INVESTIGATION OF DEVICES BASED ON COUPLING BETWEEN UNCLAD OPTICAL FIBRES

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SUMMARY

Two important optical coupling devices, the directional coupler and the star coupler (for use in the optical data bus), are investigated making use of the principle of coupling between close parallel unclad optical fibres. A theoretical treatment is given which suggest that very high coupling efficiencies should be available in devices using this principle. Measurements made on test couplers confirm this and show also that the devices have low insertion loss (less that 0.5dB for directional coupler). A method of manufacture which involves the shrinking of a small bore tube around the fibres over the desired coupling length is also suggested.

CONTENTS

1. INTRODUCTION

In recent years there has been a growing interest in the use of optical fibres in communications systems. Their advantages over present communications media, which include higher bandwidth, better noise immunity and potentially lower cost, make optical fibres a desirable alternative to copper wire or co-axial cable in a communications network.

1.1. The Optical Data Bus

An important potential application of fibre-optics is in the multi-terminal data bus. The basic concept of the data bus - a transmission line that carries many different multiplexed signals and serves a number of spatially distributed terminals - is becoming increasingly evident in both military and commercial systems, and the use of optical fibres in such a system has been the subject of much recent study in the field of optical fibre communications. (1-4). With a data bus, communication between terminals takes place over a common path with each terminal communicating to every other terminal, information being sent out on a time shared basis. There are two fundamental methods of data distribution which achieve this:-

(a) The serial or "tee" arrangement (Fig. 1)
(b) The parallel or "star" arrangement (Fig 2)

An N-terminal data bus is shown using each of these arrangements. The serial arrangement or "tapped-trunk" approach of Fig 1 involves the use of one main transmission line with N-2 "tee" couplers for data access. The parallel arrangement of Fig. 2 involves N different transmission lines but only one power mixing component, the "star" coupler which distributes signal power from one terminal to all the other terminals.

In co-axial cable systems, the favoured approach is to use the serial arrangement since the amount of cable required is significantly less than for the parallel arrangement. Nevertheless it has been shown (1) that the parallel or star arrangement is more suited to optical fibre systems since the overall loss of the data bus is much less using this approach, there being only one optical coupling device required.

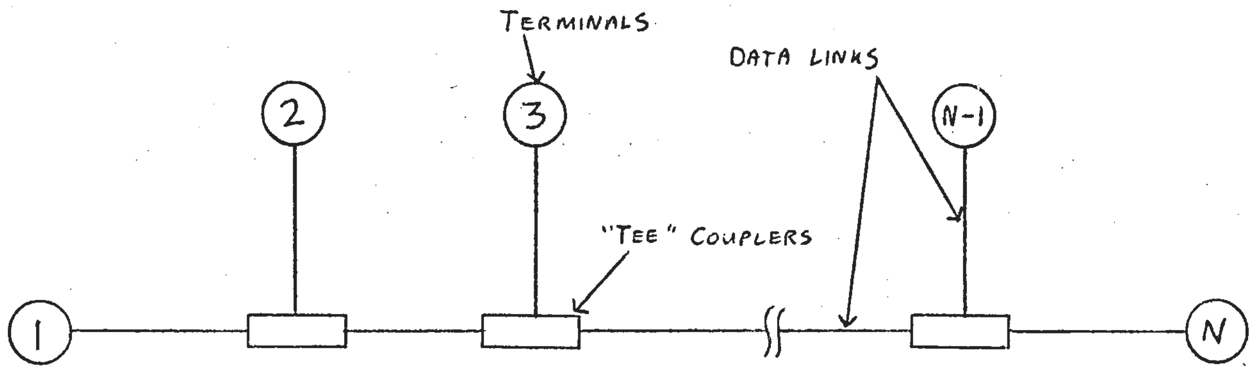

Fig. 1 An N-terminal data bus using the serial arrangement.

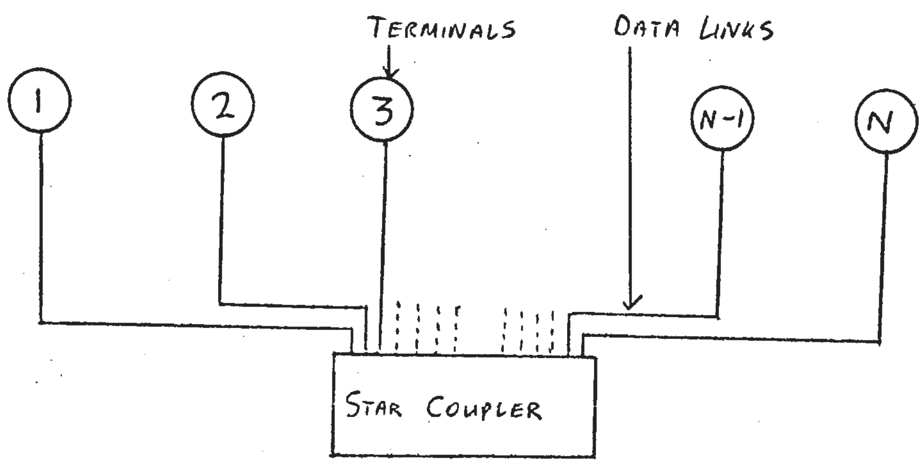

Fig. 2 An N-terminal data bus using the parallel arrangement.

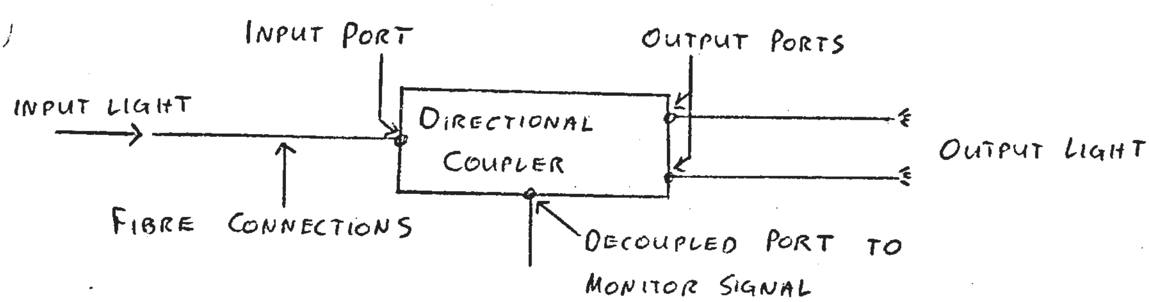

Fig. 3 The Optical fibre directional coupler

1.2. Devices to be Investigated

Here we investigate the manufacture of the star coupler since it is clearly an important optical component for data bus applications. At present the types of star coupler that have been made for test purposes fall into two categories:-

(a) Those for use in a data system using large fibre bundles (1,5)

(b) Those for use in a system using data links of single multimode fibres (6)

Here we shall be investigating a star coupler which falls into the latter category, and which serves seven single-fibre data links.

We shall also consider a somewhat simpler device, the Y-coupler or directional coupler, which involves only three main external connections. This device, illustrated in Fig. 3, has one input port and two output ports, its purpose being to divide the input signal between the two output ports. Such a component is familiar in any wire or co-axial cable system and has many applications. An added feature of the optical directional coupler is that it has a "decoupled port", which taps negligable power from the system and yet can be used to monitor the signal.

1.3. The Principle to be Used

The principle to be used here for the realisation of both the directional coupler and the star coupler is that of power sharing between close parallel unclad optical fibres.

When parallel fibres lie in close contact along their length there is an amount of signal power transfer from one fibre to another (7). This effect is illustrated for two fibres in Fig. 4. Some light "tunnels" from the illuminated fibre through the small gap between the fibres and is guided by the unilluminated fibre. This takes place whether the fibres are clad or unclad, although when the fibres involved are clad this amount of power transfer is small.

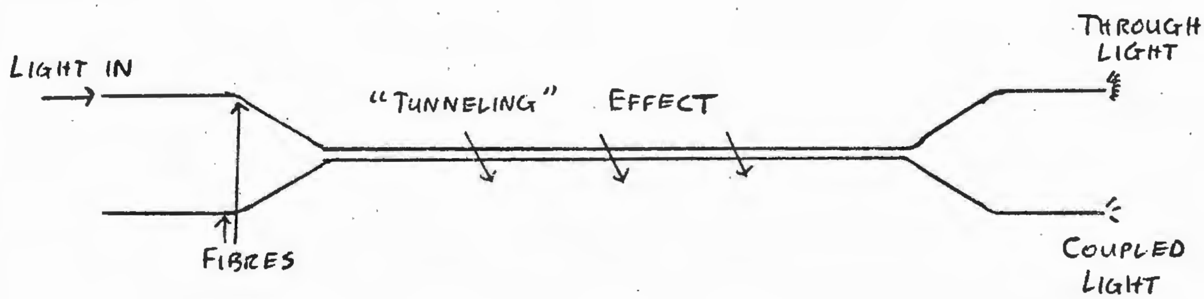

FIG. 4 Power sharing between close parallel optical fibres

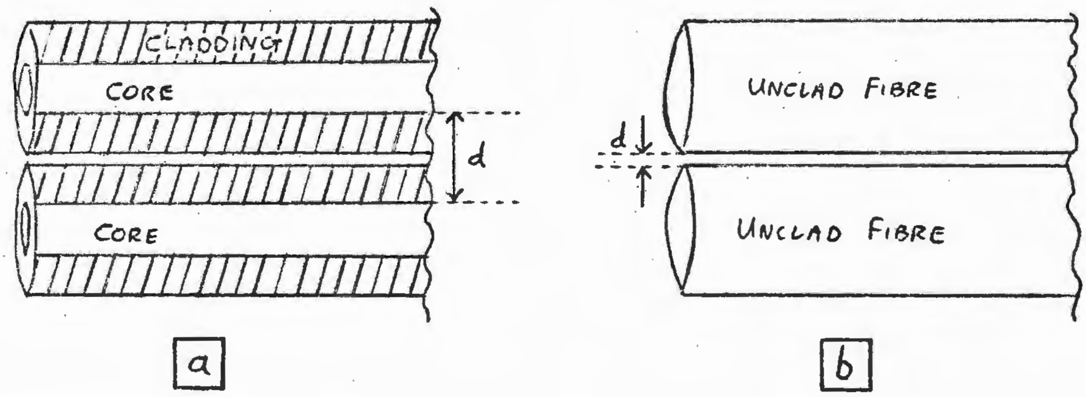

FIG. 5 Comparison between close parallel fibres, a) clad and b) unclad, highlighting the separation d between light guiding regions for each case.

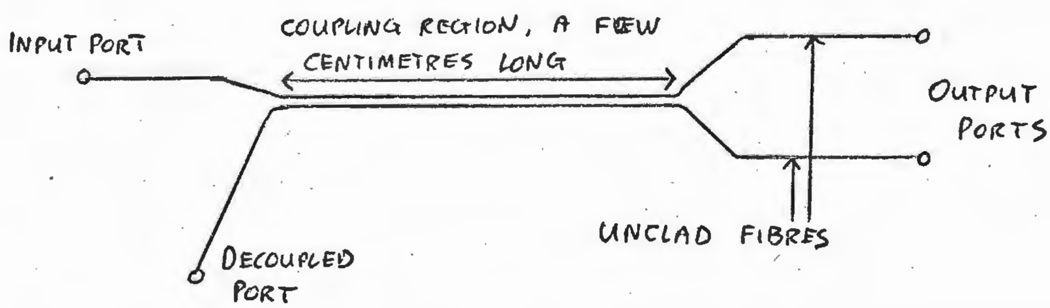

FIG. 6 A directional coupler using coupling between unclad optical fibres.

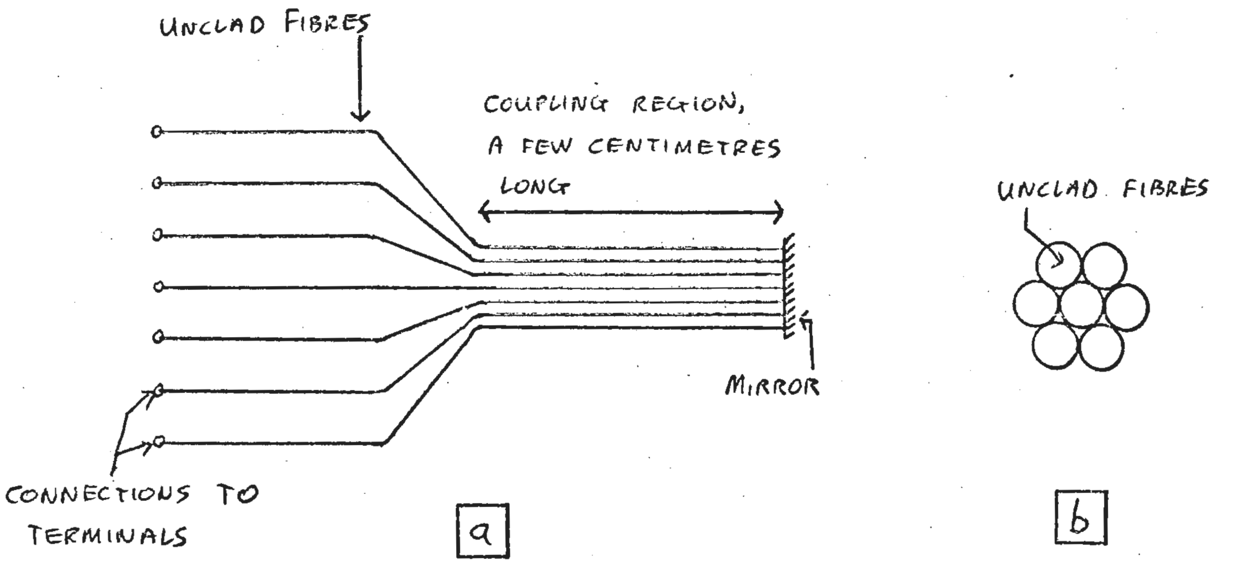

FIG. 7 A star coupler using coupling between unclad optical fibres. a) Schematic view. b) Cross section of coupling region.

