PRACTICAL SINGLE-MODE FIBRE-HORN BEAM EXPANDER

Indexing terms: Optical fibres, Optical connectors and couplers

A new design and implementation technique for the single-mode fibre-horn beam expander is outlined. This new design is more practical, both in its fabrication technique and in its application, than the previous approach. The field evolution along the beam expander has been measured and the fundamental limits to the rate of tapering examined.

Introduction: The optical fibre-horn has been proposed as a self-aligned beam expander for single-mode fibre optics.[1-3] The introduction of beam expansion optics into single-mode fibre technology is a requirement of the very small core sizes involved. Beam expansion can relax the mechanical tolerances for axial and lateral alignment by an order or two of magnitude. The cost, however, is an increased sensitivity to angular misalignment. The addition of self-aligned beam expansion in the fibre structure eliminates the need for lenses, which requires stable and critical alignment, and can be achieved by (i) 'tapering down' a fibre, as in the overjacketed beam expander,[4] where a factor of three beam expansion is practically feasible, or (ii) 'tapering up' a fibre by enlarging the cross-sectional dimension,[1] where an order of magnitude beam expansion of the modal field can be achieved with manageable taper lengths. Such beam expanders must keep the fundamental mode intact with very little mode coupling or loss. In this letter we report on the fabrication and design limitations of a practical fibre-horn beam expander containing: a fibre pigtail, which is permanently spliced to an input fibre; an expanding tapered section which yields the beam expansion; and a uniform section which facilitates axial and lateral alignment while alleviating any angular misalignment problems. The device is shown schematically in Fig. 1*a*.

Fabrication:

(*a*) *Structure:* Fibre-horn beam expanders have been fabricated by taking the taper present in the transition from fibre to preform when the normal operation of fibre drawing is stopped. The taper transition region is then approximately 6 cm long. The termination with a conic shape does not facilitate easy handling, although excellent laboratory studies have been reported.[1,2] By stretching the preform prior to fibre drawing to the required diameter and subsequently tapering to produce the fibre pigtail, a taper transition of approximately 5 cm can be achieved, but now with uniform cylindrical geometries at both ends of the transition. An important incidental advantage of this process is a much higher yield from the preform.

(*b*) *Refractive index profile:* A single-mode fibre is relatively immune to on-axis dips or perturbations to the refractive index profile in normal operation (see Fig. 2). On expanding the core, the influence of the refractive index profile on the fundamental mode field distribution can be very significant when a Gaussian-shaped mode is desired. The core refractive index should therefore be uniform (ideal step index) or graded with a maximum on the fibre axis (e.g. α-profiles). In the present study an MCVD preform with a pure silica core and a depressed cladding was fabricated, thereby avoiding the possibility of a dip on-axis due to the burn-off of dopants in the preform collapse stage.

(*c*) *Taper rate:* Mode conversion and loss from the fundamental mode in the fibre-horn can be minimised by obeying a certain slowness or adiabatic condition.[5] If z is the distance along the taper and ρ the local outside dimension of the taper, then the adiabatic condition can be written as

$$\left|\frac{d\rho}{dz}\right| \leq \frac{\rho}{z_b} \qquad z_b = \frac{2\pi}{(\beta_1 - \beta_2)}$$

where z_b is a 'beat length', β_1 is the propagation constant of the fundamental LP_{01} mode and β_2 is the propagation constant of the LP_{02} mode, which is the closest and most likely mode to which coupling will occur. The adiabatic condition is shown in Fig. 3, given that the fibre is single-moded at

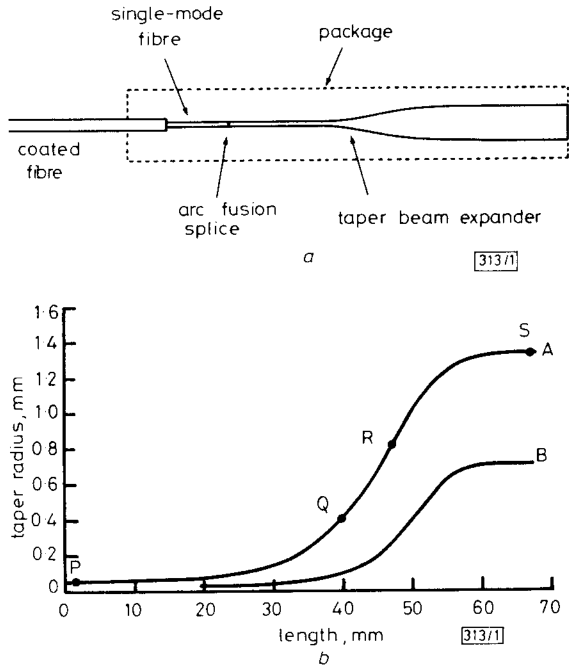

Fig. 1

a Practical self-aligned fibre-horn beam expander
b Taper radius as function of length for nonadiabatic taper (*A*) and adiabatic taper (*B*)

