Optical microfibre devices

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Abstract. In the last decade optical fibre tapers with micrometer diameter (often called microfibers) have been investigated for numerous applications ranging from sensing to wavelength convertors, telecom and optical manipulation. This paper reviews the various applications of microfibres.

1. Optical microfibres

Although microfibers with diameters comparable to the wavelength have been manufactured for nearly half of a century [1], their application in devices has been limited because of the perceived difficulty to achieve low-loss propagation [2]. Microfibres have been manufactured from a variety of different materials including silica [3-8], silicon [9,10], phosphate [11], tellurite [11], lead-silicate [12], bismuthate [12] and chalcogenide glasses [13] and a variety of polymers [14-19]. Most of the microfibers exhibited an irregular profile along their length which resulted in high propagation losses in devices. In the last decade the use of the flame-brushing technique [3-8] allowed to manufacture microfibers with losses smaller than 0.01dB/mm, sufficiently low for the manufacture of devices for sensing, comms, wavelength conversion and optical manipulation.

Optical microfibers (OMs) are optical fibre tapers with diameters comparable to the wavelength of light propagating in them. They generally fabricated by tapering optical fibres and therefore result connected to conventional optical fibres by transition regions (Fig. 1). If the transition region has a suitably small angle, a single mode launched in the optical fibre pigtail core is adiabatically transferred in a single mode guided by the cladding/external medium interface and no power occurs into other modes.

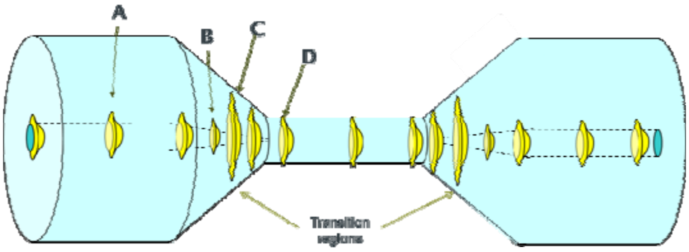

Fig.1 Schematic of operation of an adiabatic optical fibre microwire. A beam launched in the optical fibre pigtail (A) enters the transition region downtaper where it is initially focused (B) until diffraction occurs. The beam then expands and it is guided by the cladding/external medium interface (C). After this point the beam keeps focusing until it reaches the minimum waist diameter (D), where it propagates unaffected. In the uptaper the reverse process occurs and the beam leaved the optical fibre pigtail in the core.

Oms are usually fabricated using the so-called flame brushing technique [4], where a heat source – typically a flame – is repeatedly brushed under an optical fibre that is being stretched.

2. Properties

Singlemoded OMs have attracted a significant degree of attention over the last decade because they offer a number of enabling properties, which include:

OMs offer a number of enabling properties, which include:

1) Extremely low losses: the small surface roughness and well defined profile [20,21] provide negligible losses and guidance for a range of diameters down to λ/10 [22-27].
2) Configurability: OMs are manufactured from optical fibres, thus they maintain the original optical fibre size at their extremities, allowing for a prompt connection to all fiberized components.
3) Flexibility: OMs can be bent with bending radii of the order of microns, providing devices with minimal footprint.
4) Robustness: because of their negligible surface roughness, OM exhibit an extraordinary mechanical strength [28-21]. Packaging in Teflon or other polymers provide robustness at macroscopic scale [32-35].
5) Large evanescent fields: for diameters smaller than the wavelength, a significant fraction of the mode propagates in the evanescent field, outside the OM [36,37].
6) Strong confinement: for the optimised conditions, an OM can confine a propagating beam to an effective area one order of magnitude smaller than conventional optical fibres, resulting in two orders of magnitude larger nonlinearities and an extremely strong longitudinal component of the electric field [38-41].
7) Biocompatibility: as most of OMs are made from silicate glasses, they have a high compatibility with all biological matter.

This properties have been exploited for the manufacture of numerous devices, which can be grouped into three groups according to the property they exploit:

1) transition regions: the change of mode guidance from core bound to cladding bound allows to convert and filter selected modes. Devices based on this effect include modal filters, modal converters and numerous sensors based on the so-called in-line Mach Zehnder interferometry.
2) confinement; at optimised OM diameters, extremely high intensity in the minimum waist region allow for the prompt observation of strong nonlinear optical effects.
3) evanescent field: the large fraction of the mode propagating outside the OM allows for a strong interaction with the surrounding environment, which has been exploited for sensors, high-Q resonators and optical manipulation.

