TAPERED-BEAM EXPANDER FOR SINGLE-MODE OPTICAL-FIBRE GAP DEVICES

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A simple practical and controllable beam expander can be constructed from a single-mode optical fibre which has been overjacketed in a capillary of lower refractive index and then tapered. The properties of such an expanded beam in a gap device are also investigated.

Introduction: Beam expanders are required for in-line monomode fibre devices such as connectors and power splitters.[1] Such expansion has generally relied on a lens[1] to achieve the necessary beam size. In this letter we demonstrate a rugged alternative approach which is based on the expansion of the field in a monomode fibre when the fibre is tapered.

(*a*) *Tapers in single-mode fibres:*

(i) *Properties:* A single-mode taper-device, e.g. a coupler, is generally made by pulling a single-mode fibre of initial diameter 120 μm in a small oxybutane flame. A typical taper waist has a diameter of 10–20 μm. The tapering has a significant effect on the optical field as it propagates along the taper. Initially the field is guided by, and substantially confined to, the core. As the core diameter decreases the field spreads out, its spot size increasing as[2]

$$\omega_0 = a\left(0{\cdot}65 + \frac{1{\cdot}619}{V^{3/2}} + \frac{2{\cdot}879}{V^6}\right) \tag{1}$$

Eventually a point is reached when the field is no longer guided by the core but is effectively guided by the waveguide consisting of the cladding and the surrounding medium.[3] This fact accounts for the discrepancy between the experimental measurement and the theoretical prediction (assuming infinite cladding) of spot size by the authors of Reference 4. The cladding waveguide is highly multimoded and, if the taper rate is large, coupling to higher-order modes will occur, resulting in power loss from the output of the taper. The condition for a taper to remain adiabatic is[5,6]

$$\left|\frac{da}{dz}\right| \ll \frac{a}{z_b} \qquad z_b = \frac{2\pi}{(\beta_1 - \beta_2)} \tag{2}$$

where β_1 and β_2 are the propagation constants of the LP_{01} and LP_{02} cladding modes. A taper satisfying this condition will suffer negligible loss through mode coupling. The condition is easily achieved in tapers made from matched-cladding single-mode fibres.

(ii) *Implementation and fabrication:* To exploit the tapered single-mode as a practical beam expander, it is necessary to strengthen the taper along its length. To achieve this a 'Vycor' capillary sleeve of about 350 μm/270 μm external/internal diameter was placed around the fibre before tapering. The large internal diameter is necessary to facilitate the threading through of a coated fibre until a bare section of fibre could be located in the middle of the length of capillary. The capillary was then collapsed uniformly about the fibre using a symmetrical intense heat distribution provided by a miniature graphite furnace. The simple oxybutane flame would not provide the necessary symmetry (or the necessary heat) and could give rise to mode coupling, on tapering, to higher-order odd modes with resultant losses.

The combined fibre and capillary is then tapered to a minimum neck diameter of 40 μm, which is appropriate for standard fibre handling and cleaving. Vycor has a slightly lower refractive index than silica ($\Delta n \simeq 0{\cdot}004$) and the expanded fibre cladding mode is now guided by the boundary of the cladding and the Vycor. The capillary jacket also plays the role of protecting the expanded beam from external refractive-index change and cleaving damage.

The complete fibre-capillary structure allows good control and slow tapering, so that insertion losses on fabrication can be kept below 0·7 dB for taper ratios of typically 4:1. The measured near-field spot size of the mode as it evolves through one such taper is shown in Fig. 1. The measurements were made by progressively cleaving back the structure; the parameters of the taper are given in the caption.

(*b*) *Beam expanders and fibre-gap devices:* A gap cut in a single-mode fibre, Fig. 2*a*, results in a transmission loss of $-10 \log_{10} T$, where[1]

$$T = \frac{4z^2 + 1}{(2z^2 + 1)^2 + z^2} \tag{3}$$

and

$$z = \frac{D}{nk\omega_0^2}$$

The spot size of the mode when it leaves the fibre is ω_0, n is the refractive index of the intervening material, $k = 2\pi/\lambda$ and D is the separation distance.