Measurements of this coupling using clad fibres have been made, and indeed a directional coupler using close parallel clad fibres has been suggested (8) but the amount of power transfer recorded is only 50 dB (10^{-3}%). It is suggested that the use of unclad fibres would improve this figure very significantly. This can be seen from Fig. 5, which contrasts close parallel clad and unclad fibres, since the amount of power transfer involved is intuitively dependent on the separation between the light guiding regions of the fibres, (for theoretical confirmation of this see Section 2, and for experiment confirmation see Section 4). In Fig. 5a (clad fibres) the separation between the light guiding region (core) of the fibres is seen to be greater than the similar separation for unclad fibres (Fig. 5b) by an amount equal to twice the cladding thickness, since the whole of the cross section of the unclad fibre is used to guide light. Hence we conclude, intuitively, that the coupling between close parallel unclad fibres will be much greater than for clad fibres.

It is suggested that there would be no problem in inserting a device made with unclad fibres into a more standard system using clad multimode fibres. This matter is discussed in Section 5.

The layout for a directional coupler and for a star coupler using this principle is shown in Figs. 6 and 7 respectively. In the directional coupler of Fig. 6, light entering at the input port is distributed to the two output ports as required. The decoupled port can be used to monitor the signal. The star coupler of Fig. 7 involves a hexagonal array of fibres since this is the arrangement which gives maximum mutual contact between the fibres, and hence best power sharing. Incident light power from one terminal is shared with the fibres from the other terminals in the region of contact, or coupling region, and is then reflected from the end-face mirror and is distributed to all the other terminals as required.

The two fundamental parameters which limit the usefulness of optical couplers are the amount of power transfer (which we shall call "coupling efficiency") referred to above, and the insertion loss. The insertion loss is a measure of the power lost from a system due to the addition of the coupler. It is suggested that, using unclad fibres, not only will the coupling efficiency be high, but also the insertion losses of the couplers will be very low.

Neither a directional coupler not a star coupler have previously been reported using unclad fibres. Previous attempts using clad fibres have shown very poor coupling efficiency, but low insertion loss ("almost negligable" for directional coupler (8), and 2.8 dB for 4-fibre star coupler using tapered fibres (6)). Summarising, it is suggested that, using this principle of coupling between unclad fibres, the coupling efficiencies recorded in previous work will be greatly improved upon and the insertion losses will be at least matched, if not improved upon, for both directional and star couplers.

1.4. Arrangement of Report

This report is arranged as follows. Section 2 investigates the theory of coupling between unclad fibres, showing that it should be possible to build successful devices using this principle. In Section 3 the laboratory manufacture of test devices is considered. Section 4 quotes some results of the tests on these couplers and Section 5 discusses the implications of these results. The conclusions are presented in Section 6.

2. THE COUPLING BETWEEN UNCLAD OPTICAL FIBRES - THEORY

Ray or Mode Technique?

Ray theory has been used to calculate the coupling between close parallel optical fibres (9,10) but the analysis is rather tedious. Also mechanisms such as the coupling back from the unilluminated fibre to the illuminated fibre are neglected using this method, and hence the results are inaccurate.

Here we will investigate a coupled-mode approach. It has been shown (11) that only the coupling between like modes is significant. For a multimode system, as is the one considered here, the power transfer is given by the summed effect of the coupling between particular modes. Snyder and McIntyre (12) have carried out this summation (by converting it into an integration) and we use their results here.

2.1. Illumination Conditions

The amount of coupled power depends on the illumination conditions, in addition to the arrangement and physical properties of the fibres. Although we are using a mode analysis to calculate the coupled power, here we use ray concepts to describe the illumination of the fibre. The validity of this assumption is discussed in Section 2.6.

We assume that a beam of light is focused on the fibre axis as shown in Fig. 8, so that only the HE_{1m} modes are excited, i.e., those modes corresponding to meridional rays. The amount of light that enters the fibre is characterised by the radiant intensity distribution D (θ), i.e., the power per unit solid angle, where θ is the inclination of a ray to the fibre axis. We here consider two forms of D (θ) as illustrated in Fig. 9.

a) D (θ) is a step function, i.e.,

$$D(\theta) = \begin{cases} 1 & \theta < \theta_m \\ 0 & \theta > \theta_m \end{cases} \qquad \text{(1)}$$

This corresponds to an "ideal" optical system.

b) D (θ) is a Gaussian function, i.e.,

$$D(\theta) = e^{-\left(\frac{k\theta}{\theta_m}\right)^2} \qquad \text{(2)}$$

This corresponds to an imperfect optical system, with, for example, an imperfect lens or non-uniform incident beam.

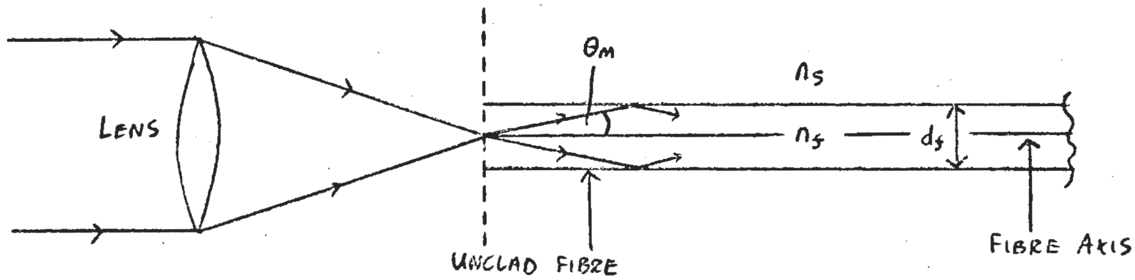

FIG. 8 Illumination of the fibre. The unclad fibre has a circular cross section of diameter d_f and refractive index n_f. n_s is the ref. index of the surrounding medium.

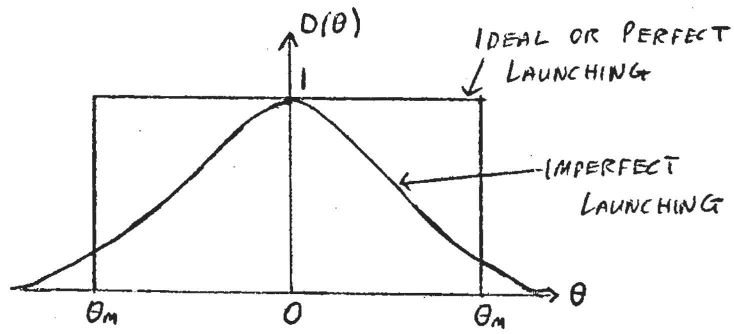

FIG. 9 The intensity distribution $D(\theta)$ of the light launched into the fibre as a function of θ, the inclination of a particular ray to the fibre axis. θ_m is defined in Fig. 8.

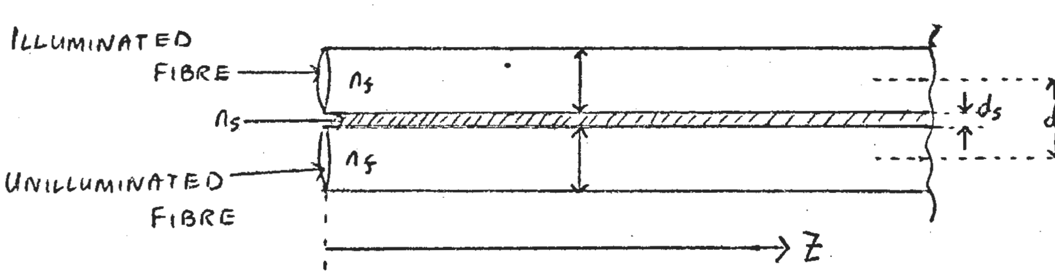

FIG. 10 Two identical parallel unclad fibres of diameter d_f and refractive index n_f. d_c is the centre separation, d_s the fibre edge separation, and n_s the ref. index of the surrounding medium. Z is the position along the fibre axis.

θ_M is the maximum ray angle able to be launched by the illumination system, as shown in Fig. 8.

K is a constant depending upon the particular imperfections of the launching system.

2.2. The Coupling Results for Two Identical Fibres

Assuming that one of the two identical fibres shown in Fig. 10 is illuminated as in Fig. 8, the coupling efficiency is given by (12)

$$C \equiv \frac{P}{P_{in}} = \frac{1}{2}\left(1 - \frac{\sin L}{L}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

for the perfect optical system characterised by eqn. 1, and by

$$C \simeq \frac{P}{P_{in}} = \frac{1}{2}\left(\frac{L^2}{L^2 + K^4}\right) \qquad K^2 \geqslant 1{\cdot}5 \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

for the imperfect optical system characterised by eqn. 2. (see also Fig. 9).

The dimensionless length L is given by

$$L = \left\{ \frac{4 \sin\theta_c}{d_f} \left(\frac{\sin\theta_M}{\sin\theta_c}\right)^2 \frac{e^{-2V(D-1)}}{(\pi V D)^{1/2}} \right\} z \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where:-

P = power transferred to unilluminated fibre

P_{in} = power into illuminated fibre

θ_c = critical angle of fibre with surrounding medium of refractive index n_s

d_f = diameter of fibre

V = normalised frequency = $\dfrac{\pi d_f n_f \sin\theta_c}{\lambda}$ .. (6)

n_f = refreactive index of fibre

λ = wavelength of incident light

D = $\dfrac{d_c}{d_f}$ .... (7)

where d_c is centre separation of fibres (see Fig. 10)

z = position along fibre axis or length of coupling region

θ_M is as shown in Fig. 8. Depends on launching lens.

2.3. Manipulation of the Results

Equations 3, 4 and 5 give us the theoretical coupling efficiency for two identical close parallel unclad optical fibres as a function of launching conditions, and the arrangement and physical properties of the fibres. The aim of this section is to present these results in a more useful way, clearly showing the effect of each important parameter on the coupling.

Owing to the presence of the exponential in equation 5, the dominant variables are the normalised frequency V (defined in equn. 6) and D (defined in eqn. 7) which refers to the separation of the fibres. Now V is dependent on the critical angle θ_c of the fibre and its surround, which in turn depends on the refractive index difference Δ between the fibre and its surrounding medium. Clearly also of great importance is the length of the coupling region z. The effects of refractive index difference $\Delta (\equiv n_s - n_f)$, the fibre edge separation $d_s (\equiv d_c - d_f)$ and the coupling length z on the coupling efficiency are illustrated in Figs. 11, 12 and 13 (for meaning of symbols see Fig. 10). The constants, relevant to the experiments performed in this laboratory, which are used to compute these curves are:-

$$d_f = 100 \mu m$$
$$n_f = 1.548$$
$$\lambda = 633 \text{ nm (He-Ne laser)}$$

To see most clearly the effect of Δ and the fibre separation d_s on the coupling, the curves of Figs. 11 and 12 are plotted for a nominal coupling efficiency of 25%. This is the order of figure that would be desirable for a practical directional coupler. The length of coupler that is necessary to give this result can then be found for different Δ (i.e. different surrounding media) and for different fibre separations directly from Figs. 11 and 12. These curves can be generalised to apply to other coupling efficiencies by using them in conjunction with Fig. 13, multiplying the coupling lengths shown on Figs. 11 and 12 by the relevant conversion factor shown on Fig. 13. As they stand, Figs. 11 and 12 refer to the ideal optical launching condition (using eqn. 3), but the effect of the imperfect launching system (using eqn. 4) is included in Fig. 13. Curves are shown for two typical values of K (as defined in eqn. 2).

