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## [INVITED] Optical microfibre devices

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#### ARTICLE INFO

#### ABSTRACT

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#### 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 0.01 dB/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.

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.

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#### 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  $\lambda/10$  [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 [28–31]. 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.







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optical manipulation. This paper reviews the various applications of microfibres.

In the last decade optical fibre tapers with micrometre diameter (often called microfibers) have been

investigated for numerous applications ranging from sensing to wavelength convertors, telecom and

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**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.

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 socalled 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 [21,42,43]. If the conversion is on one-to-one basis and there is no power transfer between different modes, the taper is called adiabatic. If  $\beta_1$  and  $\beta_2$  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  $\Omega$  is smaller than a critical angle  $\overline{\Omega}$  given by

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

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).

This effect has been exploited to eliminate high order modes from few mode fibres and couplers [43–45], selective excitation of fundamental mode in few mode fibres [46], interferometric sensors in taper tips [47], and comb-like filters for tunable lasers [48].

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 [49].

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  $\gamma$  and in phenomena like supercontinuum generation [50–55], second- and third-harmonic generation [56–69], slow and fast light [70] and bistability [70–72] being readily observed.

Supercontinuum was generated in silica [6], bismuth-silicate [12] and chalcogenide [73] glasses. In silica OM, supercontinuum has been generated over two octaves [74–77]; yet, the small size affects the overall dispersion profile resulting in a poorer spectral flatness [78]. For increasing powers, a decreasing degree of coherence has been observed and was attributed to phase noise [79]. The mechanism originating supercontinuum has been investigated both for fs- and for ps-pulses [80]: while in the former self phase modulation and solitons [81] 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 [82,83]. 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.

For optimised diameters, in phase matching conditions the overlap can reach 70% [38]. Experiments carried out on a 100 µmlong OM with  $r=245\pm10$  nm have demonstrated a conversion efficiency of  $2\cdot10^{-6}$  [56]. The low detected efficiency has been explained by the irregular diameter profile associated to thermal surface waves trapped during solidification in the OM [63]. 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 [56]. Because of the predicted high conversion efficiency, OMs have been proposed for third-order parametric amplifiers [84].

When cleaved, the OM has a rapidly divergent beam that has been exploited to optically trap particles [85,86]. Trapping of a single particle at the OM tip was carried out with a power slightly higher than 10 mW [87], lower than those used in free space (1 W)



**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<sub>11</sub>) exchange power with even higher order modes that can be leaked out if not supported by the OM in the uniform waist region.

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