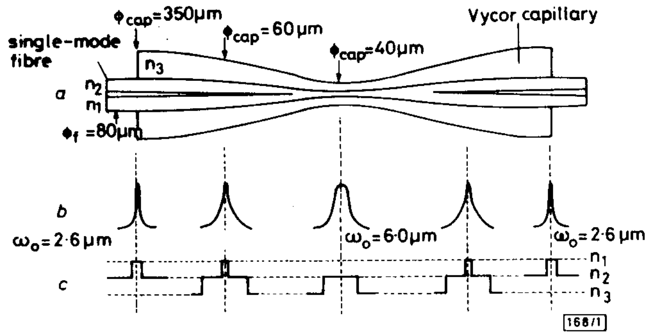

Fig. 1

a Structure of taper beam expander. ϕ_f is fibre diameter and ϕ_{cap} capillary diameter. n_1 is core refractive index (1·462), n_2 is cladding index (1·458) and n_3 is Vycor index (1·452)
b Measured field evolution along taper
c Refractive-index distributions which dominate at various stages along taper

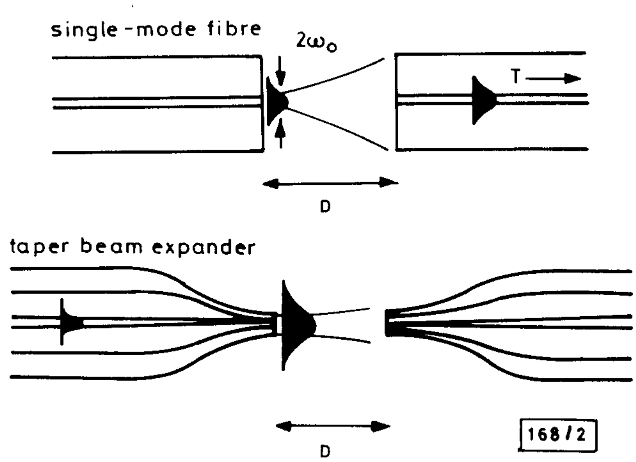

Fig. 2

a Transmission across a gap in a single-mode fibre (schematic)
b Schematic diagram of use of taper beam expander to increase gap size

Fig. 3 shows a plot of T (both as given by eqn. 3 and as measured) for a standard single-mode fibre with a spot size of 2·6 μm in an index-matching medium. A gap of about 100 μm results in a 3 dB loss. This gap size is rather small for the insertion of a field interacting device such as an acousto-optic modulator or a liquid-crystal cell.

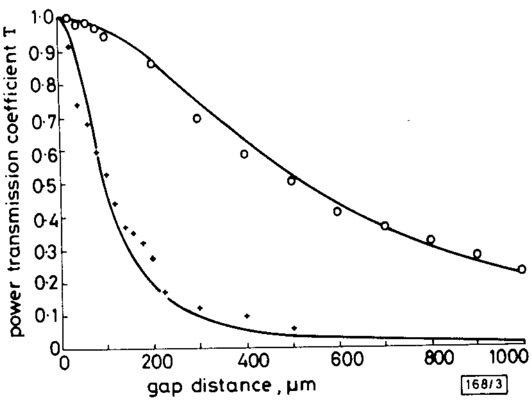

Fig. 3 *Transmission coefficient as a function of gap separation for two different spot size values*

+ + + spot size 2·6 μm straight fibre

○○○ spot size 6 μm tapered fibre

Solid curves are given by eqn. 3

From eqn. 3 we see that the gap size for a given loss increases as the square of the spot size and a moderate increase in the spot size to about 6 μm will result in a gap of 0·5 mm for a 3 dB loss. Such a spot size was achieved in our taper beam expander as depicted schematically in Fig. 2*b*. The measured transmission loss for the spot size, together with the transmission loss (as given by eqn. 3), is plotted in Fig. 3. Further increases in spot size would result in bigger gaps.

Conclusions: A single-mode tapered beam expander has been constructed and the predicted gap device behaviour measured. The Vycor capillary jacket developed here protects the expanded beam from external refractive-index changes and mechanical damage. The present size of the capillary allows the composite fibre to be reduced to 100 μm, thus matching standard fibres and cleaving tools. Further developments are possible to increase the spot size and obtain larger gaps.

Expanded-beam fibre tapers may be considered as rugged alternatives to lens beam-expanders in connectors, power splitters and other in-line fibre devices.

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