Cylindrical metal-coated optical fibre devices for filters and sensors

A. Diez, M.V. Andres, D.O. Culverhouse and T.A. Birks

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Novel fibre-optic components suitable for sensor applications and wavelength filters are reported. The devices consist of a tapered fibre whose uniform waist has been coated with a thin layer of gold. The operation principle is the resonant excitation of a surface plasma mode of the metal film.

Introduction: We have combined a fusion-pulling technique and a standard metal-coating technique to fabricate novel optical fibre devices based on a tapered single mode fibre with a metal coating. These devices can be regarded as a cylindrical version of metal-coated side-polished fibre-optic devices [1]. Both are based on an interaction of a surface plasma mode of the metal film with the evanescent field of the mode guided by the core. The polishing technique requires the removal of most of the cladding on one side of the fibre, to within a few micrometres of the core, because the evanescent fields in a standard fibre decay over such a distance. Conversely, in the fusion-pulling technique no material is removed. Instead, the reduction of the core diameter causes the evanescent field to spread across the cladding (itself reduced in size) and reach the outer boundary.

We demonstrate that the fabrication of such cylindrical devices is feasible and give the preliminary experimental results obtained. To our knowledge, this is the first time this has been reported. These novel resonant components are suitable for sensor applications (where a mesurand changes the external refractive index), and tuneable spectral filters (e.g., for gain flattening or ASE removal in fibre amplifiers). Although chemical sensors based on a narrow cladding-moded taper with a metal coating have already been described [2], here we consider wider tapers, where light is still guided substantially by the fibre core.

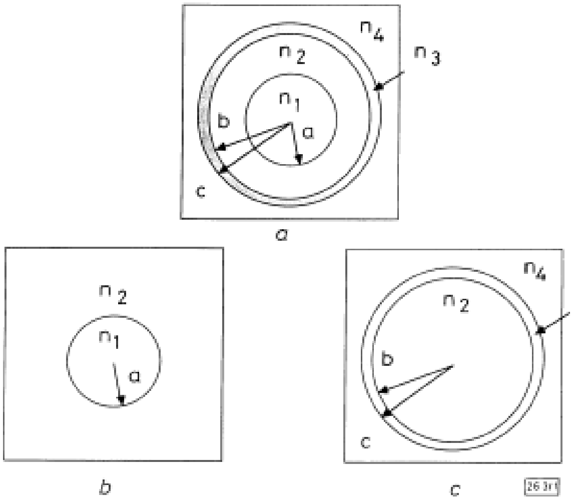

Fig. 1 *Schematic cross-sections of metal-coated optical fibre, optical fibre core and metal-coated dielectric cylinder*

a Metal-coated optical fibre
b Optical fibre core
c Metal-coated dielectric cylinder

Theory: Fig. 1*a* shows a cross section of an ideal structure, where *a* and *b* are the core and cladding radii at the waist, respectively, and *c*–*b* is the metal film thickness. Optically, it can be regarded as a step-index single mode fibre core (a dielectric/dielectric waveguide, Fig. 1*b*) and a metal-coated dielectric cylinder (a dielectric/metal/dielectric waveguide, Fig. 1*c*), which are weakly coupled together. No interactions are expected except at resonances, where the effective indices of modes of the two waveguides match. A theoretical analysis, using a standard boundary-value method, shows that most of the mode spectrum of the whole structure is the superposition of the mode spectra of these two waveguides (with no interaction between them), but coupling does occur for some particular combinations of parameters [3]. Fig. 2 shows an example where there is coupling between the fundamental mode of the fibre core and a hybrid surface plasma mode of the metal-coated dielectric cylinder: resonant excitation and power transfer is expected around the crossing point. Since any coupled light will be absorbed in the metal film, a resonant dip would be expected in the transmission spectrum of the device. Owing to the effective index of the plasma mode depending strongly on the wavelength of the light and the external refractive index, the resonance (and transmission loss) depends on both parameters.

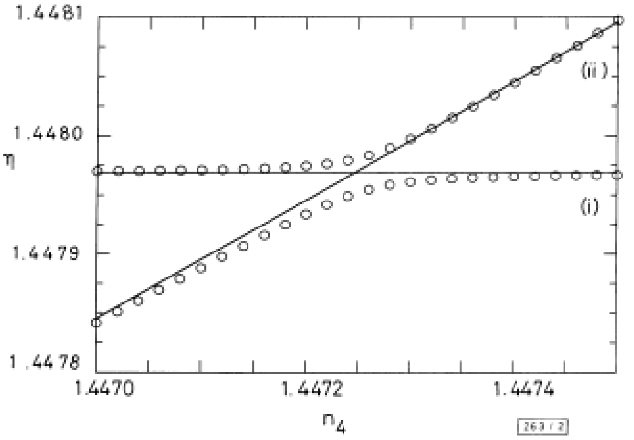

Fig. 2 *Calculated effective-index, h, against external refractive-index, n_4, at λ = 1.3mm*

