BICONICAL TAPER COAXIAL OPTICAL FIBRE COUPLER

Indexing terms: Optics, Optical connectors and couplers

The coaxial biconical taper coupler is presented as a novel type of coaxial coupler. It is modelled as a three-section alternating $\Delta\beta$ coupler, and a large range of communication fibres can now be used for the fabrication of such couplers.

Introduction: A coaxial directional coupler is formed when two waveguides are coupled coaxially. Various forms of coaxial couplers are shown in Fig. 1. For the coaxial couplers of Figs. 1*a* and *b* the coupled guides are notionally a rod and a tube, while in Fig. 1*c* the guides are two rods.

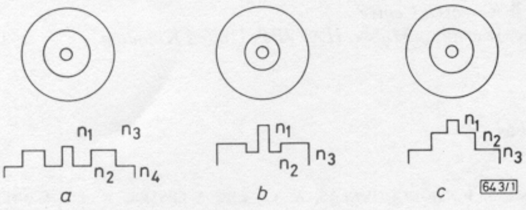

Fig. 1 *Coaxial coupler configurations*

a Typical coaxial coupler
b Depressed or w-fibre
c Raised cladding fibre

Coaxial couplers have been demonstrated[1-4] and their possible applications have been studied, but there has as yet been no serious exploitation of such devices. The main reason for this, we believe, is associated with the difficulties in phase-matching these devices for operation at a desired wavelength λ_{op}. It has been shown[3] that, in order to phase-match the rod and tube guide at λ_{op}, dimensional and refractive index fabrication tolerances would be undesirably strict. This letter presents a solution to this problem and we show how all types of single-mode fibres currently used for communication purposes can, in principle, be described as coaxial couplers.

We have applied the simple but powerful technique of fibre tapering, currently used for the fabrication of fused taper biconical couplers,[5] to the problem of phase-matching in the coaxial coupler.

Theory: The mode coupling theory applied to coaxial couplers of Figs. 1*a* and *b* has been developed,[4] and we apply this to the rod and tube guides. The beat length of such couplers can hence be calculated and the power exchange between the guides can be predicted from knowledge of the propagation constant mismatch $\Delta\beta$ ($\Delta\beta = \beta_{rod} - \beta_{tube}$) between the fundamental modes of the guides.

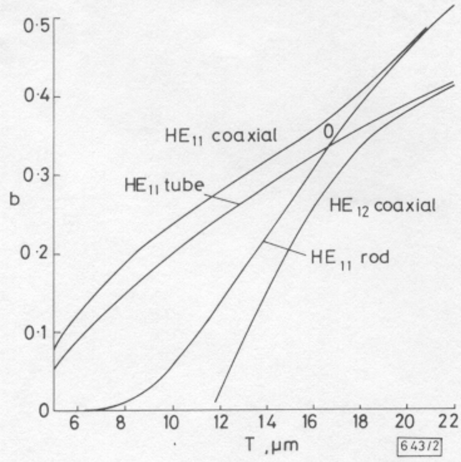

Fig. 2 *Evolution of relevant guided modes during tapering*

Such mismatch is practically always present, owing to fabrication tolerances. Furthermore, for the analysis we assume that $\beta_{rod} > \beta_{tube}$, which can easily be achieved practically, and all communication fibres have this condition satisfied. Fig. 2 shows the normalised propagation constants b of the rod and tube HE_{11}-modes against T, the outer radius having $n_1 = 1{\cdot}4483$, $n_2 = n_4 = 1{\cdot}444$, $n_3 = 1{\cdot}447$, $\delta_1 = a/\delta T = 0{\cdot}333$, $\delta = \delta T/T = 0{\cdot}683$ and

$$b_{rod} = [(\beta_{rod}/k_0)^2 - n_2^2]/[n_1^2 - n_2^2]$$

$$b_{tube} = [\beta_{tube}/k_0)^2 - n_3^2)/[n_1^2 - n_2^2]$$

This Figure shows that as the fibre is tapered (δ and δ_1 constant, T varies), the localised $\Delta\beta$ varies from positive, becomes zero (point O) and then negative. In the same Figure, the variations of the HE_{11} and HE_{12} normal modes of the coaxial structure as it is tapered are also shown. The interference of these modes can explain the power transfer between the coaxially coupled guides.

