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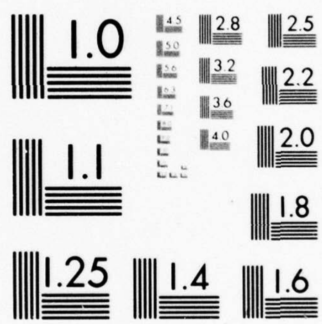

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INVESTIGATION OF A MULTIMODE

FIBER OPTIC COUPLER

by

Marvin D. Drake

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 79-0859	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Investigation of a Multimode Fiber Optic Coupler		5. TYPE OF REPORT & PERIOD COVERED FINAL rept. 1 Apr [illegible] - 31 Dec 78
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Marvin D. Drake		8. CONTRACT OR GRANT NUMBER(s) AFOSR-78-3566
9. PERFORMING ORGANIZATION NAME AND ADDRESS Florida Institute of Technology, Dept. of Electrical & Computer Engineering, Melbourne, Florida 32901		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2305/D9 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NE, Bldg. #410, Bolling Air Force Base, DC 20332		12. REPORT DATE 26 June 1979
		13. NUMBER OF PAGES 47
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 50p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fiber Optics
Multimode Coupler

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The operation of a three-fiber multimode fiber optic coupler was experimentally investigated for the dependence of the forward coupling ratio upon 1) surface conditions of the aligning rods, 2) stress on the fibers, 3) length of the aligning rods, 4) mode distribution in the main fiber, 5) make of fiber, and 6) length of input fiber. An explanation of the discrepancies between theory and experiment was also sought. The forward coupling was found to 1) increase for gross perturbations of the surface of the alignment rods, 2) increase for increased stress on the fibers, 3) increase with length of the aligning rods, next page

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increase with increasing number of higher order modes, depend strongly on type of fiber, and decrease with input fiber length. Further, the directivity of the coupler was increased greatly by reducing reflections from the ends of the fibers.

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INVESTIGATION OF A MULTIMODE FIBER OPTIC COUPLER

1.0 INTRODUCTION

In previous research, a multimode fiber-optic coupler with low insertion loss was discovered which is simple to fabricate, is directional, leaves the fibers intact, and has an insertion loss of <0.05 dB[1,2]. The coupler utilizes the energy contained in the leaky modes of the fiber. The coupler, as shown in Figs. 1 and 2, consists of three optical fibers with short sections of their protective jackets removed. The fibers are precisely held in contact with each other using three aligning rods. The three aligning rods are held together with heat shrink tubing.

In operation, light is launched into the main fiber and propagates to the far end. A portion of this power is coupled into the two other fibers at the coupler. Part of the power is coupled into the forward direction, P_2, and a much smaller portion into the reverse direction, P_3. The power P_2 depends upon the radial spatial distribution of power P_1 in the core and cladding. Greater coupling of power into P_2 can be realized if the power in the higher order or leaky modes can be increased. This can be done by changing the launching condition of the input light beam, by perturbing the fiber before or at the coupler, or by choosing a particular core/cladding structure in the fiber. In the previous research, several couplers were constructed using drill rods 25 mm long and either graded or step index glass on glass fibers from one manufacturer[1,2]. Several input fiber lengths were also used in these experiments ranging from 0.4 m to 240 m for the main fiber. Two different sources were used: a 1.5 mW