3. Transition regions

The transition regions connect the OM to the regular fibres (Fig.1) and allow for a mode transition from core guidance to cladding guidance [42-44]. If the conversion is on one-to-one basis and there is no power transfer between different modes, the taper is called adiabatic. If β_1 and β_2 are the propagation constants of two modes propagating in a fibre with radius r, and z_b their beat length, the taper is considered adiabatic if at any radius its local angle Ω is smaller than a critical angle $\overline{\Omega}$ given by:

$$\Omega < \overline{\Omega} = \frac{r}{z_b} = \frac{r(\beta_1 - \beta_2)}{2\pi} \tag{1}$$

For $\Omega \geq \overline{\Omega}$ the taper is not considered adiabatic and core modes can couple to higher-order cladding modes with the same azimuthal symmetry which can be leaked out of the fibre if that specific mode is not supported in the uniform waist region (Fig. 2).

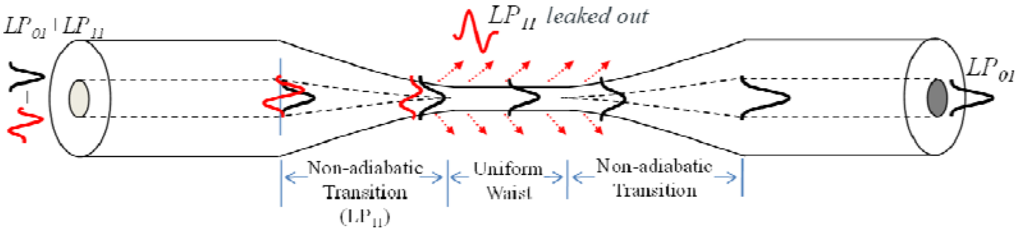

Fig.2 Schematic of operation of an optical microfiber with non-adiabatic transition regions. Two (or more) modes are injected in the optical fibre pigtail. In the transition region the higher order mode (LP_{11}) exchange power with even higher order modes that can be leaked out if not supported by the OM in the uniform waist region.

This effect has been exploited to eliminate high order modes from few mode fibres and couplers [45-47], selective excitation of fundamental mode in few mode fibres [48], interferometric sensors in taper tips [49], and comb-like filters for tunable lasers [50]. In the minimum waist region the mode propagating in the OM is effectively guided by the cladding/air interface and it is not affected by the relative core size in its pigtails. The possibility to selectively excite the fundamental mode can find application in high power fibre lasers, where single mode operation in large cores are utilised to maximise the laser brightness [51].

The non-adiabatic taper profile has found broad application in sensing, as the excitation of multiple modes and their beating resulted in the so-called in-line Mach-Zehnder interferometers.

4. Confinement

OMs usually provide efficient modal confinement to sizes smaller than the wavelength, resulting in enhanced nonlinearity γ and in phenomena like supercontinuum generation [52-57], second- and third-harmonic generation [58-71], slow and fast light [72] and bistability [72-74] being readily observed.

Supercontinuum was generated in silica [6], bismuth-silicate [12] and chalcogenide [75] glasses. In silica OM, supercontinuum has been generated over two octaves [76-79]; yet, the small size affects the overall dispersion profile resulting in a poorer spectral flatness [80]. For increasing powers, a decreasing degree of coherence has been observed and was attributed to phase noise [81]. The mechanism originating supercontinuum has been investigated both for fs- and for ps-pulses [82]: while in the former self phase modulation and solitons [83] are the most important phenomena, in the latter four wave mixing dominates.

High-order harmonics has also been generated in OMs and benefited from the possibility to achieve both phase matching and high overlap between modes at different wavelengths [84-85]. The significantly lower refractive index of the surrounding medium compensates for the increasing OM refractive index at shorter wavelengths. Fig. 3 shows the effective index dispersion for different modes at the fundamental and third harmonic frequencies, showing that intermodal phase matching can occur with different modes at different diameters. This is a particularly interesting effect because it allows for the efficient generation of different wavelengths without an external nonlinear crystal.