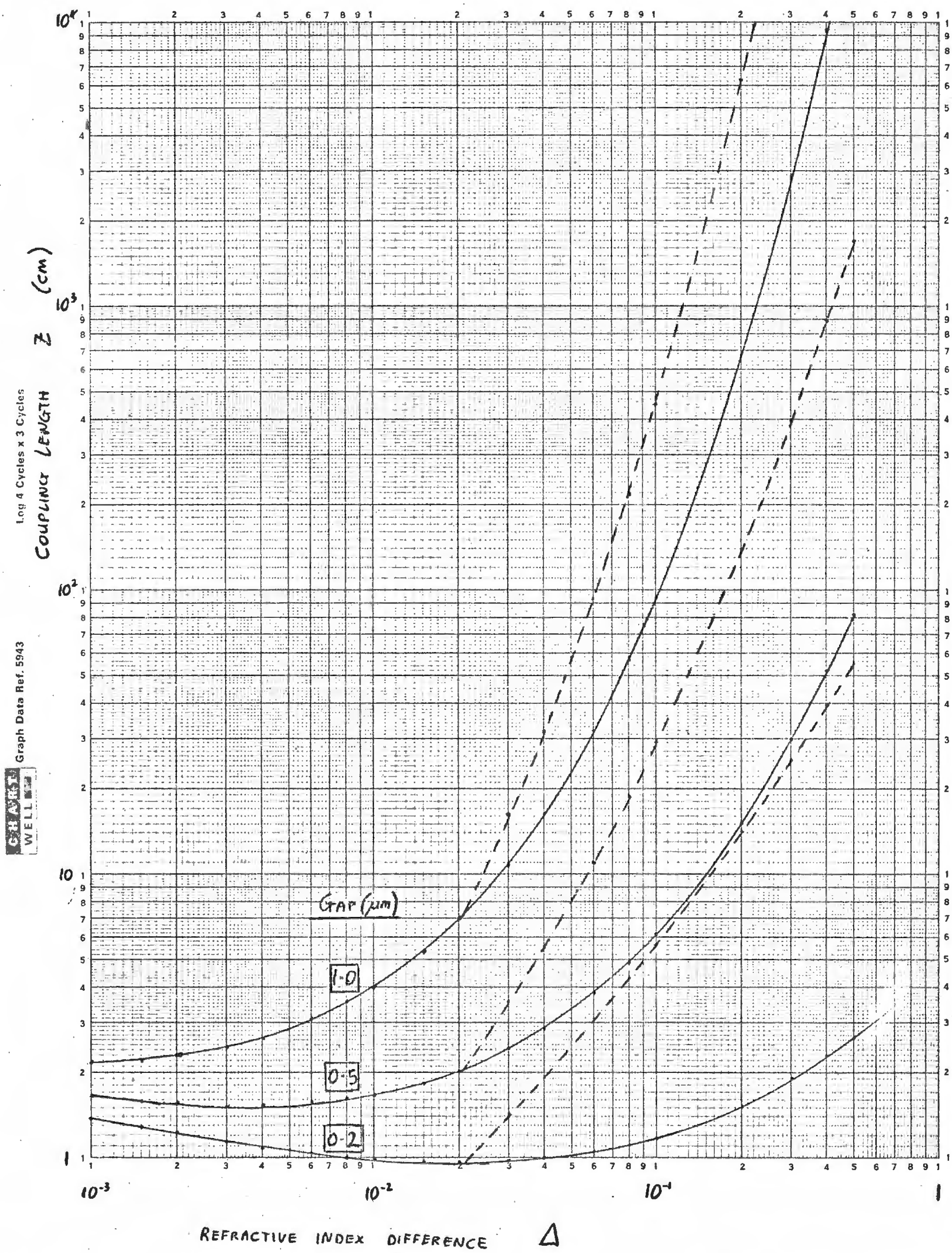

Fig. 11 The effect of refractive index difference (and gap or fibre separation) on the coupling length necessary to give a coupling efficiency of 25%. The dashed lines (----) show the effect of a launching system of numerical aperture 0·25.

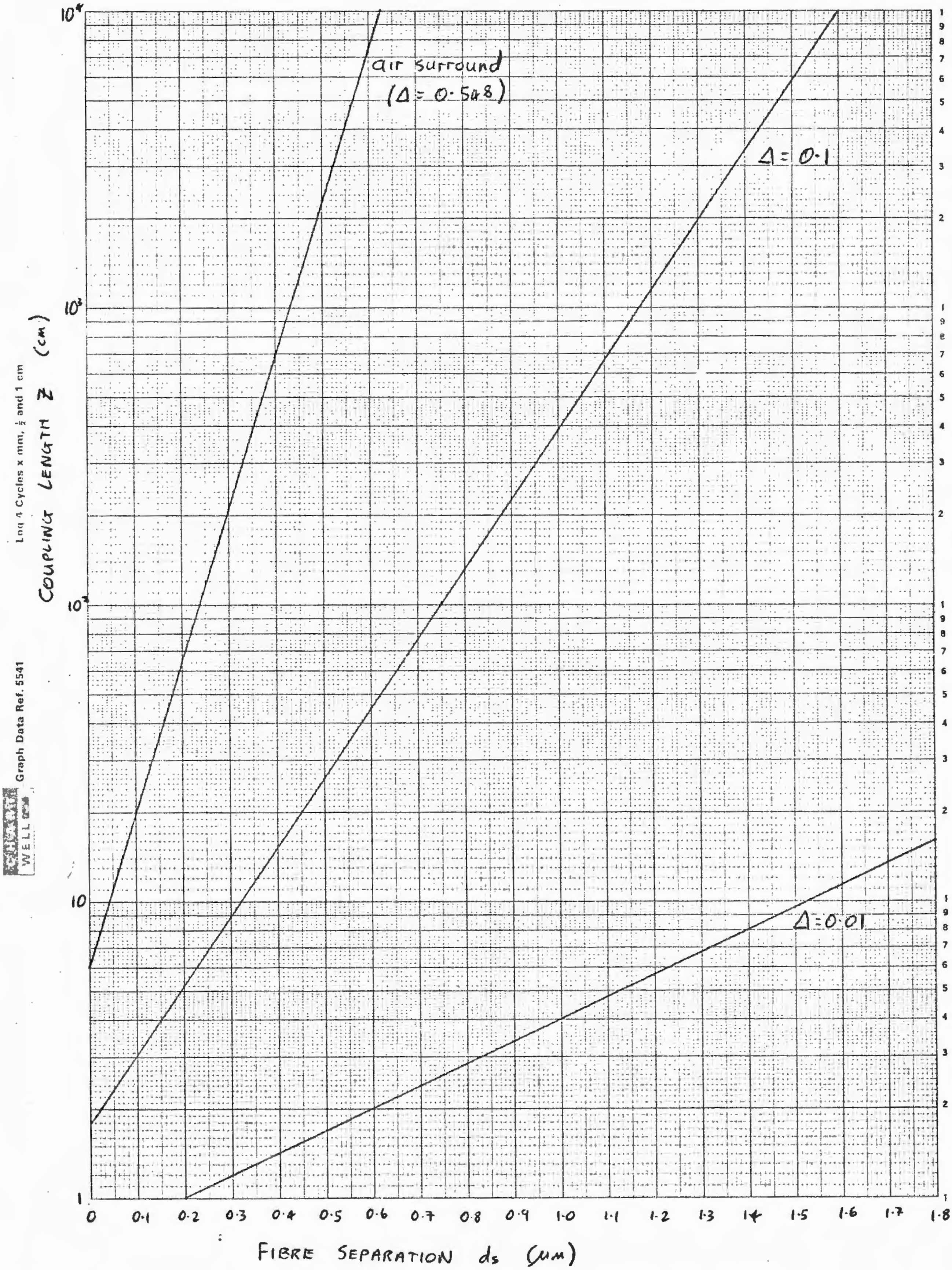

FIG. 12 The effect of fibre separation (and index difference Δ) on the coupling length necessary to give a coupling efficiency of 25%

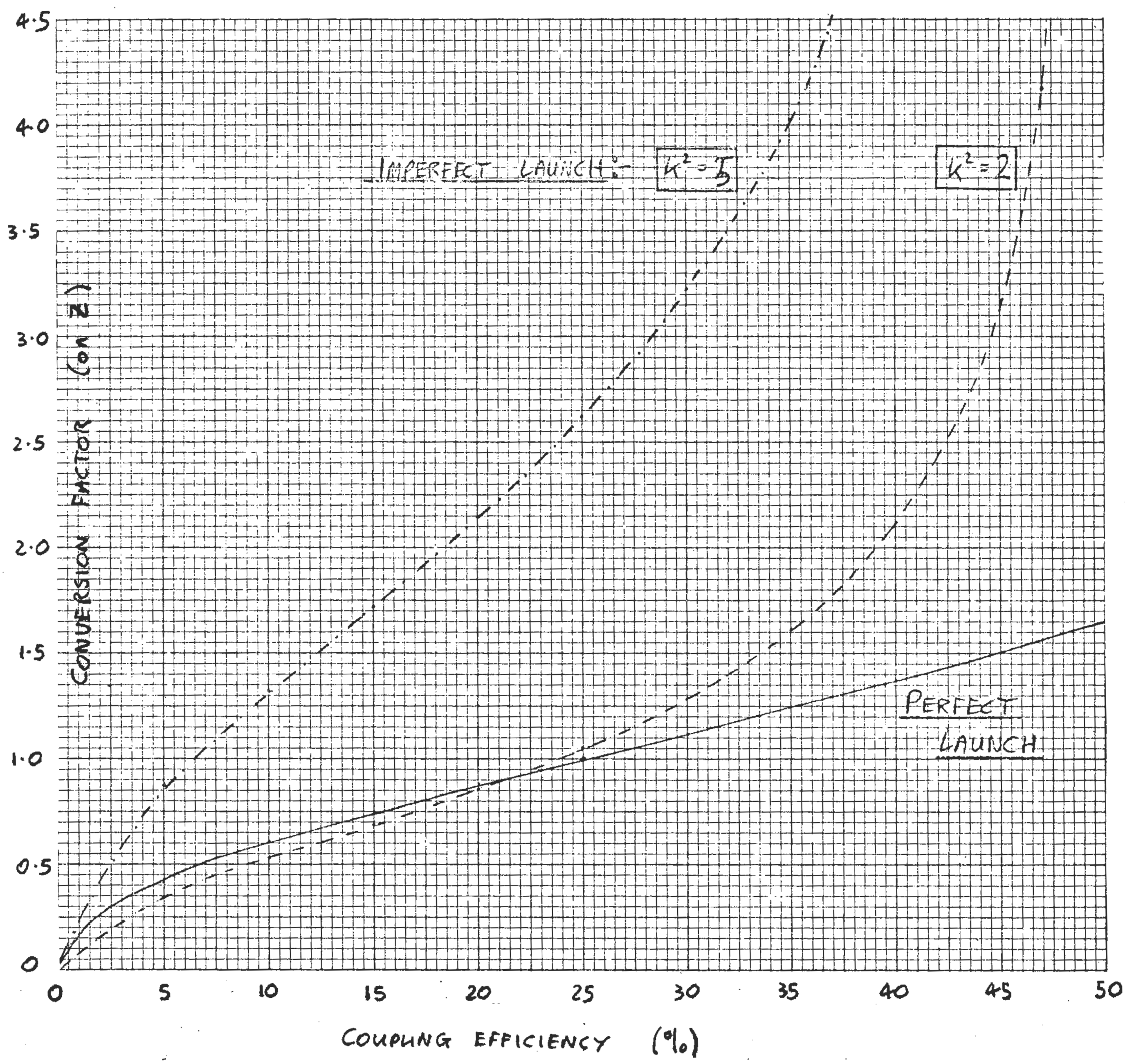

FIG. 13 Conversion factor (on necessary coupling length) to convert Figs 11 and 12 to apply to different coupling efficiencies, for case of perfect launch (——) and imperfect launch with $k^2 = 2$ (– – – –) and $k^2 = 5$ (–·–·)

An added feature of Fig. 11 is that it shows the effect of a particular launching system what cannot launch rays at a greater angle to the fibre axis than a certain θ_m (see Fig. 8). The launching system chosen here (with a numerical aperture of 0.25) corresponds to the lens system used in the laboratory for experimental work (see Section 4.2.). The implications of this launching restriction are best seen by considering the relationship between the θ_m which the launching system is capable of producing, and the θ_c (critical angle) relevant to the refractive index difference Δ between the fibre and its surrounding medium. For small Δ (i.e. small θ_c) all the guided HE_{1m} modes of the fibre arrangement are excited by the launching system (i.e. $\theta_c \leq \theta_m$). For $\theta_c > \theta_m$ (larger Δ) not all the guided HE_{1m} modes of the fibre arrangement are excited and hence a modified coupling curve is required, shown by a dashed curve in Fig. 11. The complete curve of Fig. 11 represents the case where all the guided HE_{1m} modes of the fibre arrangement are excited, i.e. $\theta_m \geq \theta_c$. Fig. 12 incorporates the effect of the launching system in the curves shown.