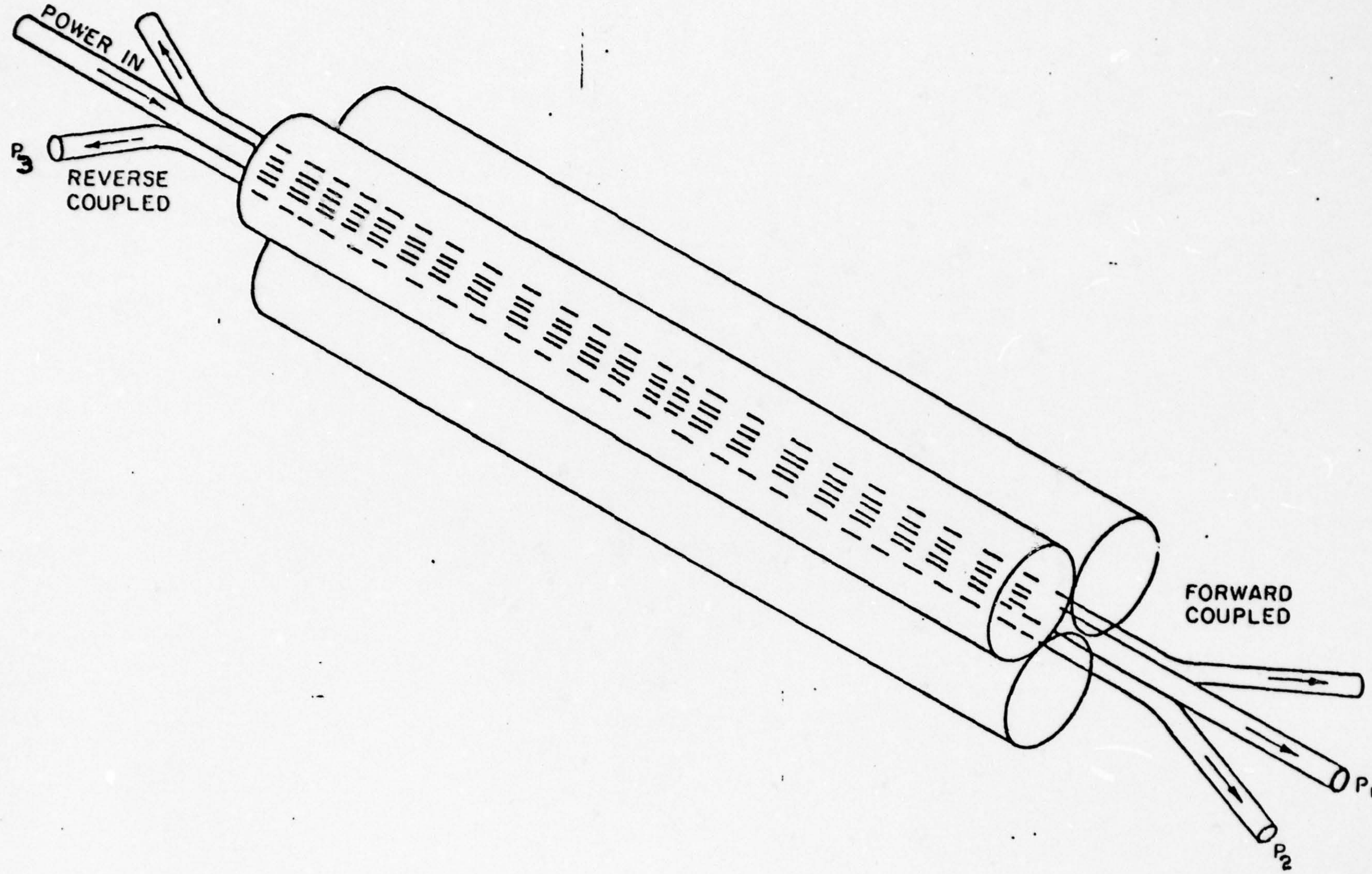


Fig. 1. Three-fiber optical coupler

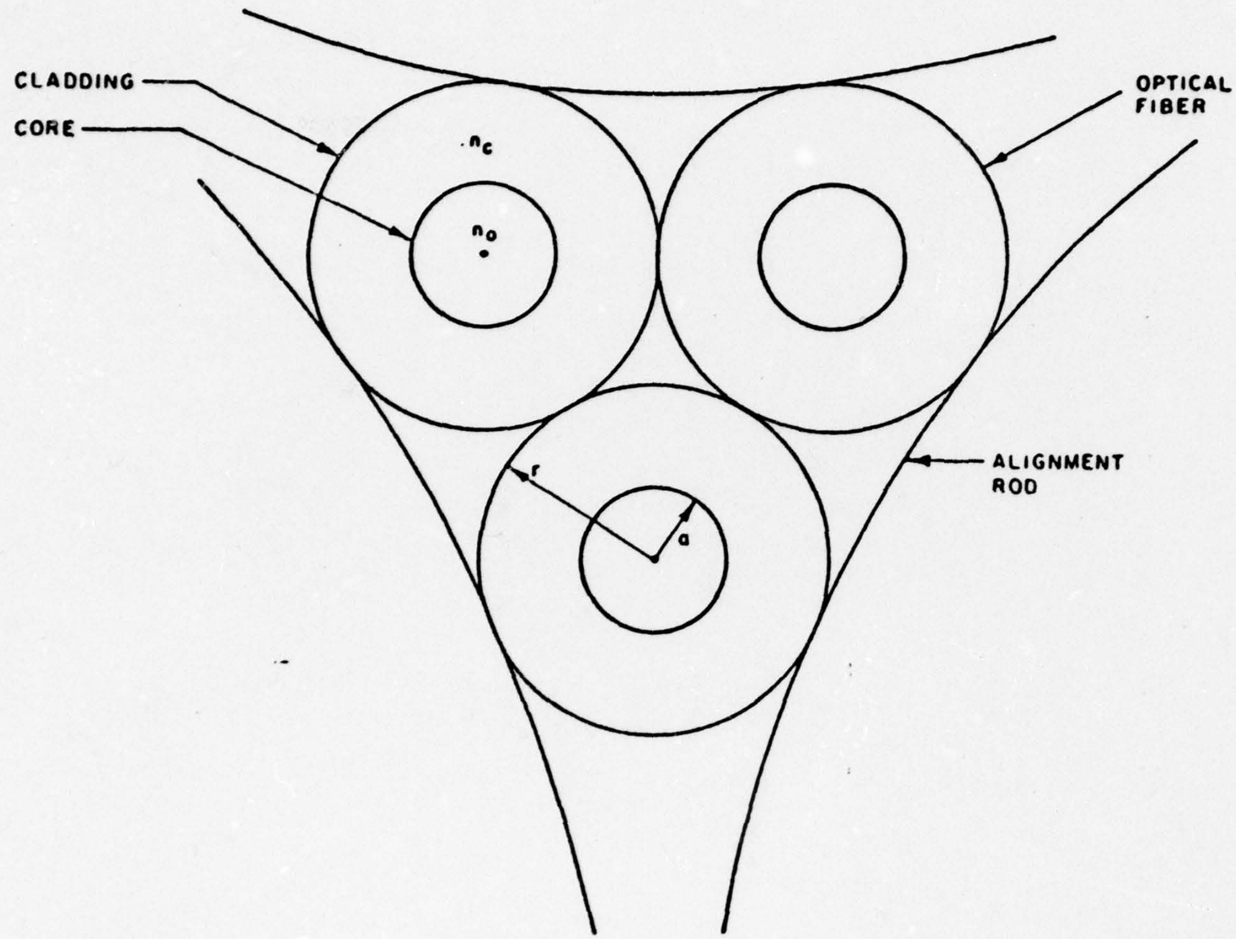


Fig. 2. Detail of cross section of three-fiber coupler

He-Ne laser and a 600 μW DH stripe geometry LED. The forward coupling ratio, η_f, varied between -5.5 dB and -40.1 dB depending upon the type of light source, the input coupling conditions, and the length of the input fiber.

A theoretical calculation of η_f was also done in the previous research based on a modification of a theory by Ogawa and Snyder[3,4]. However, the maximum coupling predicted by this theory was always less than the minimum achieved in the experiments. The discrepancy between the theory and experiments can be explained by considering the variation in the modal and spatial power distribution in the input fiber as a function of input conditions as well as distance from the input to the coupler. The theory of Ogawa considered the case of equal power in each mode, which is not the case for the present coupler. It is believed that the present coupler excites and utilizes primarily the higher order modes, and any change in the modal distribution in the main fiber will affect the coupling ratio, η_f. Two means of changing this modal distribution are 1) exciting different modal distributions at the input and 2) perturbing the main fiber just before or at the coupler. The first method can be done by varying the diameter of the input beam, the maximum input angle and/or the offset of the beam and the fiber. Perturbing the fiber by stressing or bending causes mode conversion in the main fiber from bound modes to leady modes. It is also possible that the surface conditions of the alignment rods perturb the mode distribution[5]. The type of fiber used in the coupler will also influence η_f since different core and cladding diameters, indices of refraction, and construction types (step, graded, W-type) will have different mode distributions.

The purpose of the research reported here is to examine these factors mentioned above in detail and to more fully understand the operation of the three-fiber coupler. The specific objectives are 1) to investigate the dependence of the forward coupling ratio η_f upon the surface conditions of the alignment rods, 2) to investigate the dependence of η_f upon the stress placed on the fibers by the alignment rods, 3) to verify the dependence of η_f upon the length of the alignment rods, 4) to investigate the mode distribution of the power coupled into the side fibers, 5) to investigate the dependence of η_f upon the particular make of fiber, 6) to investigate the dependence of η_f upon the length of the input fiber, and 7) to modify the theory for non-uniform input mode distribution and for localized boundary conditions.

2.0 EXPERIMENTAL EQUIPMENT

The investigation of the many factors influencing the operation of the three-fiber coupler required first of all a more precise control of the input conditions than was possible in the previous research. The input conditions to be controlled were: 1) the surface of the input fiber, 2) the diameter and cone angle of the input beam, 3) the lateral offset between the input beam and the fiber centerline, 4) the angular offset between the input beam and the fiber centerline, and 5) the stability of the input power.

