and chalcogenide have a high refractive index, thus allowing for a tighter confinement. For smaller V values, the fraction of the mode in the evanescent field increases and for silica OFN radii approaching 100 nm, the mode at λ=1.55μm in a silica OFN has a spot size 100 times bigger than the fibre physical dimension [3]. The mode still propagates in the OFN: for r=120nm and λ=1.55μm a losses of $\alpha=10^{-1}$ dB/mm has been recorded [6].

High-Q resonators

Because of the considerable fraction of mode power propagating outside the OFN, it is possible to couple power between different OFNs and/or different OFN sections by positioning them sufficiently close. One simple coil can provide a resonating structure with Q-factors of $\sim 10^6$. Other high-Q resonators have been manufactured knotting OFNs [2] or by wrapping many coils of OFNs on a low refractive index material [19]. These two types of resonators provide a better temporal stability than the microcoil because the OFN position is rigidly fixed and there is no relative movement between the different OFN sections in the region of high coupling. Besides, the fabrication of knot resonators presents a big disadvantage because the OFN needs to be broken and this induces additional losses and insertion/ extraction issues. The design of the multicoil resonator has also been optimised to easily achieve high Q-factors [18,31]. Their spectral features have been predicted using the coupled wave equations [16,18,31].

Stability/degradation issues

Although devices have been demonstrated in free-space, OFNs present degradation issues. OFN optical and mechanical properties have been studied over several days in conventional lab environment conditions and an additional loss of 1dB per hour was recorded in OFNs with r~375nm [6]. Although the loss has been partially recovered by a chemical cleaning with conventional compounds, a complete recover required a flame brushing with temperatures in excess of 1000 ^{0}C. The OFN mechanical strength also degraded and it has been related to the induced loss.

Embedding [20,32] provides a solution to the degradation issues, increases the device temporal stability and its portability. Amongst the available embedding materials perfluoropolymers seem the most promising because of their low refractive index and excellent chemical and mechanical properties.

Sensors

Because of the large evanescent fields and their compatibility with fiberised components, OFNs are ideally suited for application in sensing. Fast Hydrogen sensors have been demonstrated coating an OFN with Palladium [10]. Modelling of OFN sensors based on Mach-Zender interferometers [11] and microcoil resonators have been proposed [12, 14].

Sensors based on high-Q resonators have recently attracted much attention because of their extremely low detection limit and high sensitivity. For a coated all-coupling nanowire microcoil resonator (CANMR) sensitivities $\sim 10^3$ nm/RIU have been predicted for aqueous solutions [12]. This device is compact, robust, stable and compatible with microfluidic systems. In fact CANMR presents an intrinsic microfluidic channel inside a Teflon substrate which is used for the analyte delivery. Preliminary experiments [15] showed a sensitivity of 40nm/RIU for analyte solutions with refractive indexes of 1.34. Although this sensitivity is well below the predicted 10^3, it is comparable to the best results obtained in similar conditions with resonating structures in liquid core waveguides [33].

Optical manipulation

OFNs have found multiple applications in particle/cell handling. Large evanescent fields have been exploited for particle propulsion, while tight confinement for trapping [25]. Propulsion of polystyrene particles [22] and particle clusters [34] in water solution has been demonstrated at reasonably low powers (0.4W) at wavelengths λ~1μm.

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