A brief inspection of Figs. 11 and 12 points to some important implications to the manufacture of a directional coupler using unclad fibres. The fundamental observation is that a successful device appears to be a possibility, i.e. a 25% (say) coupling efficiency is obtainable in a few centimetres of coupling length. This is subject to conditions which are not ridiculous or unobtainable in the laboratory, namely:-

a) For $n_s = 1$ (air surround), i.e. large Δ, the fibre separation needs to be very small ($\leq 0.1\mu m$).

b) For index-matched surround (e.g. $\Delta \leq 0.01$), the fibre separation needs to be small ($\leq 2\mu m$) but is not so critical.

2.4. The Effect of Non-identical Fibres

The effect of the fibres being slightly unequal in diameter is now considered. The amount of power transfer between two parallel fibres is acutely sensitive to their diameters. If their diameters differ by a small amount Δd_1, then the "maximum coupling efficiency factor" F is given by (12)

$$F = \frac{1}{1 + X^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where

$$X = \frac{1}{2}\left(\frac{\Delta d_f}{d_f}\right)(\pi V D^3)^{1/2}\ e^{2V(D-1)} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

The coupling efficiency is then given by equations 3 and 4 with $\frac{P}{P_{in}}$ multiplied by F and L replaced by $L/\sqrt{F}$.

The effect of unequal diameter fibres is shown in Fig. 14. The curves are plotted for a nominal value of F, F=0.5 (i.e. maximum possible coupling efficiency is 25%). The graph may be interpreted as "the maximum tolerable variation in diameter $\left(\frac{\Delta d_f}{d_f}\right)$ for particular arrangements of the fibres (Δ and separation)". Roughly speaking, if the value of $\frac{\Delta d_f}{d_f}$ shown on the graph is multiplied by 3 or more, then the coupler is no longer useful (i.e. $0 < F \leq 0.1$) and if the value of $\frac{\Delta d_f}{d_f}$ is divided by 3 or more the effect of the variation in diameter can be neglected (i.e. $1 > F \geq 0.9$). More fully, Fig. 15 shows the relevant conversion factor for $\frac{\Delta d_f}{d_f}$, for different values of F.

Again a brief inspection of Fig. 14 leads to some implications to the manufacture of a directional coupler. The main observation is that the fibres need to be almost identical for significant power transfer. Some rough figures for this are:-

a) For large Δ the maximum tolerable diameter variation is around 0.001%.

b) For small Δ the maximum tolerable diameter variation is around 0.1%.

2.5. Hexagonal Array of Fibres

The star coupler to be investigated involves coupling in a hexagonal array of fibres. The theory for two fibres can easily be modified to apply to a hexagonal array of seven fibres. The comments made at the end of the previous two sections referring to directional couplers are also relevant here, but the numerical value of the coupling is modified.

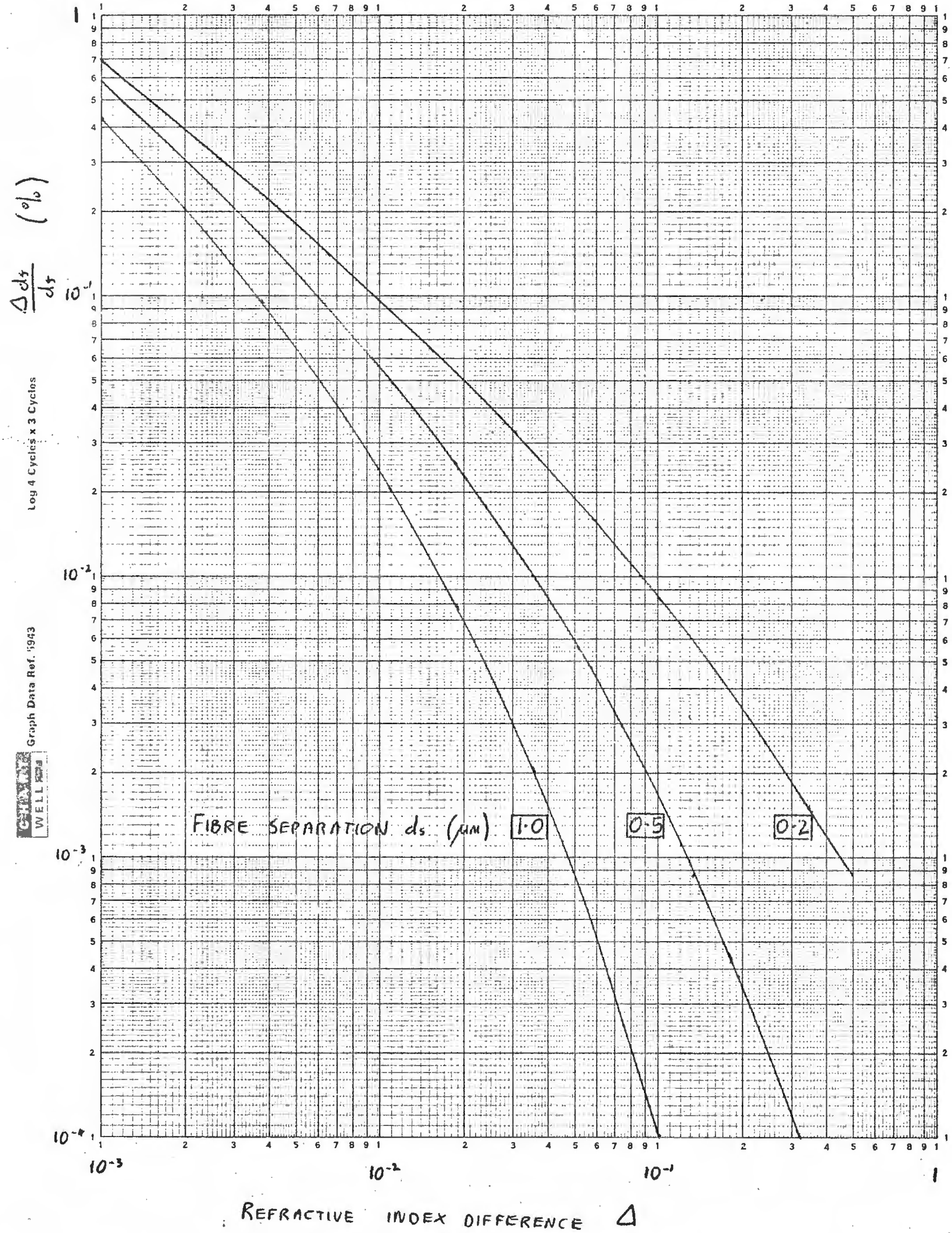

FIG. 14 The variation in fibre diameter $\left(\frac{\Delta d_s}{d_s}\right)$ necessary to reduce the maximum coupling efficiency by half, versus the index difference Δ.

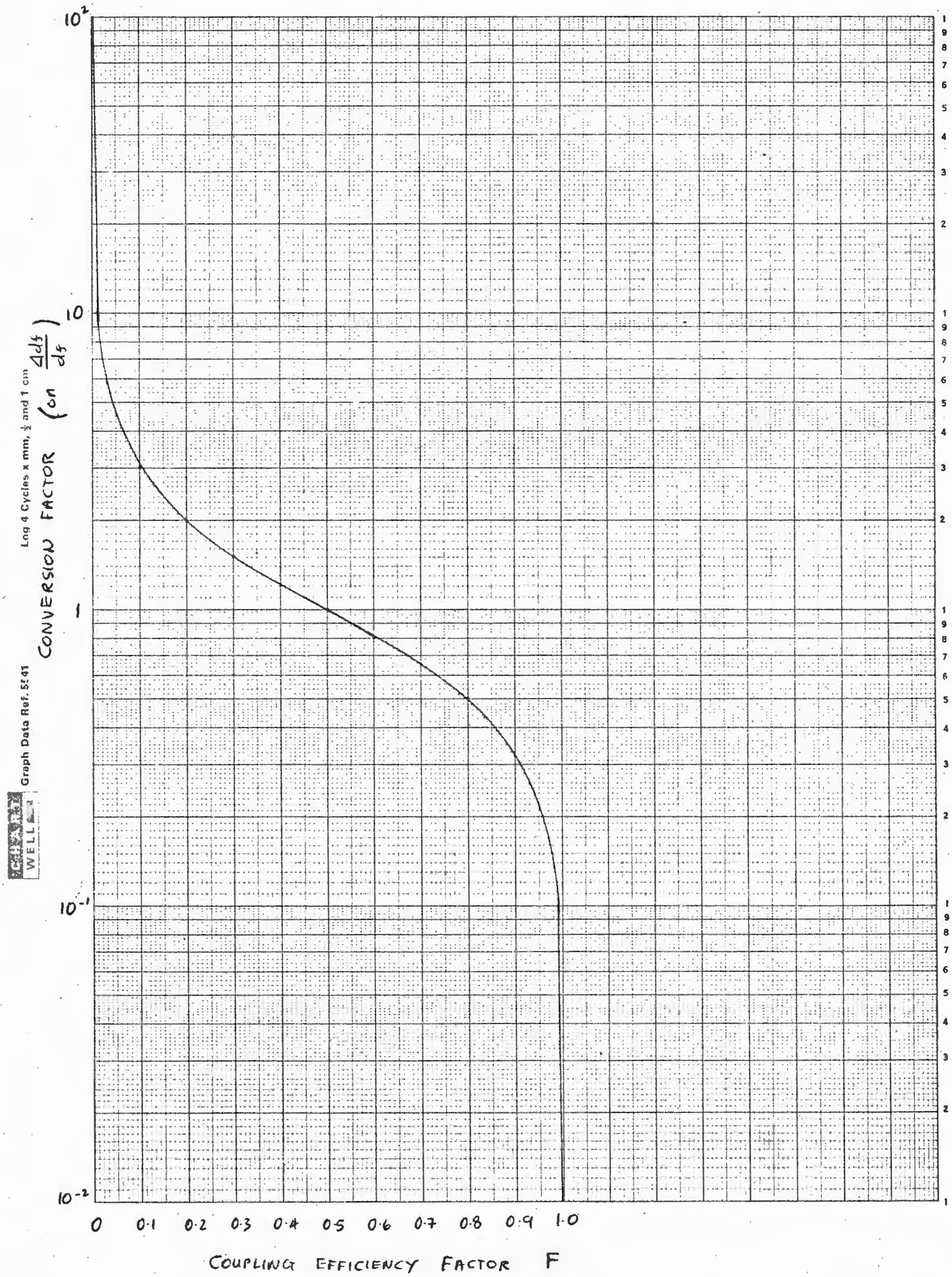

Fig. 15 The required factor (on $\frac{\Delta d_f}{d_f}$) to convert Fig. 14 to apply to different values of "maximum coupling efficiency factor" F.

If the centre fibre is illuminated, the coupled power is distributed evenly among the other six fibres and the coupling efficiency to each is given by (11,12)

$$C' \equiv \frac{P'}{P_{in}} \doteq \frac{1}{7}\left(1 - \frac{\sin\sqrt{7}\,L}{\sqrt{7}\,L}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

(a modified version of eqn. 3) for the perfect optical launching system, and by

$$C' \equiv \frac{P'}{P_{in}} \doteq \frac{1}{7}\left(\frac{7L^2}{7L^2 + K^4}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

(a modified version of eqn. 4) for the imperfect launching system.

C' = modified coupling efficiency
P' = power transferred to one of the unilluminated fibres.

In this case the maximum possible coupling efficiency to each fibre is 14.3%. Figs. 11 and 12 can easily be modified to apply to the hexagonal array condition:- if the coupling length shown is divided by a factor of 1.6, then the curves apply to the condition for maximum coupling efficiency, i.e. 14.3%.

2.6. Discussion of Approximations Made

The fundamental approximations made in this section, and their justifications, are as follows:-

1) The launching is such that only the HE_{1M} modes, those corresponding to meridional rays, are excited, i.e. no skew rays are launched.

   This necessitates that the incident light is focused exactly on the fibre axis and that the launching lens is exactly perpendicular to the fibre end-face. This is hard to achieve perfectly in the laboratory, but since the coupling between skew rays is intuitively less than the coupling between meridional rays, and only few skew rays are launched, this approximation can be justified.

2) Ray concepts can be applied to launching of light down the fibres.

   This is justified when the normalised frequency $V \gg 1$. Now V is dependent of the refractive index difference Δ

Some values of V for different Δ are quoted in Table 1 to see if we are justified in this approximation. Table 1 shows that if this approximation significantly breaks down, it would be for very small values of Δ .

This error could be the source of the unexpected trend shown in Fig. 11 for small values of Δ and small fibre separation, namely the apparent increase in coupling length as Δ is reduced.

good!

3) The incident light radiant intensity distribution is characterised by either a step function (ideal case) or a Gaussian (Imperfect launching case). See Fig. 9.

   It is possible that the distribution is neither a step function nor a Gaussian. Nevertheless, if the launching is not perfect, it is suggested that a value of K (see eqn. 2) could be chosen to give a Gaussian approximation which is near enough to the actual distribution.

