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THE BEHAVIOUR OF SINGLE-MODE TAPER AND ITS GAP-DEVICE APPLICATION

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

1. Properties

A single-mode taper-device, e.g. a coupler, is generally made by pulling a single-mode fibre of initial diameter of 120μm in a small oxy-butane flame. A typical taper waist has a diameter of 10-20μm. 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 spotsize increasing as[2]

$$\omega_0 = a\left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right) \qquad (1)$$

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 spotsize by the authors of ref. 4. The cladding waveguide is highly multimoded and, if the taper rate is large, coupling to higher-order modes aill occur, resulting in power loss from the output of the taper. The condition for a taper to remain adiabatic is[5,6]

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

where $_1$ and $_2$ are the propagation constants of the LP_{01} and LP_{02} cladding modes.

2. Implementation and Fabrication

In order to exploit the tapered single-mode as a practical beam expander, it is recessary to strengthen the taper along its length. To achieve this a "Vycor" capillary sleeve of about 350μm/270μm 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 lenght 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 oxy-butane 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 40μm, which is appropriate for standard fibre handling and cleaving. Vycor has a slightly lower refractive index than silica ($\Delta n = .004$) 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 fibre-capillary structure allows good control and slow tapering so that insertion losses on fabrication can be kept below .7dB for taper ratios of typically 4:1. The measured near field spotsize of the mode as it evolves through one such taper is shown in Figure 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, Figure 2(a) results in a transmission loss of $-10 \log_{10} T$ where[1]

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

and

$$z = \frac{D}{nk\,\omega^2}$$

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

Figure 3 shows a plot of T (both as given by Equation (3) and as measured)) for a standard single-mode fibre with a spotsize of 2.6μm in an index-matching medium. A gap of about 100μm results in a 3dB loss. This gap size is rather small for the inscrion of a field interacting device such as an acousto-optic modulator or a liquid crystall cell.

From Equation (3) we see that the gap size for a given loss increases as the square of the spotsize and a moderate increase in the spotsize to about 6μm will result in a gap of .5mm for a 3dB loss. Such a spotsize was achieved in our taper beam expander as depiced schematically in Figure 2(b). The measured transmission loss for the spotsize, together with the transmission loss (as given by Equation (3)), is plotted in Figure 3. Further increases in spotsize 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 100μm, thus matching standard fibres and cleaving tools. Further developments are possible to increase the spotsize 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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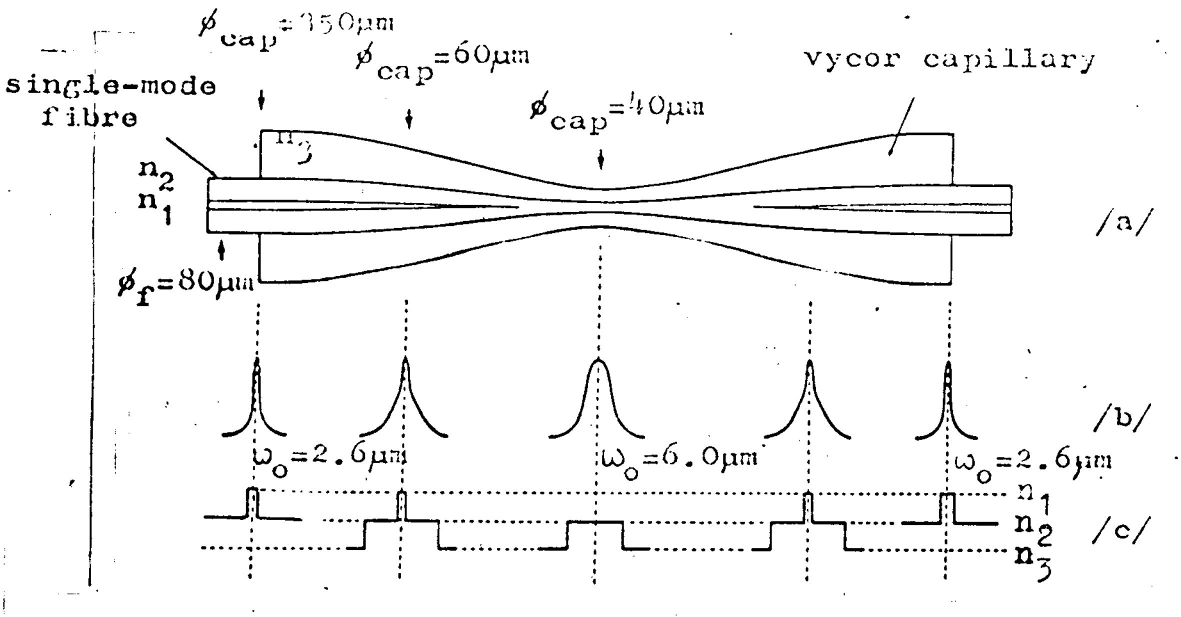

Fig.1. (a) Structure of the taper beam expander. ϕ_f is the fibre diameter and ϕ_{cap} the capillary diameter. n_1 is the core refractive index (1.462), n_2 is the cladding index (1.458) and n_3 is the vycor index (1.452). (b) Measured field evolution along the taper. (c) Refractive index distribution which dominate at the various stages along the taper.