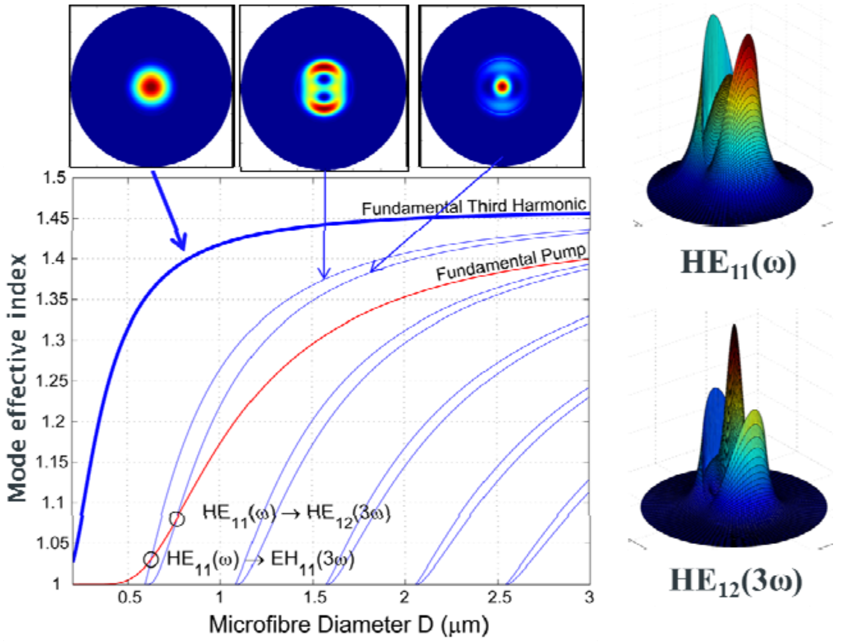

Fig.3 Effective index dispersion at λ=1.55μm for the fundamental mode at the pump wavelength ω and high order modes at the third harmonic wavelength 3ω. Different phase matching diameters exist for different modes at different effective indices. The mode field profile of HE_{11} and HE_{12} modes at the phase matching diameter are shown on the right.

For optimised diameters, in phase matching conditions the overlap can reach 70% [38]. Experiments carried out on a 100µm-long OM with r=245±10nm have demonstrated a conversion efficiency of $2\cdot10^{-6}$ [58]. The low detected efficiency has been explained by the irregular diameter profile associated to thermal surface waves trapped during solidification in the OM [65]. Efficiencies larger than 60% have been predicted for optimised OM with an idea diameter [38]. Second harmonic was also generated, albeit with an efficiency one order of magnitude lower than that observed in the third-harmonics experiments [58]. Because of the predicted high conversion efficiency, OMs have been proposed for third-order parametric amplifiers [86].

When cleaved, the OM has a rapidly divergent beam that has been exploited to optically trap particles [87,88]. Trapping of a single particle at the OM tip was carried out with a power slightly higher than10mW [89], lower than those used in free space (1W) [90] or with lensed fibres (22mW) [91-93].

Because of their minimal footprint, OM have found numerous applications in in-vivo, in-situ intracellular sensing.

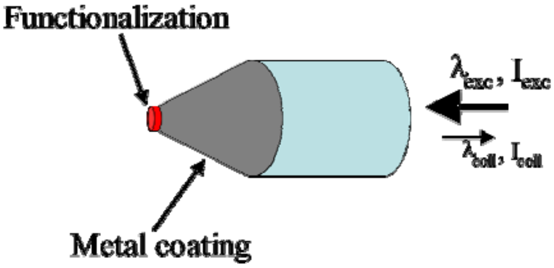

Fig.4 Schematic of an OM tip sensor used for in-vivo, in-situ monitoring of molecules of particular interest in biological applications. The tip is coated with a thin layer of metal and its distant end is functionalised with a highly selective receptor which emits light at the wavelength λ_{coll} when excited at λ_{exc}.

Fig. 4 shows a common configuration for OM tips used in biological sensing: the OM tip is metal coated [94] and a small aperture is left at end face for functionalization and covalent immobilization of biorecognitors. Fluoresceinamine photo-copolymerised with acrylamide-methylenebis(acrylamide) was used for pH sensing [94]; antibodies allowed to detect benzopyrene tetrol, and benzo[α]pyrene [95-99], cytochrome c [100] and caspase-9 [101]. Plasticized polymeric membranes coatings were used to detect ions [102], including potassium [101], calcium [103] and nitric acid [104].