4) The unclad fibres are embedded in an infinite medium of refractive index n_s .
   In practice, this is not the case as will be seen in Section 3. We define n_s as the refractive index of the region directly between the fibres, as shown in Fig. 16a. We assume that Fig. 16b is an approximation to Fig. 16a. This is valid since nearly all the coupling takes place in the region directly between the fibres. A point worth noting here is that the number of guided modes of the fibre is limited by n_0 or n_s , whichever is the smaller. This point is raised in Section 4.1.

5) Much of the mathematics is simplified (12) by making the same basic assumption as that in assumption 2 listed above, i.e. $V \gg 1$.

   The validity of this is discussed with assumption 2.

We conclude from these discussions that the errors in the results in this section will be small.

Refractive index difference Δ	Normalised frequency V
0·548 (air surround)	590
0·1	274
0·01	88
0·001	28

TABLE I Values of normalised frequency V for different ref. index difference Δ.

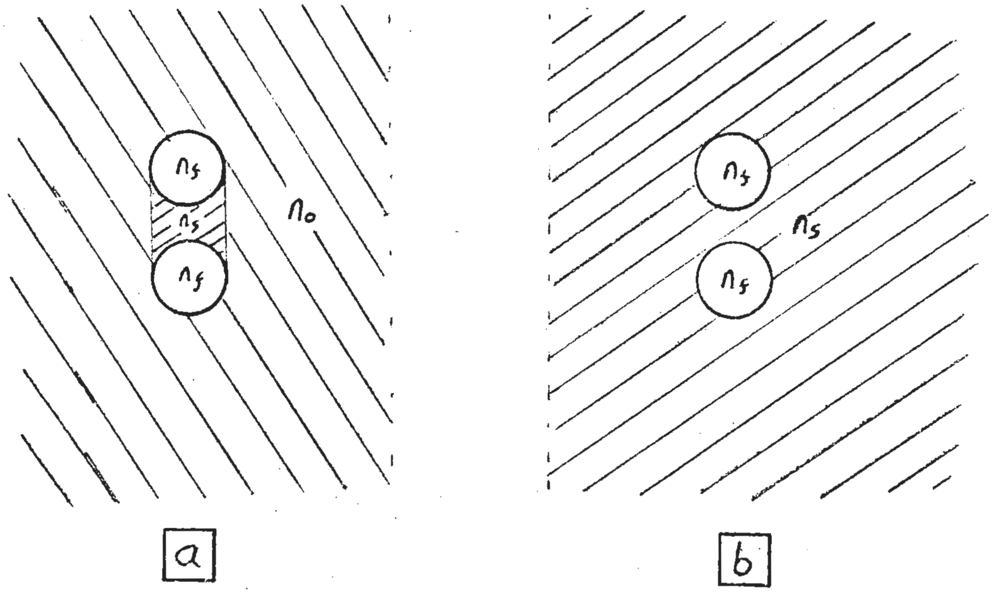

FIG. 16 a) Two fibres of refractive index n_f separated by a region of refractive index n_s. The surrounding medium is of refractive index n_o. b) Two fibres of refractive index n_f in an infinite region of refractive index n_s.

3. MANUFACTURE OF THE TEST COUPLERS

Section 2.3 outlined that the three most important controlable parameters which affect the coupling between unclad fibres are:-

a) fibre separation d_s

b) index difference Δ (Between fibre and medium between fibres)

c) coupling length z

Each of these needs to be taken into account when manufacturing a test coupling device. First we shall consider the manufacture of a directional coupler and then go on to the more complex star coupler (as described in Section 1).

3.1. The Directional Coupler

In the manufacture of the directional coupler (two fibres) the first difficulty to be overcome is that of maintaining a small fibre separation over a reasonable coupling length. This difficulty arises due to the small diameter of the fibres (about a hairbreadth) which makes them difficult to handle. Also care has to be taken not to scratch the fibres in manipulating them since this would cause them to lose light by scattering at the imperfect interface. Two methods of overcoming these difficulties were developed:-

a) The"Glue Method"

The first method uses the properties of a quick setting and free running glue (see Table 2).

Two fibres (see Table 2), each of about 50 cm in length (cut from a long length of unclad fibre by the "score and bend" proceedure to obtain good end faces), are cleaned and then suspended vertically together as shown in Fig. 17a. The fibres are held by a piece of plasticene at the top and a small weight (plasticene) of about 20g is attached to the fibres at the bottom in order to keep them taught. The glue is then applied along the required coupling length as follows:- A small V-groove is cut in the plastic applicator for the glue as shown in Fig. 17b. The groove is filled

Material	Type	Ref. Index	Diameter (μm)	
FIBRE	LLF1 Optical Glass	1·548	106	
GLUE	Permabond 101 Cyanoacrylate	1·45	-	
			internal	external
TUBING	"Portex" Nylon	1·53 [13]	330	620

TABLE 2. Materials used in manufacture of the directional coupler

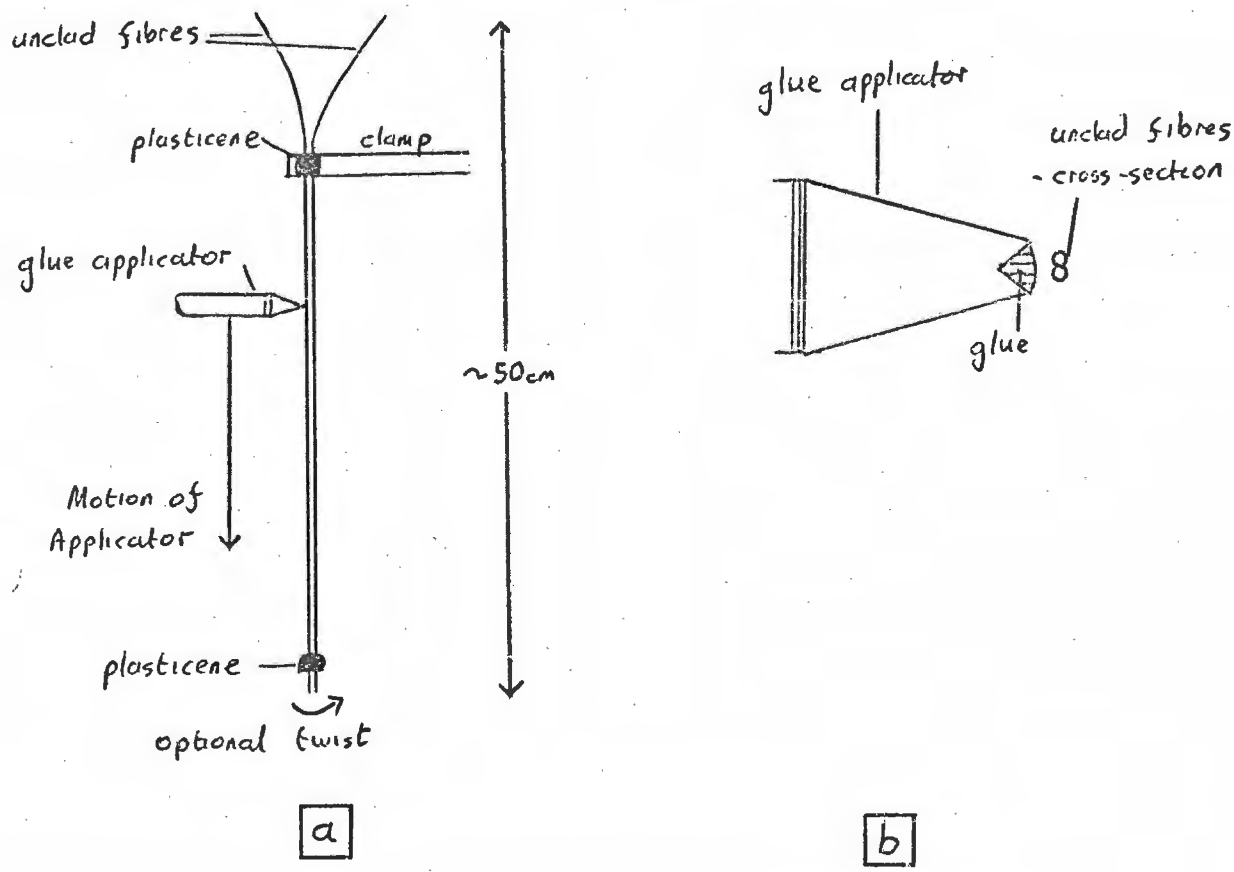

FIG 17. a) Apparatus for manufacture of directional coupler by "glue method". b) Close-up view of glue applicator showing V-groove and relative size of fibres.

with glue and is then placed around the fibres at the beginning of the required coupling region. The applicator is then drawn swiftly downwards over the fibres covering the desired coupling length. This length is easily variable between, say, 5cm and 25cm for test purposes. The surface tension of the glue tends to draw the fibres to each other and the glue, being free running, leaves only a very thin "cladding" around the fibres. It is also possible to twist the fibres together before glueing to see whether this might achieve a smaller fibre separation. Couplers were made with three different amounts of twist for test purposes:-

i) no twist

ii) slight twist, i.e. one complete twist every 4cm of coupling length

iii) large twist, i.e. one complete twist every 1cm of coupling length.

One restriction using this method of manufacture is that the surrounding medium to the fibres is of fixed refractive index (that of the glue), hence Δ is fixed.

Brief details of materials used here are shown in Table 2. The measured internal characteristics (fibre separation, index difference) of couplers made by this method are given in Section 4.1, and the coupling results obtained are given in Section 4.3.

b) <u>The "Nylon Tube Method"</u>

This second method of obtaining small fibre separation over the coupling length involves the use of small bore nylon tubing (see Table 2). Two fibres, each of about 30cm in length, are threaded through a piece of nylon tubing of a slightly greater length than the required coupling length, and are then mounted vertically as shown in Fig. 18. Most of the nylon tubing section (typically of length about 10cm, i.e.

coupling length about 7cm) is enclosed by a heating coil. The tube and the fibres are held by a piece of plasticene just above the heating section, as shown in Fig. 18. A small weight (plasticene) of about 20g is attached to the bottom of the nylon tubing section so that, when heat is applied, the tubing stretches and its diameter (both external and internal) shrinks, thus bringing the fibres inside the tube into contact. The heat is applied such that the tubing is softened rather than melted. The medium directly between the fibres in this case is air; it also is possible to insert liquids of different refractive index into this region when making measurements. The coupling length of test couplers made by this method is limited, by the size of the heater used, to about 8cm. Again details of materials used here are shown in Table 2 and internal characteristics and coupling results are given in Sections 4 and 4.3 respectively.

3.2. The Star Coupler

The manufacture of the star coupler involves the same basic difficulty as does the manufacture of the directional coupler, i.e. that of obtaining small fibre separation over the required coupling length. In this case the problem is more involved since a close-packed hexagonal array of seven fibres is required.

The method developed to achieve this array is the "nylon tube method" described above for the 2-fibre directional coupler. In this case tubing of larger internal diameter (500μm in place of 330μm) is used. The method is as described above (see Fig. 18) except that seven fibres are used and simultaneously thread through the required length of nylon tubing (again about 10cm) with care taken so that they are not twisted together. As the diameter of the tubing shrinks

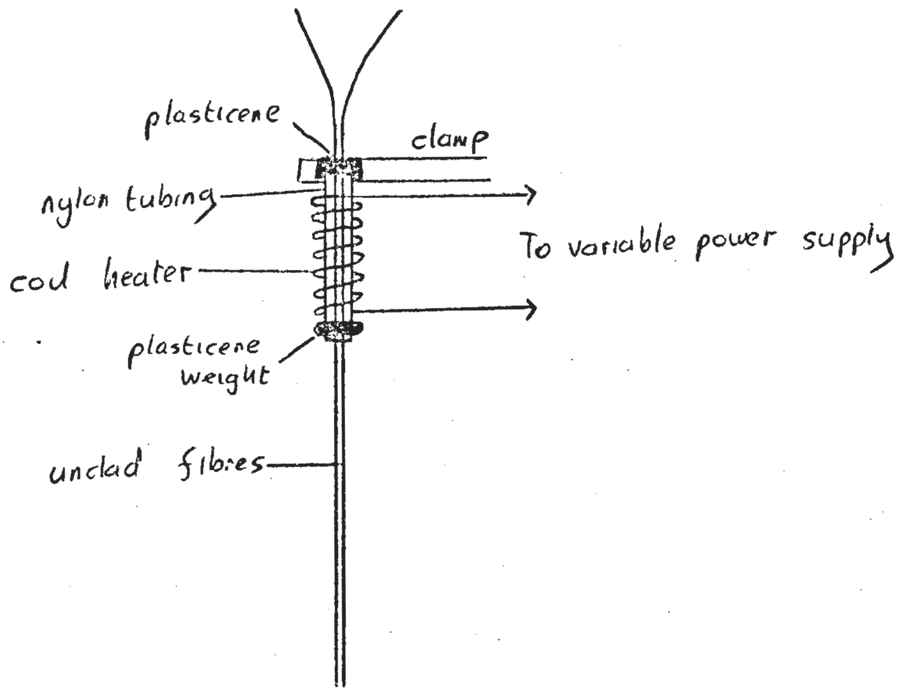

FIG 18 Apparatus for manufacture of directional coupler by "nylon tube method".