A fiber cleaving wheel with a diamond scribe was designed and constructed to yield a flat end on the input end of the fiber that was within 5° of perpendicular to the centerline of the fiber (see Figure 3). Several adjustments were built into this cleaver for varying the position and angle of the diamond scribe and the tension applied to the fiber. After initial

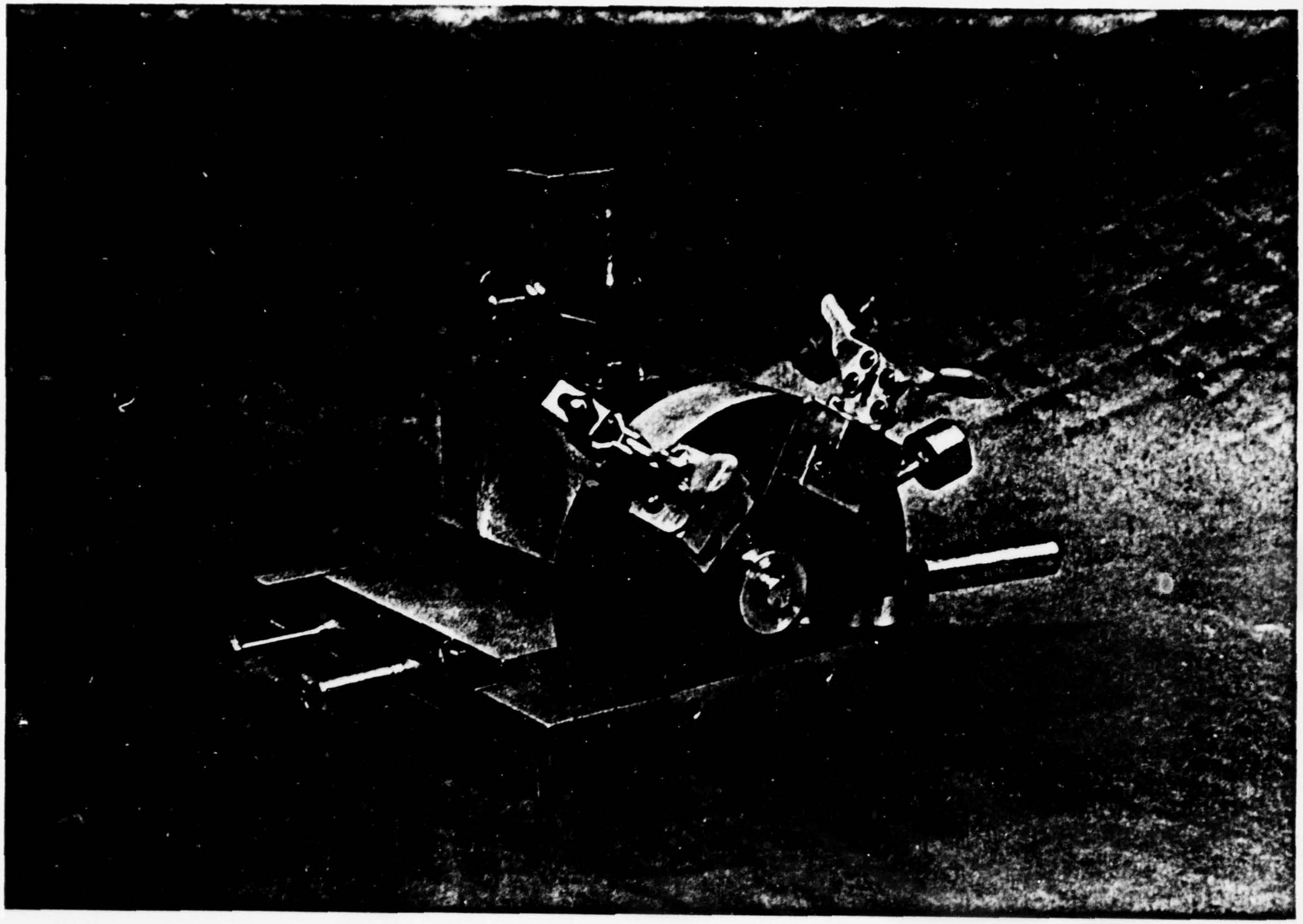


Fig. 3. Fiber cleaving wheel.

trials with the cleaver, approximately 9 out of 10 cleaves met the requirements.

A 2.0 mW polarized He-Ne laser with λ = 633 nm was used for the power source. After initial warmup of 20 minutes, the total output power drifted less than 10% over several hours. The mode structure shifted very slowly and was observed to be stable over periods of several minutes. The diameter of the beam was 0.5 mm and divergence angle was less than 1.7 mrad. full angle at e^{-1} points.

The diameter and cone angle of the light input to the fiber were controlled by a microscope objective which focused the beam upon the input end of the fiber. The diameter of the beam at the input end of the fiber, d_2, for a gaussian beam at the e^{-1} points is given approximately by $d_2 = f\theta$, and the cone angle at the input end of the fiber by $\theta_2 \approx \tan^{-1}(d_1/f)$ where f = focal length of the microscope objective, d_1 = diameter of laser beam, θ_1 = divergence angle of laser beam. Table I shows d_2 and θ_2 for the microscope objectives used.

TABLE I

Diameter and Cone Angle of Input Beam to Filter

Microscope Objective	N.A.	E.F.L.(f) (mm)	θ_2	d_2 (μm)
5x	0.10	30.0	0.96°	102.0
10x	0.25	14.8	1.94°	50.3
20x	0.40	7.5	3.84°	25.5
40x	0.65	4.3	6.66	14.6

The lateral offset and the angular offset between the beam and the fiber were controlled by mounting the microscope objective and also the fiber in separage 5 degree of freedom positioners: x, y, and z position and rotation about x and y axes were controlled. The laser was mounted on a 4 axis position: z and y position and rotation about y and z axes. The laser, the microscope objective, and the fiber, on their respective positioners were mounted on an optical rail as shown in Figure 4. This experimental arrangement could be adjusted to excite the minimum number of leaky modes in the fiber by selecting the 20x or 40x objective, placing the end of the fiber at the focal point of the lens, and adjusting the centerline of the fiber to the centerline of the beam. This gave maximum power through the main fiber and minimum power coupled out. Conversely, by offsetting the fiber laterally in the beam, leaky modes could deliberately be excited. This gave maximum power coupled out and reduced power through the main fiber. An example of this is shown in the data in Table II for a coupler constructed of graded index fiber.

TABLE II

Sample Data from a Coupler Constructed from ITT Graded Index Fibers with 25 mm Alignment Rods. Input Length of Fiber = 30 meters.

Microscope Objective	Power Maximized	η_f(dB)	η_r(dB)	η_d(dB)
5x	P_1	-20.2	-41.0	20.8
5x	P_2	-17.9	-39.6	21.7
10x	P_1	-24.1	-46.7	22.6
10x	P_2	-13.7	-35.7	22.0
20x	P_1	-35.4	-46.1	10.7
20x	P_2	-13.1	-35.7	22.6
40x	P_1	-33.5	-46.7	13.3
40x	P_2	-13.3	-34.3	21.0