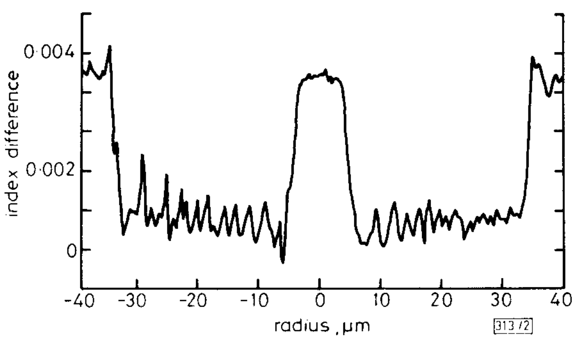

Fig. 2 *Refractive index profile of a pure-silica-core fibre from which fibre horns were fabricated*

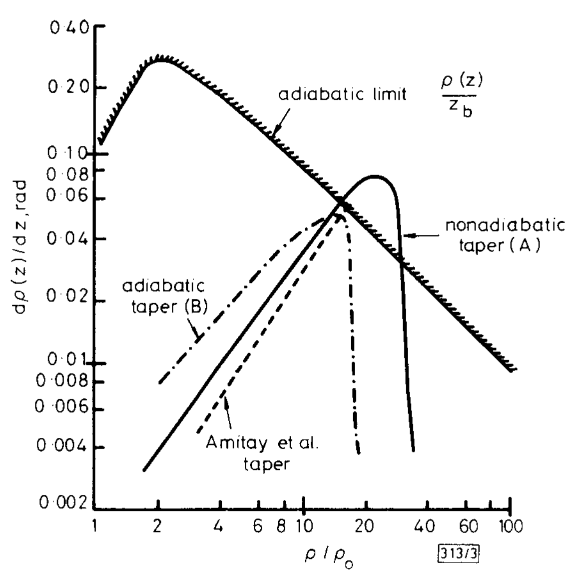

Fig. 3 *Actual taper angles for nonadiabatic taper (A), adiabatic taper (B) and taper in Reference 1, compared with adiabatic limit*

$\lambda = 633$ nm (core radius $= 2\,\mu$m, NA $= 0{\cdot}11$), for the fibre radius fibre-horn in Reference 1 and the fibre-horns of Fig. 1*b*. Clearly for case A the adiabatic condition is exceeded. Examining this horn by measuring the near-field distribution

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(Fig. 4), it is found that the optical field, which initially expands as a Gaussian beam in the adiabatic region P-Q, undergoes severe mode conversion on exceeding the adiabatic limit in the region R-S.

Discussion: The adiabatic condition shows that it is possible to achieve any level of beam expansion, provided that the length of the fibre-horn is sufficiently long. In practice, it would be desirable to minimise the length of the horn while achieving a suitable level of beam expansion. By stretching the present preform to a 1 mm diameter, say, a beam expansion factor of up to ten is possible. In this case the fibre pigtail can be cleaved using standard tools: the 1 mm section could be cleaved using a 'hand' cleave or polished depending on the quality of surface required. The splice to the fibre can be

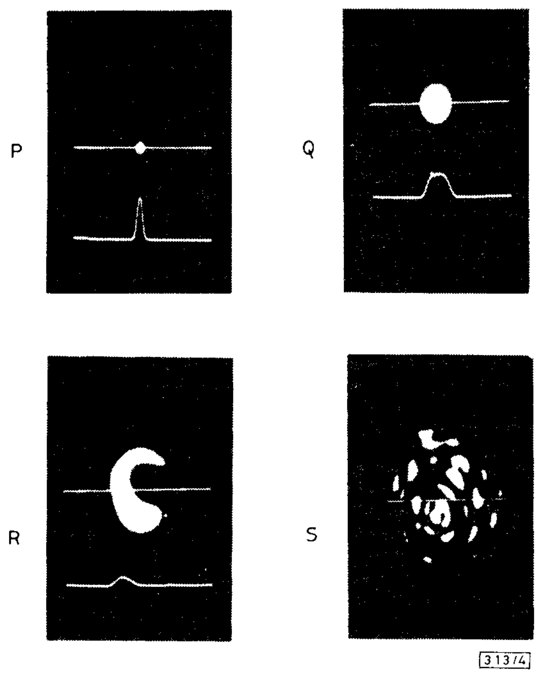

Fig. 4 *Measured near-field distribution at points indicated in Fig. 1b of nonadiabatic taper (A)*

achieved with a standard splicing machine. We can routinely package both the beam expander and splice in a single protective package of up to 7 cm long. This new beam expander should prove useful for rugged single-mode fibre connectors and for gap device applications. It will also facilitate the study of nonlinear phenomena in fibres, since a high intensity in the core can be achieved for a small surface intensity on the large taper endface, thereby eliminating the problem of surface damage when attempting to launch high intensities into the core of the straight fibre.

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