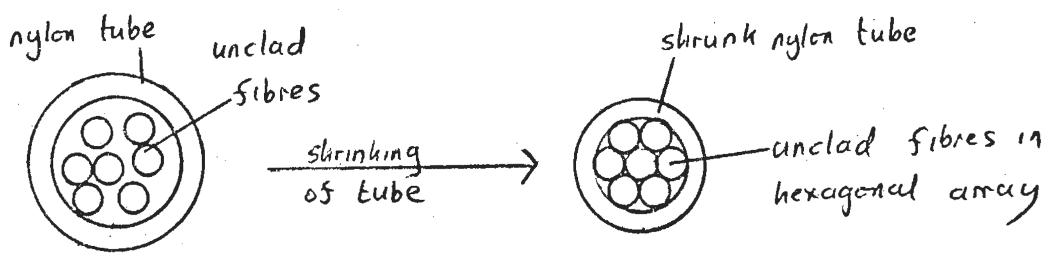

FIG 19. The formation of a hexagonal array of fibres by the shrinking of a surrounding tube.

an even radial force to the fibres, the fibres tend to be made to lie in the most closely-packed array (i.e. close-packed hexagonal) as illustrated in Fig. 19.

The coupling section of the device (i.e. the length enclosed by the nylon tube) is then mounted in epoxy between two microscope slides as shown in Fig. 20. Care is taken so that the epoxy (n=1.547) does not come into contact with the actual fibres (n=1.548) since owing to their similar refractive indices, this would result in the leaking away of most of the light power (the epoxy used is "Vitrolit" ultra-violet curing glue). The mounted device is cut (with a diamond saw) at the end of the coupling region (see Fig. 20) and the end is polished using silicon carbide and Jeweller's Rouge. A mirror, silvered on the front face, is then attached to the end of the coupler, as shown in Fig. 21, giving the device the properties of a star coupler as described in Section 1 (see Figs. 2 and 7). The mirror is held in position by the surface tension of an index-matching liquid (liquid paraffin, n=1.468).

The array obtained by this method in the laboratory is discussed in Section 4.1, and the coupling results for this coupler are given in Section 4.4.

Other possible methods of obtaining a close-packed hexagonal array considered were:-

a) Insertion of the fibres into a correctly sized glass tube (i.e. internal diameter is three times fibre diameter).

b) Carefully placing the fibres into a circular cross-section glass taper.

Method a) proved to be possible when using a tube of soft glass, but the refractive index of the soft glass was such (n=1.55) that none of the light could be guided by the fibres (n=1.548).

Method b) was abandoned due to the difficulty of practically carrying out the proceedure.

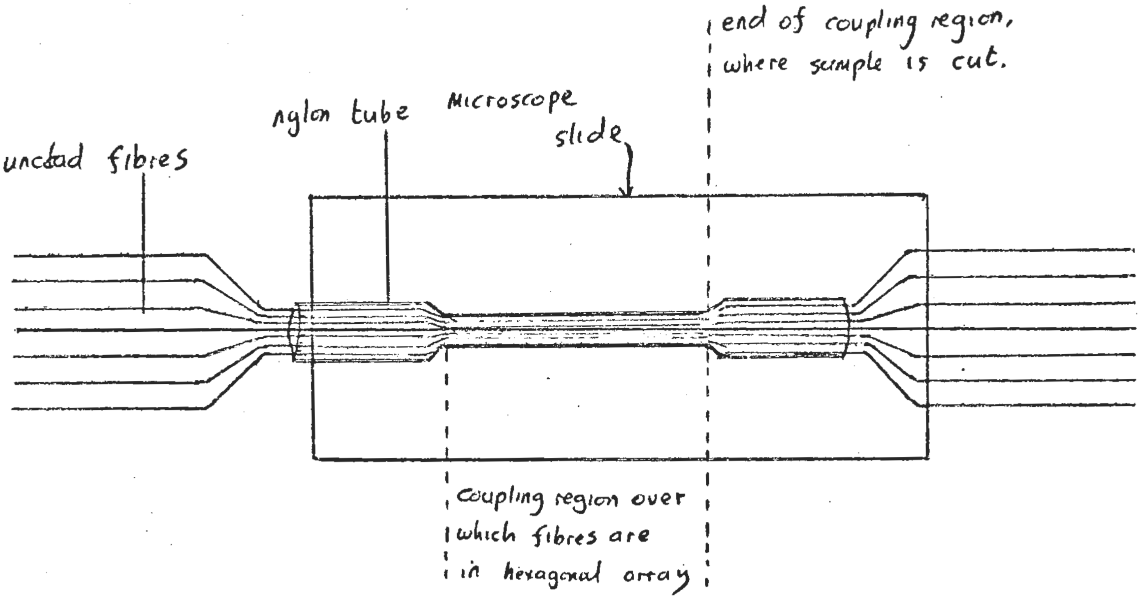

FIG 20. Hexagonal array of fibres mounted in epoxy between two microscope slides. Top view.

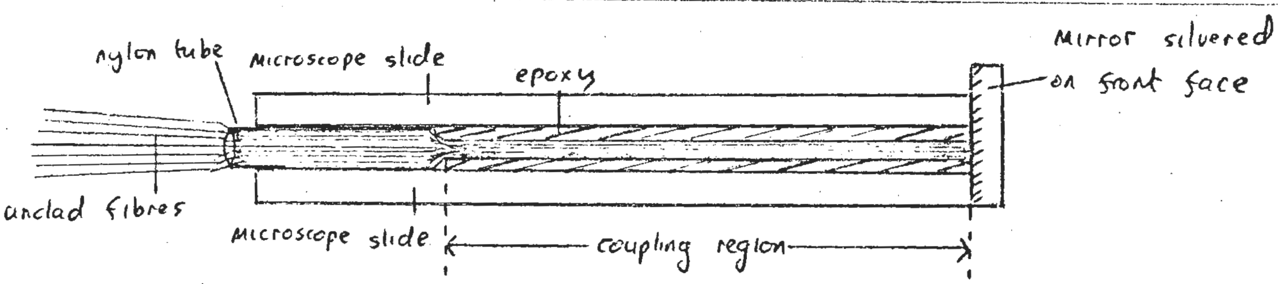

FIG. 21. The star coupler manufactured by the shrunk nylon tube method. Side cross-sectional view.

4. MEASUREMENTS AND RESULTS

In this section we quote the measurements made with the couplers described in Section 3, with a view to confirming the theoretical predictions of Section 2.

4.1. Internal Characteristics of the Couplers

a) The directional coupler

The fibre separation obtained for the directional couplers described in Section 3.1 is shown in the photographs of Figs. 22 and 23. A 100 μm scale is shown in Fig. 24 to show the dimensions involved. Fig. 22 shows a cross-section of a coupler made by the "glue method" described in Section 3.1. Fig. 23 shows one made by the "nylon tube method" described also in Section 3.1. The measured characteristics of these couplers are shown in Table 3.

The fibre separation quoted in Table 3 is found from measurements made on the photographs of Figs. 22 and 23. As would be intuitively expected, the fibre separation for the coupler made by the glue method is greater than for that by the nylon tube method; i.e. there must be some fibre separation for the glue method due to the layer of glue laying in between the fibres, whereas for the nylon tube method there need not be any fibre separation at all. The 0.5 μm quoted for the glue coupler represents the thickness of this glue "cladding" which forms around and in between the fibres. The fibre separation for the nylon tube coupler is immeasurably small as can be seen from the photograph of Fig. 23; i.e. the fibres do appear to be in contact.

The index difference Δ for the glue coupler is fixed. For the nylon-tube coupler, Δ can be varied by insertion of liquids of different refractive index into the region between the fibres. We now consider the light guidance properties of the nylon tube coupler.

Picking up the point mentioned in assumption 4 of Section 2.6 about the two different media which surround different areas of the fibre, as illustrated in Fig. 16a; the number of HE_{lm} modes guided by the fibre arrangement is limited by the refractive index of the nylon tubing. (n=1.53). In conjunction with the fibres (n=1.548) this

FIG. 22

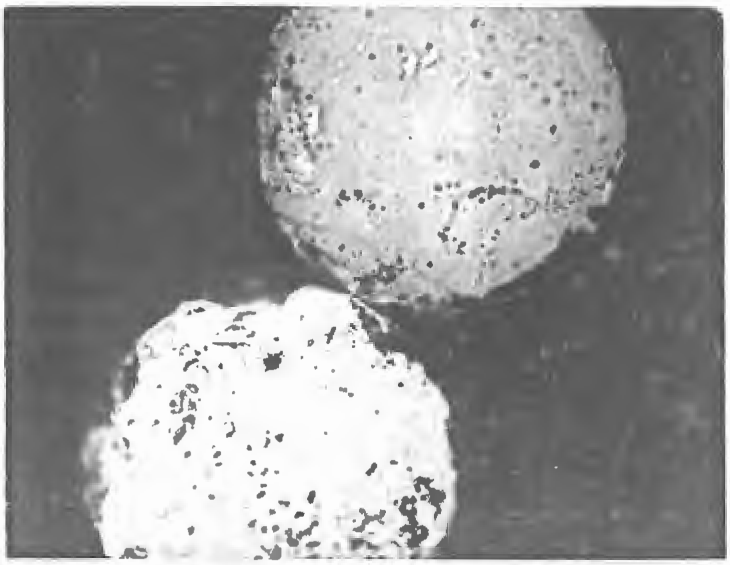

FIG. 23

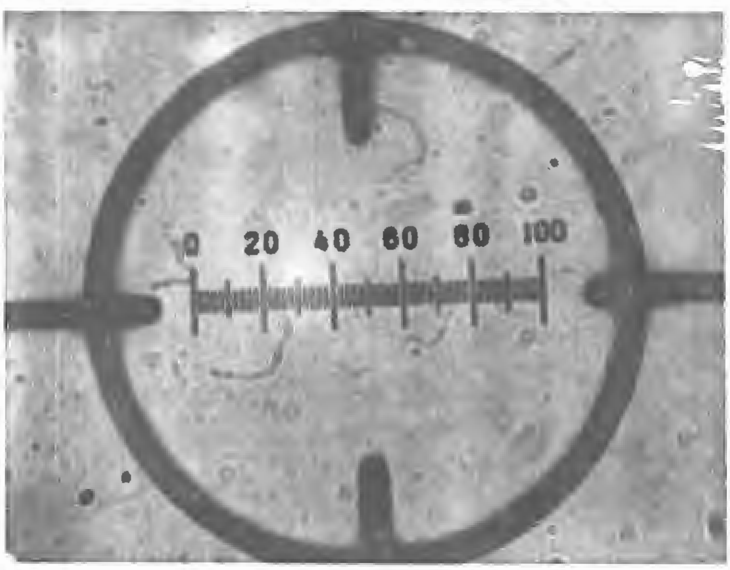

FIG. 24

A cross-sectional view of the two-fibre directional coupler made by the glue method (Fig. 22) and by the nylon tube method (Fig 23), with 100µm scale (Fig.24)

Manufacturing Method	Fibre Separation (μm)	Index Difference Δ	Coupling Length (cm)
GLUE	0·5	0·1 fixed	5 - 25
NYLON TUBE	< 0·2	0·5 & 8 (variable)	5 - 8

TABLE 3 Internal characteristics of the directional couplers

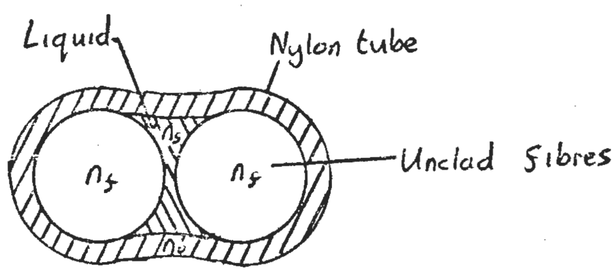

FIG. 25 Cross-section of directional coupler made by nylon-tube method after introduction of liquid of refractive index n_s into region between fibres (index n_f). The index of the nylon is n_0.

represents a numerical aperture of 0.24. The NA of the test launching system used is 0.25 and so we can assume that all the power from the launching system is guided by the fibre arrangement, neglecting any losses due to absorption in the nylon. We now consider the theoretical effect on the guiding properties of the arrangement of the insertion of a liquid of refractive index n_s into the region directly between the fibres, as shown in Fig. 25. The refractive index of the fibres n_f is 1.548 and that of the nylon n_o is 1.53. This effect depends on the value of n as follows:-

i) $1 \leq n_s \leq 1.53$

In this case nearly all of the power launched into the fibres is guided by the fibres themselves.

ii) $1.53 < n_s \leq 1.548$

In this case the light launched into the fibres is guided by the whole region enclosed by the nylon, including both fibres and the region between them. For n near to 1.53, only the higher modes are guided by the region between the fibres, but as n approaches 1.548 the light "sees" this region simply as a continuation of the fibre material.