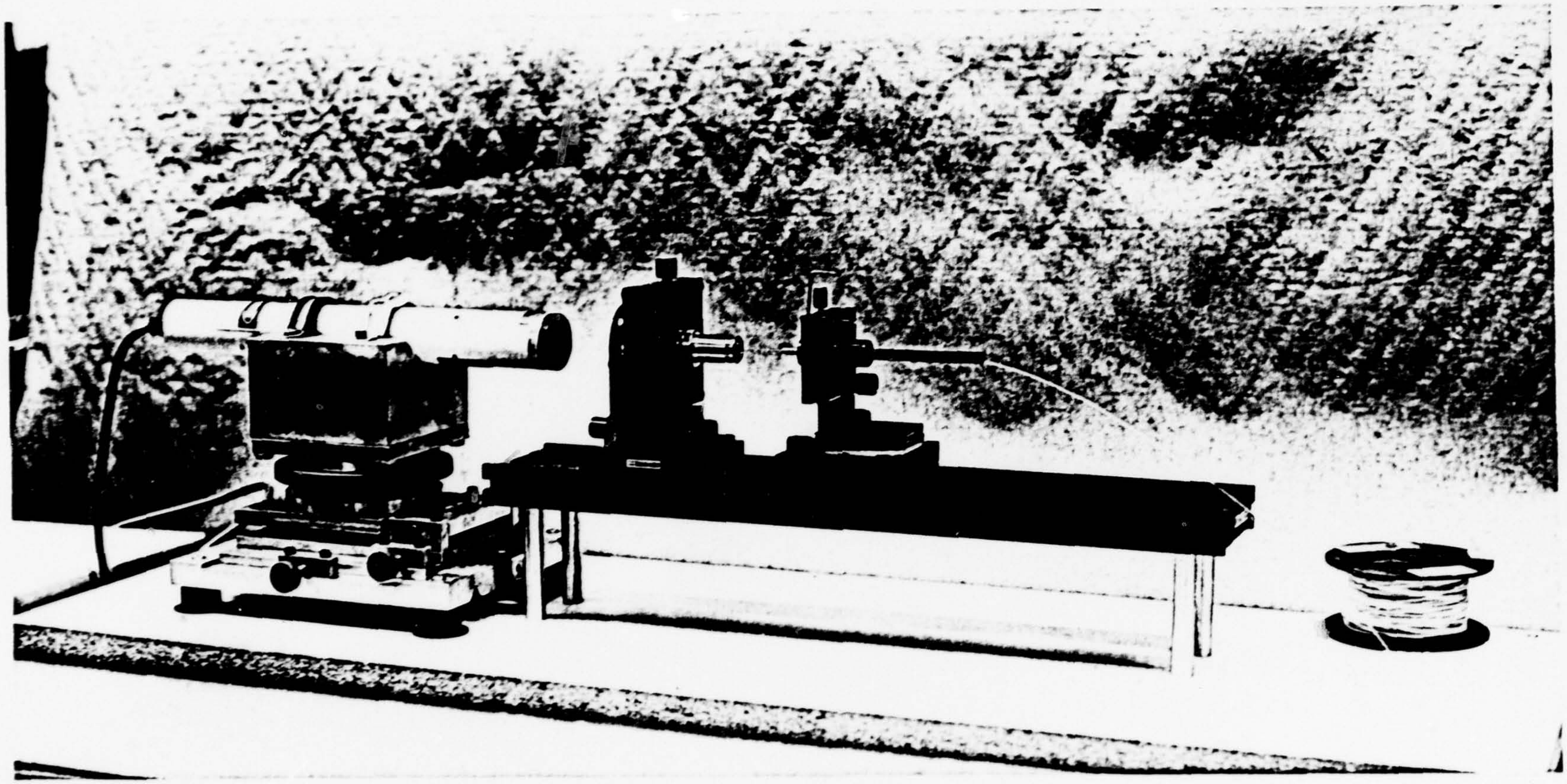


Fig. 4. Experimental Apparatus.

The forward and reverse coupling ratio, η_f and η_r, and the directivity, η_d, were calculated from

$$\eta_f = 10 \log\left(\frac{P_2}{P_1}\right), \quad \eta_r = 10 \log\left(\frac{P_3}{P_1}\right), \quad \eta_d = 10 \log\left(\frac{P_2}{P_3}\right)$$

When the fiber is exactly centered in the beam (P_1 maximized), and the diameter of the input beam decreased (increasing power of the objective), the forward coupling ratio is reduced. However, at 40x some of the rays of the input beam exceed the maximum acceptance angle of the fiber (the numerical aperture) and leady modes are launched, increasing η_f. When the fiber is deliberately offset (P_2 maximized), and the diameter of the beam reduced (increasing power of the objective), the forward coupling is increased. Several different fibers were used in these experiments. The properties of these are shown in Table III.

TABLE III

Properties of Fibers Used in Experiments

	Manufacturer			
	ITT	ITT	Corning	Valtec
Type of index gradient:	Step	Graded	Graded	Graded
Type number:	GS-02-08	GG-02-08	1054	MG05-01
Fiber core diameter:	50 μm	50 μm	63 μm	51.3 μm
Fiber outer diameter:	125 μm	125 μm	125 μm	127.5 μm
Core index of refraction n_o:	1.48	1.48	1.47	1.47
Numerical aperture:	.25	.25	.20	.23
Loss (dB/km):	5.33	3.90	9.1	9.56
Remarks:	W-type	W-type	-	-

The fibers were chosen because of their differences in N.A., type of index gradient, losses, core diameter, and type of construction. They were also chosen for their similarity in outer diameter and composition (glass on glass). The techniques of construction of the couplers including the alignment rod diameters were the same for all these fibers. Thus, the differences in coupling ratio due to fiber differences could be separated out.

3.0 DEPENDENCE OF COUPLING UPON SURFACE CONDITIONS AND STRESSES OF ALIGNMENT RODS

The couplers for the experiments were constructed from one of three different kinds of alignment rods: 1) drill rod blanks, 2) drill rod stock, and 3) threaded drill rod stock. The drill rod blanks (45 mm long) as received had been ground, polished, heat treated, and had champfered ends. The rods used were further selected for straightness and absence of burrs, and were then polished with jewelers rouge. The drill rod stock was received in untreated 3 ft. long sections which were cut to length (13 mm, 24 mm, 34 mm, and 45 mm) and the ends champfered. The rods used were selected for straightness and absence of burrs, but no effort was made to remove striations from the rods. Additionally, a number of the 24 mm long rods from the drill rod stock were threaded with a #0-80 die to yield approximately a 75% thread. The diameter of the alignment rods is related to the diameter of the optical fibers by $D_R = (5+2\sqrt{6})d_f$ where D_R = diameter of alignment rod, and d_f = outer diameter of optical fiber. For optical fibers with a 125 μm O.D., the alignment rods should have a diameter of 1.237 mm. The rods used were nominally 1.230 mm in diameter ±.003 mm to ensure that the fibers would be securely held in the coupler.

To begin the experiments, a coupler was constructed using ITT step index fiber and the polished drill rod blank alignment rods. The coupling ratios, η_f, η_r, and η_d were measured and the coupler was disassembled. The coupler was reassembled using the same fibers but with the rough drill rod stock alignment rods. The coupling ratios were again measured. No significant difference of the coupling ratios was measured between the smooth and the rough alignment rods. Other couplers constructed from the rough rods did show lower forward and reverse coupling if the rods were not straight. In this case the fibers were not in contact along the full length of the coupler.

The investigation of surface condition effects was continued by constructing a coupler using the threaded drill rod stock 24 mm long and the ITT graded index fiber. The same type of fiber was used to construct a coupler from the rough drill rod stock, also 24 mm long. The data is shown in Table IV.