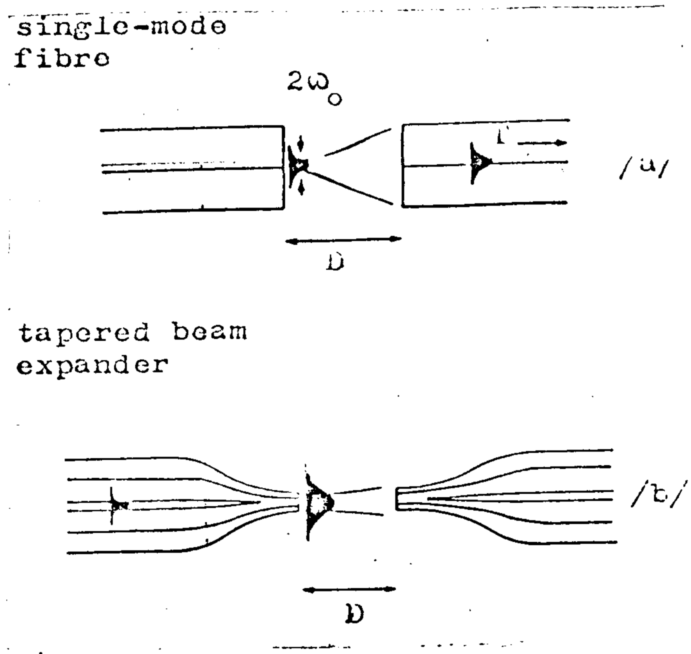

Fig.2. (a) Transmission across a gap in a single-mode fibre (schematic)
(b) The use of the taper beam expander to increase the gap size (schematic).

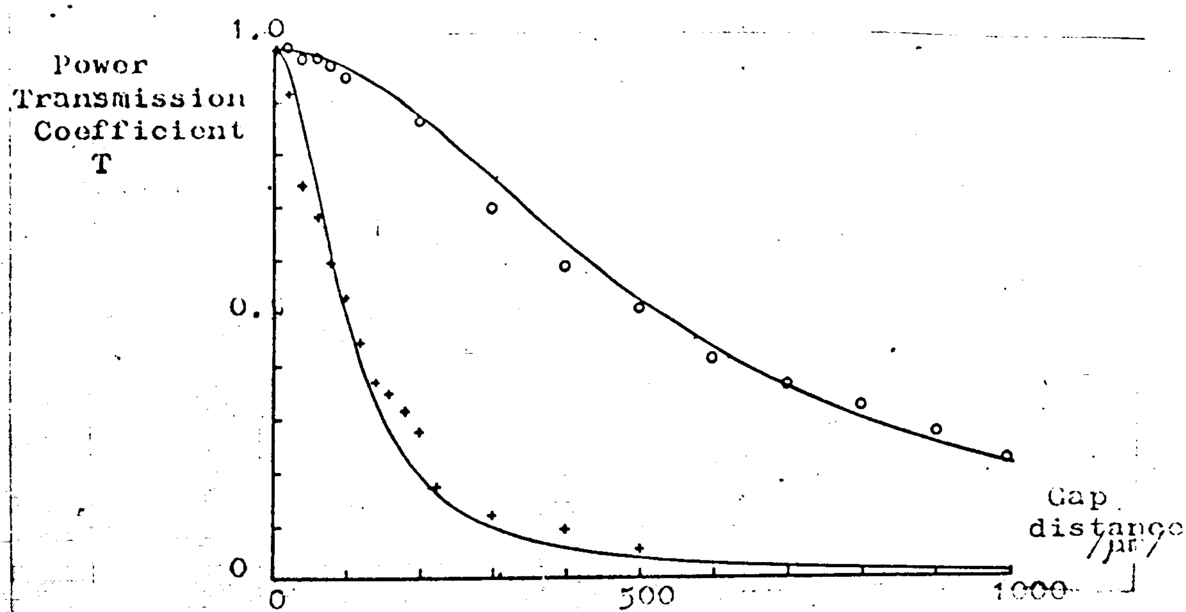

Fig.3. Transmission coefficient as a function of gap separation for two different spot size values; +++ spotsize 2.6μm straight fibre, ooo spotsize 6μm tapered fibre, the solid curves are given by equation (3).