A device made with such an n would have a higher insertion loss than one made subject to case i), since light power guided by the region between the fibres would be lost at the end of the device coupling region.

iii) $n_s > 1.548$

In this case, light would be guided by the region between the fibres in preference to the fibres themselves and this would result in a device with a high insertion loss.

b) The star coupler

The hexagonal array of fibres obtained by the method described in Section 3.2 for the star coupler is shown in Figs. 26, 27, 28 and 29.

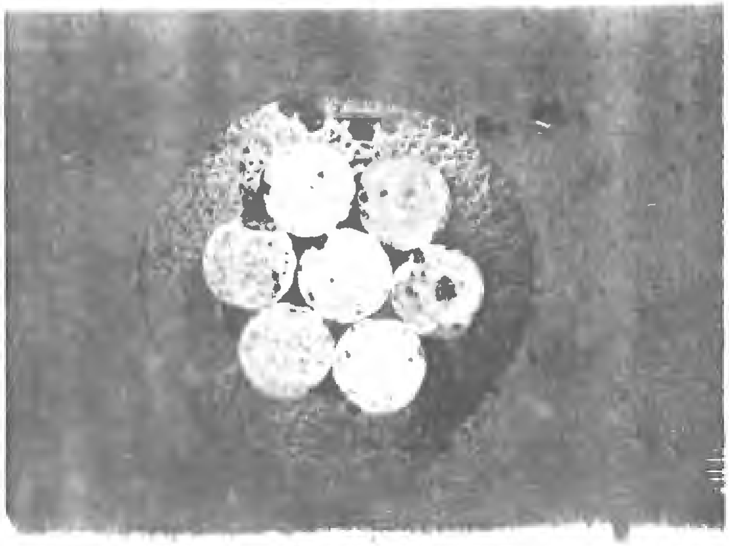

FIG. 28 Cross-section of star coupler 1cm along coupling length

FIG. 29 Enlargement of Fig 28 showing more clearly the fibre separation.

Fig. 26 shows the end view of a star coupler (without the mirror present) and Figs. 27 and 28 show the cross-section of the coupler further alongthe coupled length in order to show the uniformity of the array. Fig. 29 is an enlargement of Fig. 28 to show more clearly the fibre separation. This photograph shows that at that particular point the hexagonal array is not perfect. The fibre separation between some fibres is immeasurably small, whereas between others it is as much as 2μm. This difference is seen in the results quoted in Table 6.

Another important consideration is the uniformity of the hexagonal array from device to device. Several test couplers were made but owing to lack of time the number was not sufficient to be able to make conclusive assertions about the reproducability of the array. Nor was time available to make complete coupling measurements on each test device. Nevertheless the array of each test device was inspected and two out of five appeared (through the microscope) to be perfectly hexagonal, the others having one or two fibres badly misplaced. This matter is discussed further in Section 5.

The comments about light guidance made above referring to the nylon tube directional coupler also apply here to the star coupler.

A further characteristic of the star coupler is the reflectivity of the end-face mirror. The reflectivity of the mirror used in the test device was measured to be $>$ 99%.

The variation in diameter of the fibres used in both the directional and the star couplers is not known exactly but is known to be less than 0.02% per 10cm length (a typical coupling length). Here we assume that it is such that its effect is negligable, even for large Δ (i.e. variation in diameter $\leqslant$ 0.001% - see Section 2.4).

4.2. Coupling Measurement Procedure

The experimental arrangement of equipment used in the laboratory measurements of coupling efficiency and insertion loss is illustrated in Fig. 30.

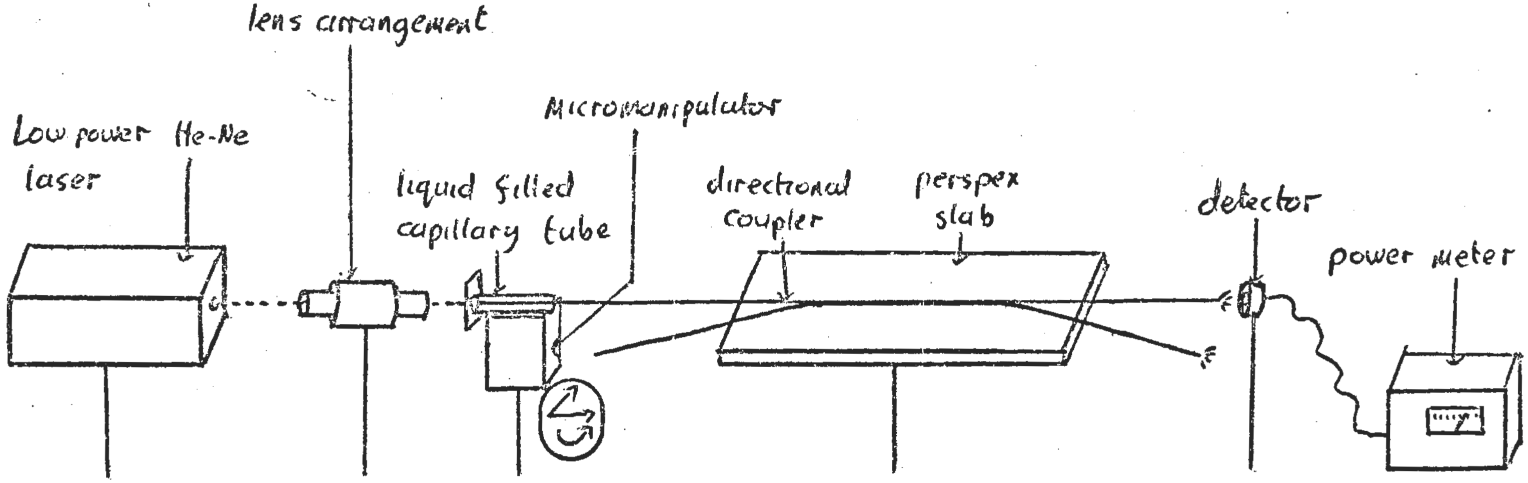

Fig.30 The experimental arrangement for coupling measurements

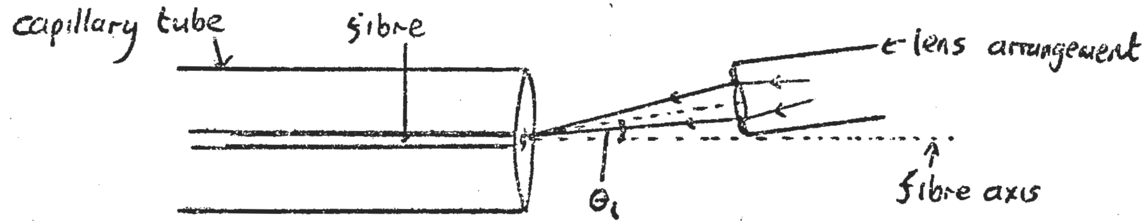

Fig.31 Launching of light down fibre (top view) showing angle of launch θ_i

The launching system consists of a low power He-Ne laser with a lens system (two x 10 microscope objectives) to give a numerical aperture of 0.25. This arrangement would excite all the guided HE_{1m} modes (those corresponding to meridional rays) of a fibre arrangement with an index difference Δ of 0.02 or less.

The fibre down which light is to be launched is mountedin a liquid filled capillary tube with a thin cover-slip on the end. The liquid used is liquid paraffin with a refractive index of 1.468. The capillary tube is mounted on a micromanipulator so that its position can be varied to make the fibre end lie exactly at the focus of the lens arrangement.

The angle of launch can also be varied in order to excite just the higher modes. It was seen, as intuitively expected, that coupling between higher modes (more steep ray paths) is greater than that between lower modes. For example a coupler made by the glue method of Section 3.1. which had a coupling efficiency of 14% with zero angle of launch θ_l (as defined in Fig. 31) had a coupling efficiency of 19% for 6° angle of launch, and 40% for 12° angle of launch. This mode dependency of the coupling is discussed further in Section 5.

The coupler itself is temporarily mounted on a perspex slab (see Fig. 30) for measurement purposes. The ref. index of perspex (n=1.492) is considerably less than that of the fibres, so that no light is lost where the fibres touch the slab. The light power is measured using a highly sensitive power meter and detector (Coherent Radiation Type, with large photodiode detector of area $\sim \frac{1}{2}cm^2$).

4.3. The Directional Coupler

As outlined in Section 1, two important parameters of the optical fibre coupler, are its insertion loss and coupling efficiency. Firstly we discuss the insertion loss of the directional coupler.

Although strictly speaking not the insertion loss of the device itself, the overall loss may depend on the system into which the device is inserted, since joints must be made between the coupler and the transmission fibres. However joints between similar fibres have been made with insertion losses as low as 0.25 dB (14) and we may therefore assume that similar losses can be expected when jointing fibres to coupling devices.

An attempt to measure the device insertion loss of the two-fibre directional coupler was made using the apparatus described in Section 4.2. The insertion loss was estimated by comparing the combined power from the two output ports of a test coupler with the output power from a single fibre of a similar length to the coupling device, the launching arrangements being the same for each case. In each test the combined power from the two output ports of the devices was about 300 μW ($\pm$10%), and the output power for a similar length single fibre was also 300 μW. Non-consistent launching conditions and end preparations (all made by the "score and bend" proceedure) prevented more definite results being quoted here. In all cases the light power out of the decoupled port (see Figs. 3 and 6) was immeasurably small (i.e. less than 0.1 μW). From this we conclude that the intrinsic loss of the coupler is very low, providing the fibre loss over a few cm is small. It was not thus possible to accurately determine the device insertion loss with the simple equipment available. However the loss could be estimated to be less than 0.5dB.

The coupling efficiency of each test coupler was measured using the apparatus described in Section 4.2. The coupling efficiency is defined as (see eqn. 3):-

$$C = \frac{P}{P_{in}}$$

where P = power transferred to unilluminated fibre

P_{in} = power into illuminated fibre

Here we assume that power launched into the unilluminated fibre is equal to the summed output power of the two output ports (i.e. that the device loss is negligable). The coupling efficiency can then be found simply by launching light power down one fibre of the coupler and measuring the output power at the two output ports.

The results found in this way are shown in Table 4 for the directional couplers made by the "glue method" described in Section 3.1, and in Table 5 for those made by the "nylon tube method". The column in each table headed "Theoretical fibre separation" is included in order to make a comparison between the theoretical predictions and the coupling results obtained. The figures shown under this heading are computed with the aid of Figs. 11 and13. The case for perfect launching conditions (intensity distribution as defined by eqn. 1) is assumed. It can be seen that the theoretical fibre separation (that separation which, according to theory, would give the coupling length and efficiency measured) fits quite well that measured using Figs. 22 and 23 (i.e. 0.5μm for the glue coupler, < 0.2μm for the nylon tube coupler). The variation, from coupler to coupler, in this apparent fibre separation can be attributed simply to the difficulty in reproducability of the manufacturing processes as they stand. This is discussed in Section 5.

A graph representing some of the results shown in Table 4 is plotted in Fig. 32. This curve confirms the general trend predicted by the theory. The coupling efficiency rises as the coupling length is increased in a similar way to that predicted by the theory as shown in Fig. 13 (perfect launch case).

Table 4 shows that there is apparently little difference in the fibre separation obtained by the different amounts of twist applied to the fibres in the glue method (see Section 3.1). If any, the slight twist approach seems to produce the smaller fibre separation.