TABLE IV

Comparison of Forward Coupling Ratio for Couplers Made from Rough and Threaded Drill Rod Stock (Fibers: ITT graded index, Input objective 20x; Interaction length: 24 mm)

Power Maximized	Rough Rod	Threaded Rod
	η_f (dB)	η_f (dB)
P_1	-35.4	-33.5
P_2	-13.1	-6.9

This data shows that when the power in the fiber is contained principally in the lower order or propagating modes (P_1 maximized), the periodic perturbation of the threads causes only a small increase (<2 dB) in the forward coupling ratio. However, when the leaky modes are deliberately excited (P_2 maximized), then a much larger increase (>6 dB) in the forward coupling occurs.

The conclusion is that for maximum forward coupling ratio the couplers should be constructed using threaded rods. This is even more true when the source is a light emitting diode (LED) or an injection laser diode (ILD) since the output light beam from such sources has an angular beam spread much greater than the N.A. of the fibers considered in this research. A large amount of the power launched into the fiber from these sources will be carried in leaky modes, and can be coupled out by the type of coupler studied in this research.

The influence of stress placed on the fibers was investigated by changing the means of holding the coupler together. A coupler was first made from ITT graded index fiber and 34 mm rough rods held in place with three bands of heat shrink tubing, each 4 mm wide, with one band in the middle and one at either end. The coupling ratios were measured and the coupler disassembled. The coupler was reassembled with a single sleeve of heat shrink tubing extending the full length of the coupler. The data is shown in Table V.

The increased stress slightly increases (1.6 dB) the coupling ratio when the power is carried mainly in the lower order modes (P_1 maximized) and gives a higher increase (4.2 dB) when the power is carried in the leaky modes (P_2 maximized). The conclusion is that for maximum forward coupling, the couplers should be assembled using a single sleeve of heat shrink tubing. However, this increases the difficulty of assembling the couplers, and the easier 3 band construction was used in the remainder of the experiments.

TABLE V

Comparison of Forward Coupling Ratio, η_f, for Normal (3-4 mm bands) and Increased Stress (1-34 mm sleeve) on Fibers (ITT graded index fibers; 20x input objective; 34 mm interaction length)

Power Maximized	Normal	Increased
	(3-4 mm bands)	(1-34 mm sleeve)
	η_f (dB)	η_f (dB)
P_1	-41.5	-39.9
P_2	-17.7	-13.5

A more definitive experiment investigating the influence of stress on the coupling ratio could not be accomplished during the period of this contract. The difficulty of accurately measuring the force placed on the fibers was the major experimental obstacle. However, the experimental apparatus necessary is being constructed and the experiments will be carried out utilizing the fibers and equipment assembled under the present contract. The results will be published later[6].

4.0 DEPENDENCE OF COUPLING RATIO ON HIGHER ORDER MODES - INSERTION LOSS

The power coupled out of the main fiber in this type of coupler depends upon the mode distribution in the main fiber[3]. Maximizing the power through the main fiber (P_1) minimizes the forward coupling ratio, η_f, and maximizing the forward coupling ratio reduces P_1 while maximizing P_2. One method to achieve maximum η_f is to deliberately launch more higher order (leaky) modes by laterally offsetting the input fiber with respect to the input beam axis. The results are shown in Figure 5 where the forward coupling ratio and the insertion loss are plotted versus the percentage of maximum power transmitted through the main fiber (% of $P_{1_{max}}$). The insertion loss at 100% $P_{1_{max}}$ is $\leq$0.05 dB (the accuracy of the measurement). The very low value of η_f at 100% $P_{1_{max}}$, occurs when the offset is very precisely controlled to within a few microns of the centerline and is only then achieved because of the high degree of collimation of the He-Ne laser. A less collimated source such as an ILD or an LED would yield much higher forward coupling ratios at minimum offset. The values shown in Figure 5 illustrate two possible uses of this type of coupler: 1) as a mode volume monitor on the fiber, which will indicate by an increase in P_2 or η_f when the fiber has been perturbed in front of the coupler, and 2) as a maximum transmitted power monitor which will indicate by a minimum of P_2 or η_f when the source input has been adjusted such that maximum amount of power has been coupled into the lower orders (trapped modes) of the fiber.

This latter application was explored in greater detail and the results published separately[7]. The starting point of that investigation was to find out how quickly after launching did off-axis modes at the input end of the fiber mix until the mode volume was again cylindrically symmetrical. The three stub connector shown in Figure 6 was constructed using three Dupont Crofon (TM) plastic fibers in place of the three alignment rods with the main fiber held in the interstice of the three plastic stub fibers (each 0.030" in diameter). The four fibers were held together with heat-shrink tubing and the flush ends of the fibers polished to an optical finish. The fibers were held together by the heat shrink tubing for a few centimeters and then the main fiber was separated from the bundle of the