It is worth pointing out that all typical communication fibres belong to one of the three categories shown in Fig. 1. Even the matched cladding fibre ($n_2 = n_3$, $n_4 = 1$) is a special case of that in Fig. 1*c*, and, if stretched long enough, a similar graph to Fig. 2 could be obtained. From Fig. 2 we clearly see that the HE_{12}-mode is cut off[6] when the tube outer thickness reaches $\sim 11{\cdot}5\ \mu m$; hence the mode coupling theory gives erroneous results below this thickness. Fig. 2 also allows us to model any tapered fibre as a three-section alternating $\Delta\beta$ coupler, as shown in Fig. 3 with $\Delta\beta$ a function of z. This is an important observation, since it indicates that the dimensional tolerances are now relaxed in this fibre coupler, in a similar manner as described in Reference 7 for integrated optic directional couplers.

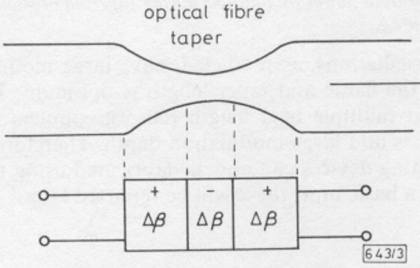

Fig. 3 *Alternating $\Delta\beta$ configuration of tapers*

To predict the output power from the rod guide at the taper end (the power in the acrylate coated tube being stripped out), we have divided the taper into a large number of thin uniform cascaded coaxial couplers, and a numerical program was compiled using the results of mode coupling theory. The output power from parabolic shaped tapers is shown plotted against the taper minimum waist in Fig. 4. Fig. 4*a* is the result from a 7·5 mm-long parabolic taper ($Z^2 + C$), and we can clearly see that, as the fibre is tapered, the power oscillates between the rod and tube guides, with significant depth of oscillation. Fig. 4*b* shows the effect of another parabolic taper ($1{\cdot}5Z^2 + C$) of length 6·1 mm; we can now see oscillations of deeper modulation. Finally, Fig. 4*c* shows oscillation of

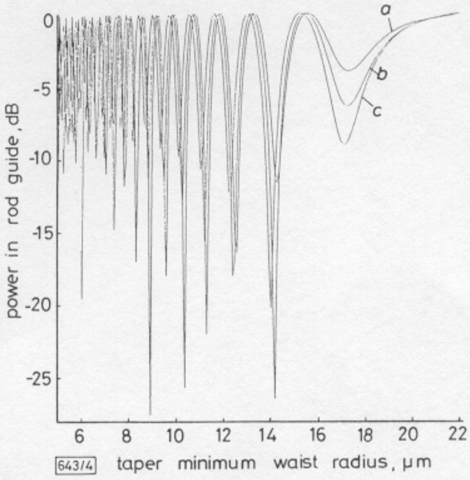

Fig. 4 *Computed output power from rod guide during tapering (using mode coupling theory)*

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>25 dB modulation, for a parabolic taper $(2Z^2 + C)$ of 5·3 mm length.

The results show that there is an optimum taper shape and length for large modulation power transfer. In practice this is achieved by the choice of flame and tapering speed. The adiabatic condition must be maintained for all tapers,[8] otherwise the tapering is lossy. Although the previous analysis has been developed for couplers of Figs. 1*a* and *b*, similar analyses and results for couplers of Fig. 1*c* can easily be derived.

Experimental: Communication fibres with slightly depressed claddings were used for our experiments on tapering. Fibres were tapered with the aid of a motorised positioning jig and an oxybutane flame. Power from a 1·5 μm laser was launched into the fibre core, and any cladding power was removed by the self mode stripping acrylate coating. In the taper region, coupled power could be guided in the tube guide, since it is there stripped of the acrylate coating. During tapering the output power was detected and plotted on a chart recorder. Fig. 5 shows a typical recorded trace.

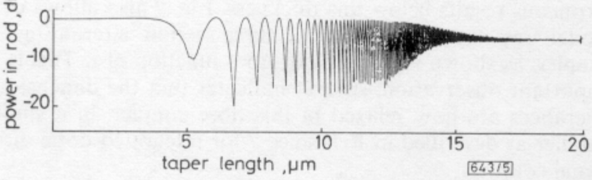

Fig. 5 *Typical transmitted power oscillations during tapering of slightly depressed cladding fibre*

The intensity oscillations, as predicted, have large modulation depth when the flame and taper length is optimum. The Figure shows that multiple beat length (40–50) couplers are possible, of low loss and large modulation depth. Therefore, a number of interesting devices can now be fabricated using this simple coupler as a basic unit; these will be reported later.

Conclusion: A new simple method of fabricating coaxial couplers is described and demonstrated. A large number of standard telecommunication fibres can be used with this technique, which makes use of tapering to phase-match the coupler at the desired wavelength. The taper can be modelled as a three-section alternating $\Delta\beta$ coupler. The effect of flame size is also examined in connection to the modulation depth.

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