(i) Fundamental mode of step-index optical fibre
(ii) Hybrid surface plasma mode of gold-coated dielectric cylinder
○ Hybrid modes of metal-coated optical fibre
Parameters (see Fig. 1): a = 2.52μm, b = 22.4μm, c–b = 9.2nm, n_1 = 1.45152, n_2 = 1.44725 and n_3 = 0.38–j8.8

Experimental procedure and results: The devices were fabricated from a standard singlemode fibre with a cutoff wavelength of 1.2μm, a core diameter of 7.5μm and a cladding diameter of 125μm. The fibre was stripped of its coating and narrowed using a fusion-pulling technique. The diameter at the taper waist was reduced to ~30μm and was uniform over a 15μm length, these values being controlled using the methods in [4]. A thin layer of gold was evaporated onto the taper waist, either on one side or on two opposite sides. This simple technique gives a nonuniform coating. Finally, transmission spectra were recorded for different external refractive indices, specified by applying a standard index fluid to the waist.

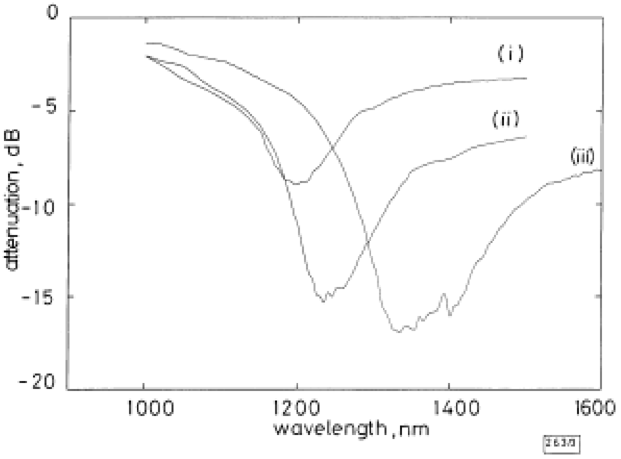

Fig. 3 *Transmission spectra of taper with waist diameter and gold thickness of 30μm and 24nm respectively, for three values of nominal external refractive-index*

a 1.436
b 1.438
c 1.440

Fig. 3 gives the transmission spectra of a device with a taper waist of 30μm and a 24nm gold film, evaporated on two opposite sides of the taper. The external refractive-index values stated in the figure caption are the nominal values of commercially available fluids, without allowing for dispersion.

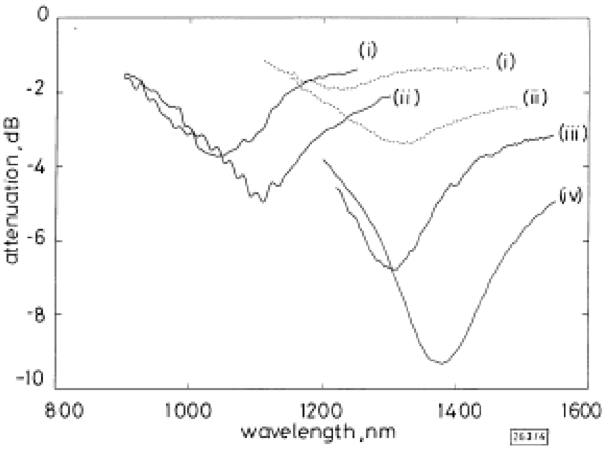

Fig. 4 *Transmission spectra for two tapers with waist diameters and gold thickness of 31.5µm, 24nm, 38µm and 23nm for four values of nominal external refractive-index*

(i) 1.440
(ii) 1.442
(iii) 1.446
(iv) 1.448
——— 31.5µm, 24nm
– – – – 38µm, 23nm

Fig. 4 gives the transmission spectra of two devices with waist diameter of 31.5 and 38µm, and gold films of 24 and 23nm, respectively. In these devices the metal was evaporated on one side of the taper waists only.

In each case, substantial dips in the transmission spectra were observed. The wavelength of minimum transmission could be varied by changing the external index. Equivalently, the transmission at a particular wavelength was dependent on the index. The device with metal evaporated on two opposite sides (Fig. 3) exhibits stronger absorption peaks than the devices coated only on one side (Fig. 4), as might be expected. The resonances are broadband. We are not yet able to experimentally evaluate the effects of nonuniformity of our coatings. However, because the effective index of the plasma wave depends on the film thickness, nonuniformity will chirp the resonance, giving the observed broad resonances. Hence, a uniform coating (a true cylindrical metal layer) would reduce the width of the absorption peak. In contrast, suitable conditioning of the absorption spectrum (for specialist filter applications) should be possible by controlling the longitudinal variation of the taper diameter [4], and the longitudinal and azimuthal variations of the film thickness.

Conclusions: Novel cylindrical metal-coated optical fibre devices can be fabricated by coating the waist of a tapered fibre with a metal layer. The devices exhibit strong resonant coupling between the fundamental fibre mode and the surface plasma mode, which depends on the external refractive-index and the wavelength, as well as other parameters. Applications include optical sensors and spectral filters.

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