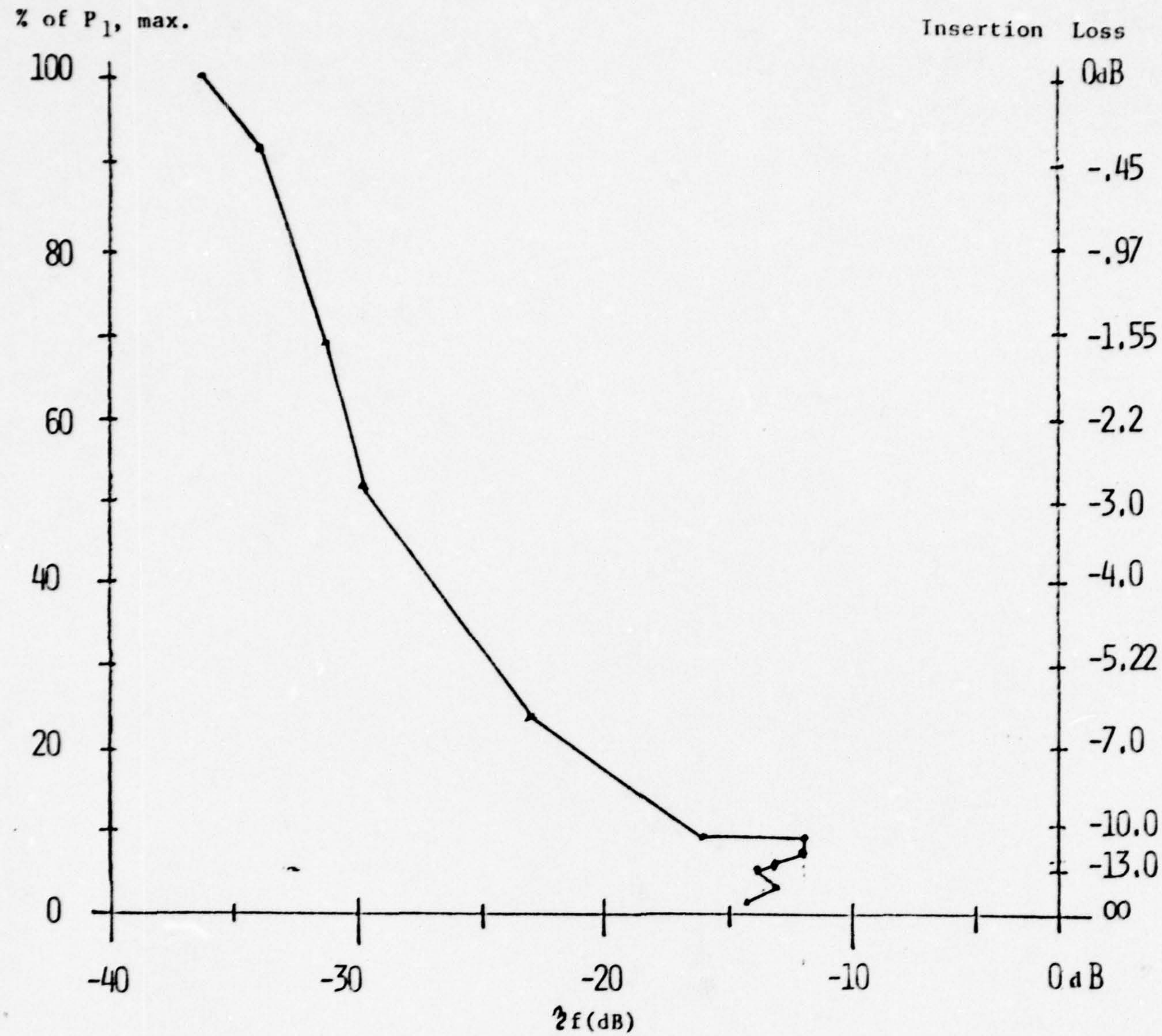


Figure 5. Percentage of maximum power through main fiber ($\%P_{1,max}$) versus forward coupling ratio, η_f for lateral offset method of launching higher order modes. (ITT graded index fiber, 34mm alignment rods, 30m input fiber length).

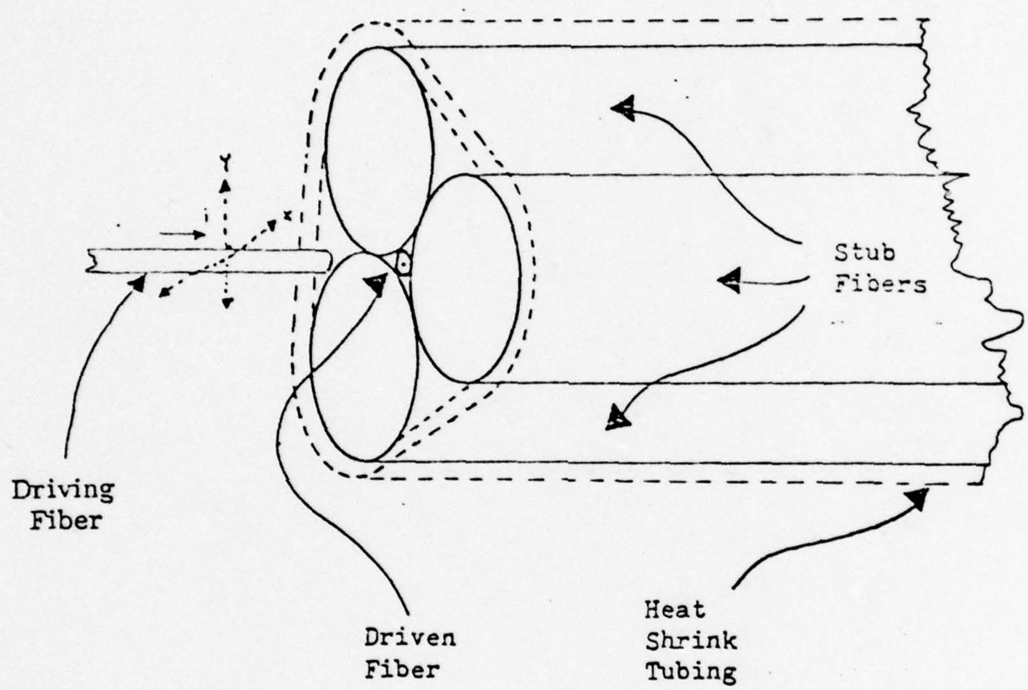


Fig. 6. Experimental fiber coupling fixture.
(after Richards[7], with permission)

the three stub fibers. The stub fibers used were approximately 40 cm long and the main fiber (driven fiber) was 250 m long. The input end (driven end) of this four fiber assembly was illuminated by the output end of a 40 meter length of ITT step index fiber (driving fiber). The optical power in the driving fiber itself was coupled into it from the He-Ne laser and the microscope objective-fiber holder apparatus described in section 2.0 of this report. Precise adjustment of the offset as well as the use of mode strippers on the 40 m length insured that the power in the driving fiber was contained in the transmitting (lower order) modes. The light coming from the output end of the driving fiber was thus constrained to angles less than or equal to the N.A. of the driving fiber.

In the experiments, the power at the end of the 250 m length and the power from each of the stub fibers was recorded as a function of lateral offset between the driving and driven fibers. When the offset was large and the driving fiber illuminated only one of the stub fibers, this stub fiber showed maximum power out. The other two stubs and the main fiber showed very little power out. However, once the driving fiber offset was reduced until it illuminated only the cladding of the main fibers, then all three stub fibers showed approximately the same power. At the same time, the main fiber showed an increase in transmitted power. As the lateral offset was reduced toward zero, the power in the three stub fibers reduced equally to a minimum and the transmitted power in the main fiber to a maximum, all simultaneously. These results are illustrated in Figures 7 through 9[7].

The equal intensity of light in the three stub fibers when only the cladding was illuminated indicated that the mode volume in the main fiber became cylincrically symmetrical within a length of a few centimeters.