5. Evanescent field

When the OM diameter becomes smaller than the wavelength, an increasingly large fraction of the mode in propagating in the evanescent field and can interact with the surrounding environment. This has been exploited in a number of sensors, for optical manipulation, high-Q resonators and even gratings.

OM based sensors rely on the change in the propagation mode resulting from a change in the surrounding environment. Hydrogen [105], humidity [106] NO_2 and NH_3 [16], refractive index [107] and even sub-monolayers of 3,4,9,10-perylene-tetracarboxylic dianhydride (PTCDA) [108] have been monitored with OM sensors.

Optical manipulation relies on the momentum of the photons traveling in the evanescent field to propel particles in close proximity of the OM surface. Optical propulsion has been demonstrated for 3µm [109] and 10µm [110] polystyrene microspheres using the fundamental and high order modes[111], cells [112], nanoparticles [113], molecules [114] and even atoms [115-118]. Because of the geometry, atom fluorescence can be efficiently collected into the OM guided mode [119], resulting in wide applications in quantum optics [120-127], electromagnetically induced transparency [128] and slow light [129].

High-Q resonator exploit the evanescent field to couple the mode back into a different section of the OM where it previously travel: the modes propagating in the two different OM sections can couple, creating an extremely compact resonator. Different geometries have been proposed (fig. 5): knot [130-140], loop [141-147] and microcoil [24-27,148-152].

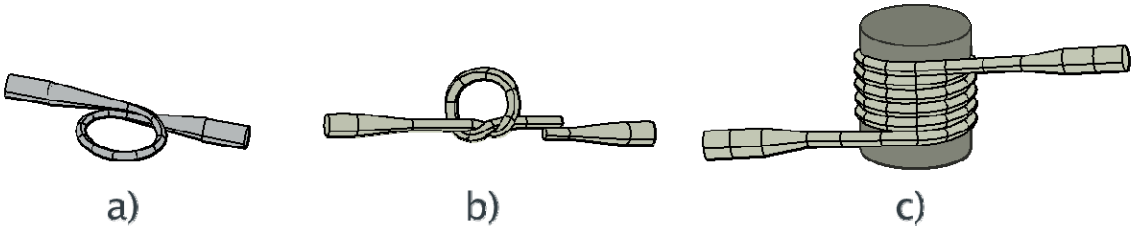

Fig. 5 Schematic diagram of OM resonators: (a) loop; (b) knot and (c) microcoil.

Embedding has been proposed [131] to improve the resonator stability and durability. Application to lasing has been demonstrated using an Er:Yb-doped phosphate glass OM [132], by immersing a KR in a rhodamine 6G dye solution [135] and using zinc oxide nanowires [136] on the OM surface. Resonating sensors have been proposed for biological applications [144], refractometrics [145-146, 151-152], and electric current [147].

As a large fraction of power propagates in the evanescent field, by positioning an OM in proximity of a periodical structure, it is possible to form external gratings [153] which can be used for sensing [154-156]. Bragg gratings and long period gratings have been inscribed in OMs also using ion-beam milling [157] fs and CO_2 lasers [158] and lead to numerous applications of OM gratings [159]. The OM large evanescent field has also been used in conjunction with graphene to modulate light and sensing applications [160-162].

6. Conclusions and outlook

This review analyses optical microfibers (OMs) and their applications in devices and sensors. OMs devices have been grouped according to the property they exploit: transition regions, confinement or evanescent field. Although a relatively new platform, devices based on OM promise a tremendous impact, especially in nonlinear optics, quantum optics and sensing.

Because of their nature, OM exhibit few issues, most notably the optical degradation, the mechanical robustness and above all the relatively high cost of photonics technologies with respect to their electronic counterparts. While degradation and robustness are easily addressed by suitable packaging (or working in vacuum, for quantum optics), the cost element will remain a main issue and will most probably limit the OM applications into fields were electromagnetic interference and accessibility remain an issue or in research labs, where they provide better performance than conventional bulk optical components.

In particular, it is easy to predict that in the near future OM will find a broad range of applications in the quantum optics field, where the greater collection efficiency of photons allows for easier experimental set-ups, in nonlinear optics, where the tunable dispersion characteristics and high nonlinearity allow for easy observation of nonlinear effects, and in nanosensing, where the small footprint allows for invasive measurements in biological entities.

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