An attempt was made to determine the coupling efficiency of the nylon tube devices as a function of the refractive index of the surround by introducing liquids of various index into the tube. The liquids were inserted into the region between the fibres by use of simple capillary action but due to apparent blockages in this region, perhaps due to a small section where the nylon softened too much and filled the voids between the fibres, the liquids penetrated only a small fraction of the coupling length. Because of this it was impossible to verify in detail the theoretical predictions for the effect of index difference Δ on coupling efficiency. Nevertheless the correct trends

Coupler number	Amount of twist	Coupling length (cm)	Coupling efficiency (%)	Theoretical fibre separation (μm)
1	None	20	13·5	0·52
2	None	8	0·55	0·70
3	Slight (1 every 4cm)	25	22·7	0·51
4	"	23	21·7	0·49
5	"	8	2·1	0·53
6	Large (1 every 1cm)	20	3·5	0·64
7	"	8	1·8	0·54

TABLE 4 Coupling results for test directional couplers made by glue method (estimated fibre separation = 0·5 μm, $\Delta = 0{\cdot}1$)

Coupler number	Coupling length (cm)	Coupling efficiency (%	Theoretical fibre separation (μm)
8	5·8	6·0	0·06
9	6·0	6·0	0·07
10	6·0	12	0·04
11	6·5	3·8	0·09
12	6·5	2·2	0·12
13	6·5	3·8	0·09
14	6·5	2·3	0·12
15	6·5	4·0	0·09
16	7·0	6·6	0·08
17	7·0	3·7	0·10
18	7·0	8·1	0·07
19	7·0	10·8	0·05
20	7·0	5·7	0·08
21	7·0	5·4	0·08

TABLE 5 Coupling results for test directional couplers made by nylon tube method (fibre separation is < 0·2 μm, $\Delta = 0{\cdot}548$)

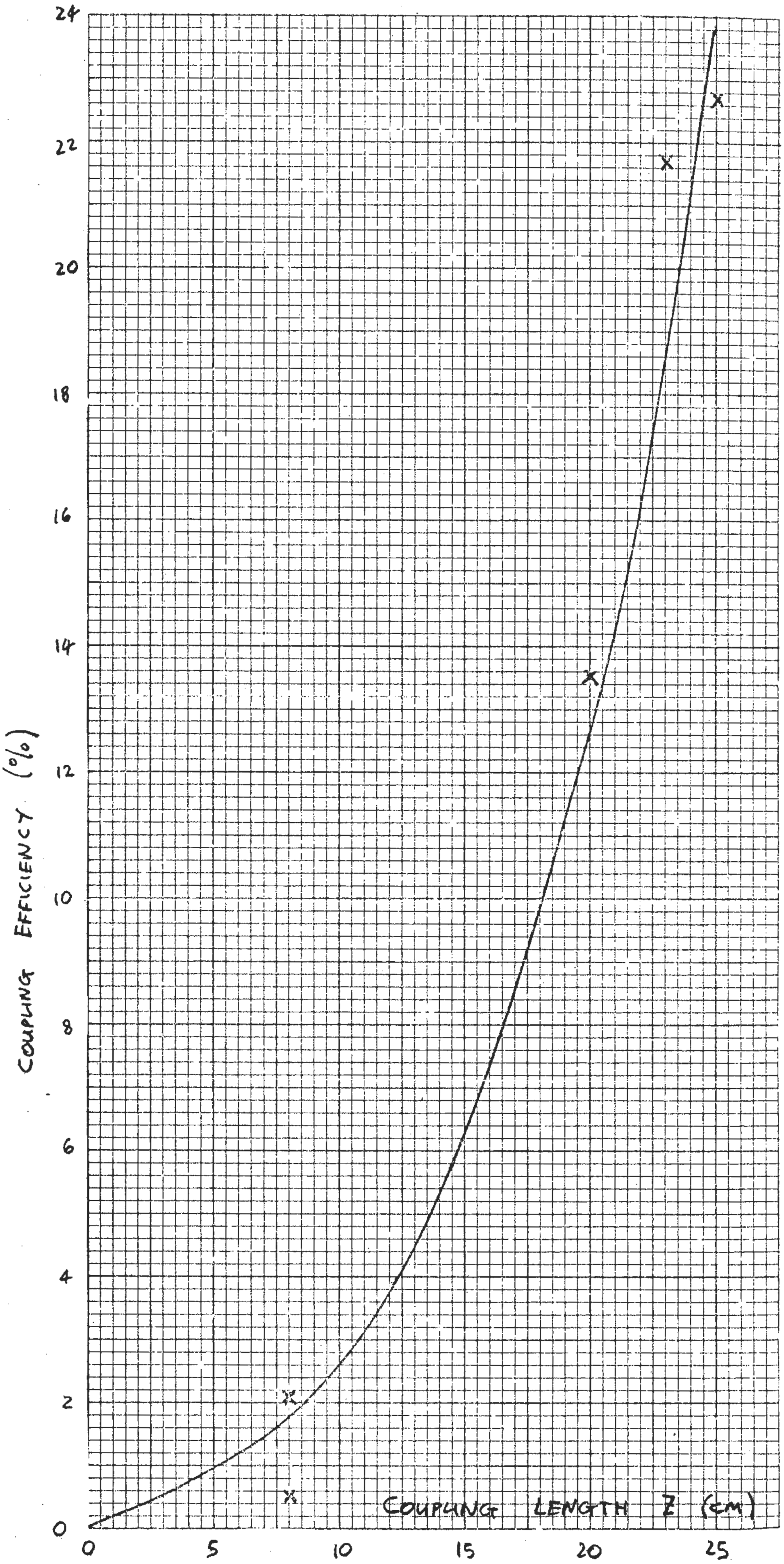

FIG. 32 Coupling efficiency versus coupling length for test couplers made by the glue method (from Table 4)

were seen, i.e. the smaller the Δ introduced the greater the increase in coupling efficiency. Even over the short length involved (around 1cm) the introduction of a liquid to give $\Delta = 0.004$, for example, caused an increase in coupling efficiency from 2.23% to 22.7%

4.4. The Star Coupler

The coupling results obtained for the illumination of the centre fibre of a star coupler made by the method described in Section 3.2 are shown in Table 6. The measurements taken were on the same sample as that photographed in Figs. 26-29, with a coupling length of 3cm.

As in Tables 4 and 5 a theoretical fibre separation, which would give the quoted results, is shown. In this case, this figure is only an approximation since it neglects the power transferred to the fibre in question by any fibre other than the illuminated one, and assumes that the full illumination power travels back down the centre fibre to the source (i.e. effective coupling length is not 3 but 6cm). The apparent separation between the centre fibre and the others shows less variation than one would imagine from Fig. 29, which suggest that one of the gaps could be as much as 2μm. This is due to the fact that Fig. 29 shows the cross-section of the coupler at a particular point, and it is likely that the cross-section will not be identical to this at other points along the coupling length. This can be seen by close comparison of Figs. 26, 27 and 28.

Again the theoretical predictions have been confirmed, if not quantitively, at least qualitatively.

The results obtained when the coupler is illuminated by other than the centre fibre are shown in Table 7. As would be expected, a wider variation in coupling efficiences, and a lower overall coupled power, is seen.

The insertion loss of the star coupler is an important factor which, owing to lack of time, has not been measured here. It is expected to be higher than that for the directional coupler since there are more terminals involved and since the addition of an external

Fibre	Coupling efficiency (%)	Theoretical fibre separation (μm)
2	0·9	0·17
3	3·5	0·10
4	3·8	0·10
5	1·3	0·15
6	1·0	0·16
7	2·2	0·12

TABLE 6

Fibre	Coupling efficiency (%)
1	0·7
2	0·4
3	1·3
4	0·3
5	0·2
6	0·6

TABLE 7

Coupling results for star coupler sample (coupling length = 3cm) with centre fibre illuminated (Table 6) and off-centre fibre illuminated (Table 7)

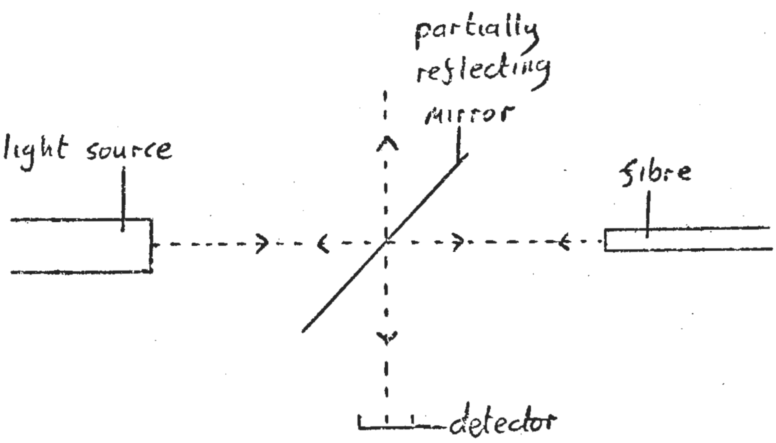

FIG. 33 Suggested approach to the measurement of the power reflected back down the illuminated fibre, for the star coupler.

component, namely the mirror, would introduce additional loss. The latter could be minimized by evaporating a metal or dielectric film onto the end of the finished coupler.

In order to obtain a figure for the insertion loss of the star coupler, two fundamental measurements wculd have to be made.

a) Measurement of the signal light power entering the device

b) Measurement of the power leaving the device by the output ports.

The first of these was performed in the laboratory in order to calculate the coupling efficiencies already quoted. The method was simply to remove the end-face mirror (see Fig. 21) and measure the light output from the 7-fibre array, the input light being launched down one of the fibres. (The reflectivity of the fibre-air interface must be taken into account) It is assumed that the fibre-loss over the length of the coupler is negligable (i.e. light in = light out).

With reference to the second measurement, the light leaving the device by the six unilluminated fibres was easily measured. The most difficult measurement involved is that of the amount of light power returning back down the illuminated fibre after reflection from the end-face mirror. A possible way of performing this measurement would involve a "beam splitter" placed between the light source and the fibre to be illuminated, as illustrated in Fig. 33. The beam splitter would simply involve a partially reflecting mirror placed at 45° to the light source as shown. Time did not permit this experiment to be carried out with sufficient accuracy to be able to quote a figure for the insertion loss of the star coupler.

5. DISCUSSION

We have suggested the use of unclad optical fibres in the manufacture of two types of optical coupler, the two-fibre directional coupler and the seven-fibre star coupler for use in optical data buses.

The theoretical predictions suggested that very useful coupling results would be obtained using the principle of coupling between close parallel unclad optical fibres. The laboratory measurements of Section 4 have confirmed these predictions, and therefore it is suggested that there is a future for this type of coupler.

An area not covered by the scope of this report is that of the insertion of a device using unclad fibres into a system using clad fibres. It is suggested that this would be possible, and low losses could be achieved. The lowest possible losses would be achieved when inserting the devices into a system of step-index multimode fibres with the core index identical to the index of the unclad fibres.

It is suggested that the "nylon tube" manufacturing process described here for the directional coupler in Section 3.1, and for the star coupler in Section 3.2, uses a principle which could be utilised in the industrial manufacture of the devices. The two main limitations of the process as it stands are:-

a) lack of reproducability
b) non-ideal material (i.e. the nylon)

Using the apparatus described in Section 3.1 there is a lack of consistency from one device to the next. The directional couplers have coupling efficiencies varying by a factor of six for the same coupling length (see Table 5), and not all the star couplers manufactured had the required hexagonal array. It is suggested that the tightening up of the manufacturing proceedure could remove this problems. Some areas where this is necessary are:-

i) The temperature of the heater and the time for which heat is applied,
ii) The position of the tube and fibres in the heating coil (i.e. should be perfectly central),
iii) The weight attached to the tube (should be identical for each coupler),

iv) The length of tubing used,

v) The length of the fibres used,

vi) The end preparation of the fibres used.

It is suggested that the principle we used (shrinking down of tube around fibres) is a very useful one, but that a better material than nylon could probably be found. The nylon tubing used was not optically perfect (some absorption), and its shrinking properties were not ideal (i.e. it tended to soften too much and in places fill the voids between the fibres).

Another matter arising from the report (Section 4.2) is that the coupling is mode-dependent, i.e. that higher modes couple more than lower modes. This property is not particular to the coupling between unclad fibres, but is common to most other methods of coupling - certainly those involving power transfer between parallel fibres. It is suggested that this mode-dependency is not a serious limitation of the devices.

6. CONCLUSIONS

A theoretical treatment, using coupled mode theory, of the coupling between unclad optical fibres has been given which suggests the possibility of making successful devices using this principle. Measurements in the laboratory have confirmed this.

A coupling efficiency of 12% has been measured for a directional coupler of length 6cm (Table 5), using the nylon tube method of Section 3.1. This coupling could be increased further by the insertion of some index-matching medium into the region between the fibres. It is suggested, for example, that further experimental work could produce a coupling of 25% in 5cm, using a fibre separation of 0.2μm and Δ (index difference between fibres and surrounding medium) of 0.1, as predicted by theory (Fig. 12). This is not beyond the reach of simple experimental technique.

An overall coupled power of 13% has been measured for a star coupler (Table 6) of coupling length 3cm. Again it is suggested that this figure could be improved as for the case of the directional coupler.

The insertion loss of the directional coupler was found to be very low (less than 0.5dB). It is suggested that the insertion loss of the star coupler is also low.

A method of manufacture of a directional coupler and a seven-fibre star coupler has been suggested here, namely the shrinking of a tube around the fibres over the desired coupling length. The material used (nylon) is not recommended for a practical device owing to its poor optical qualities, but if a better material were found the method described is expected to produce a successful device.

It is suggested that it would be profitable to carry out further work to perfect the manufacturing method for the couplers and to obtain even more conclusive results, since the principle of coupling between unclad fibres clearly has important applications in the field of optical couplers.

APPENDIX A - COSTING OF THE PROJECT

The cost incurred on this project was very small. It could be estimated as follows:-

Nylon Tubing	-	10p.
Heater Wire	-	10p.
Glue	-	20p.
Fibres	-	50p

This underlines the fact that were these couplers to go into production in industry, their cost would be very low.

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