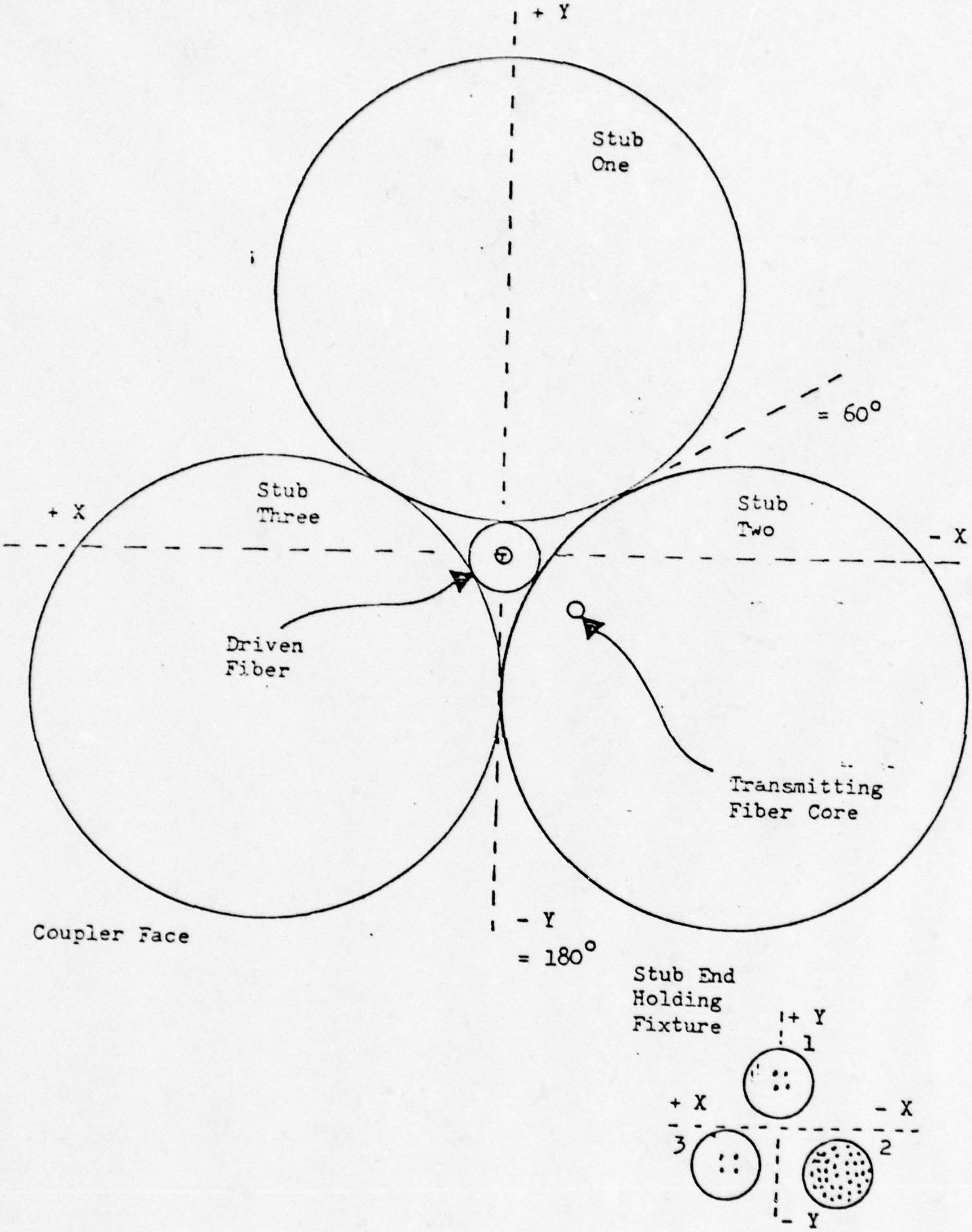


Fig. 7. The offset transmitting fiber core located somewhere in the section of the coupler face bound by the γ = 60° and γ = 180° radials. The relative light intensity is represented by the number of dots in the circle representing a given fiber end. (after Richards[7], with permission.)

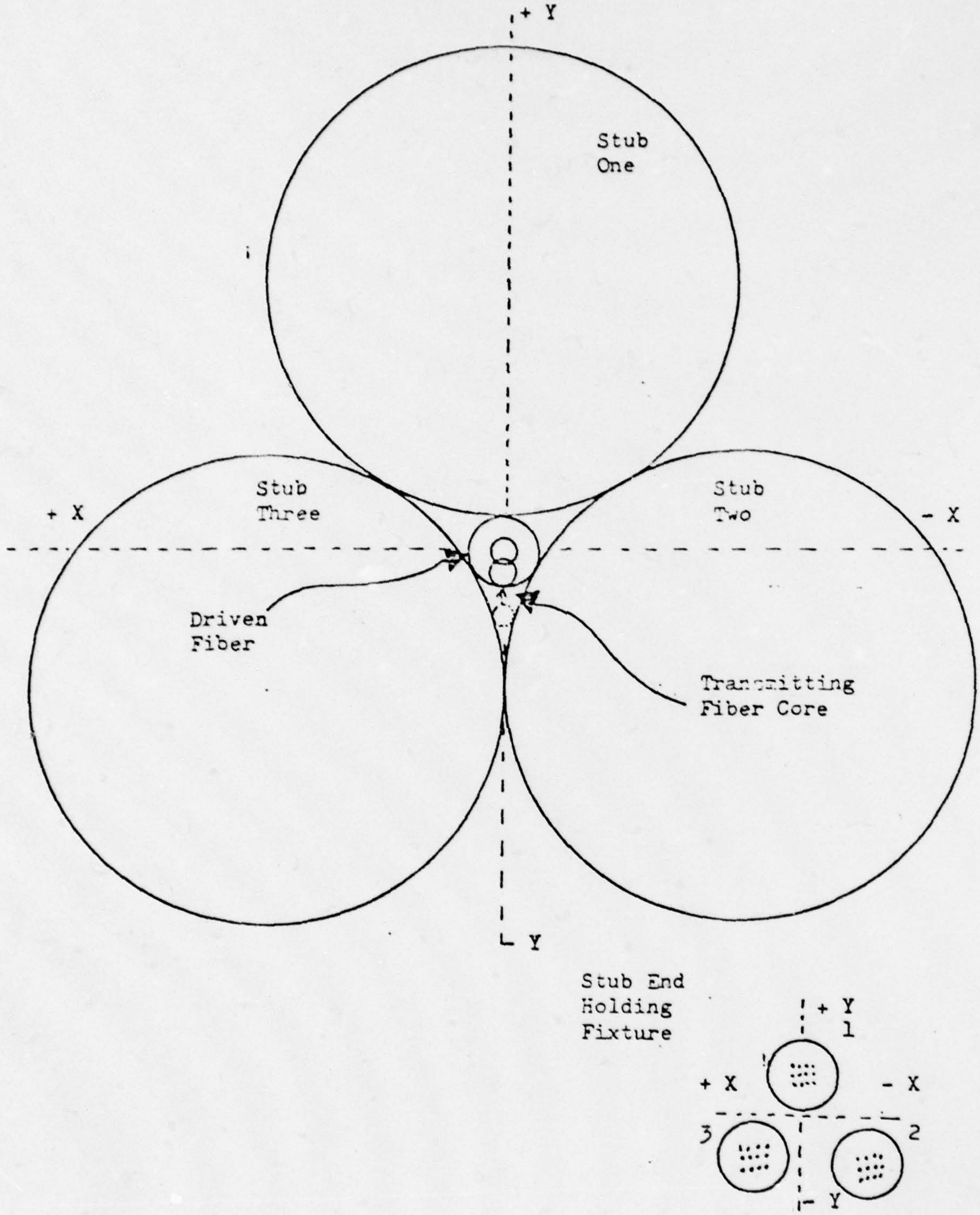


Fig. 8. The offset transmitting fiber core translated to within the cladding circumference of the receiving fiber. The relative light intensity is represented by the number of dots in the circle representing a given fiber end. (after Richards(7), with permission.)

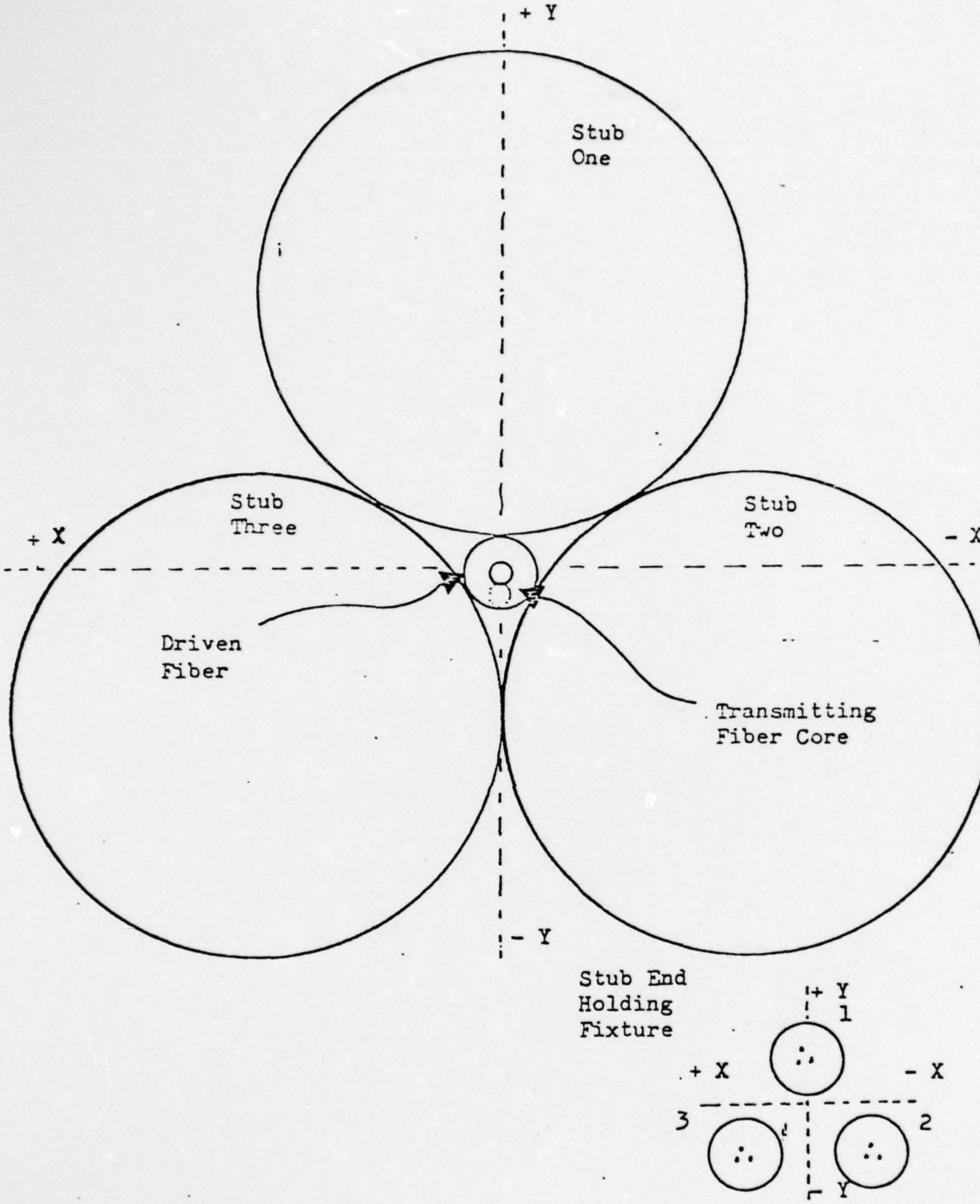


Fig. 9. The transmitting fiber core adjusted to zero offset. The relative light intensity is represented by the number of dots in the circle representing a given fiber end. (after Richards[7], with permission.)

This was an important result for the present research since any perturbations of the main fiber a few cms before the three rod coupler or perturbation due to the three rods themselves would not result in assymetrical coupling of light into the side fibers.

The results of the stub fiber connector suggests an important application for this connector. It can be used to insure that maximum power is transmitted to the distant end of a length of fiber without having access to the distant end. It requires only a simple x-y translation device to hold the four fiber assembly and a portable optical power meter to read the output of the three stubs when the wavelength used is in the infrared. Another use would be as an adjustable "T" coupler where the stub fibers could be used as the input and output of the side port.

5.0 DEPENDENCE OF COUPLING RATIO UPON LENGTH OF ALIGNMENT RODS

In the previous research a theoretical calculation of η_f was done based on a modification of a theory by Ogawa and Snyder[3,4]. The model for the calculation was that of two fiber cores completely immersed in an infinite volume of cladding material. Ogawa derived an average value of the coupling coefficient/unit length between the i th mode of the main fiber A and the i th mode of the side fiber B for two identical fibers:

$$|C_i| = \frac{2^{3/4}\Delta^{1/2}}{(\pi k n_o a^3)^{1/2}}\left(\frac{i}{N}\right)\left(1-\frac{i}{N}\right)^{1/4} \times \frac{\exp\left[-(2N-2i)^{1/2}\left(\frac{d}{a}-2\right)\right]}{\left(\frac{d}{a}\right)^{1/2}}$$

where: a = radius of core
k = $2\pi/\lambda$
n_o = refractive index of core
Δ = $1-(n_c/n_o)$
d = distance between centers of fiber cores
N = total number of modes in the main fiber
i = number of the mode ($1\leq i\leq N$)

The power coupled from the i th mode of the main fiber A to the i th mode of the side fiber B is then $P_{A\rightarrow B,i} = \sin^2(|\overline{C_i}|z)$ where z = length of coupler. If the mode number i is treated as a continuous variable, and if all modes carry equal power, the coupling efficiency is

$$\eta_f = \frac{P_{A\rightarrow B}}{P_{in}} \leq \frac{1}{N}\int_0^N \sin^2(|\overline{C_i}|z)\, di$$

For the present case, where $d/2a \simeq 2.5$, and for z = a few centimeters,

$$\sin^2(|\overline{C_i}|z) \cong |\overline{C_i}|^2 z^2$$

and carrying out the integration,

$$\eta_f = \frac{2z^2A^2}{d/2a} F(b)$$

where: $A = (2\Delta)^{1/4}/(\pi k n_o a^3)^{1/2}$

$$b = 4\sqrt{2N}\left(\frac{d}{2a} - 1\right)$$

$$F(b) = \left(\frac{2}{b^3} - \frac{48}{b^5} + \frac{720}{b^7}\right) - \exp(-b)\left(\frac{8}{b^3} + \frac{72}{b^4} + \frac{312}{b^5} + \frac{720}{b^6} + \frac{720}{b^7}\right)$$

Figure 10a shows the theoretical value of η_f as a function of coupling length z and as a function of d/2a, allowing for variations in d in the fibers, evaluated for the ITT step index fiber of Table III.

The experimental results for couplers of 13 mm, 24 mm, 34 mm, and 45 mm in length are shown in Figure 10b. These couplers were constructed using the same three fibers by assembling, disassembling, and reassembling the couplers in sequence. The maximum values for η_f are for P_2 maximized and the minimum values are for P_1 maximized. In all cases, the experimental values exceeded the theoretical values, indicating that a much stronger coupling effect is occurring than the theoretical model considers. The data at z = 34 mm is noteworthy since it indicates that the approximation of $\sin^2|\overline{C_i}|^2 z^2) \cong |\overline{C_i}|^2 z^2$ is no longer valid. In Ogawa's theory, this approximation is valid for $d/2a \geq 1.05$ whereas the present case is for

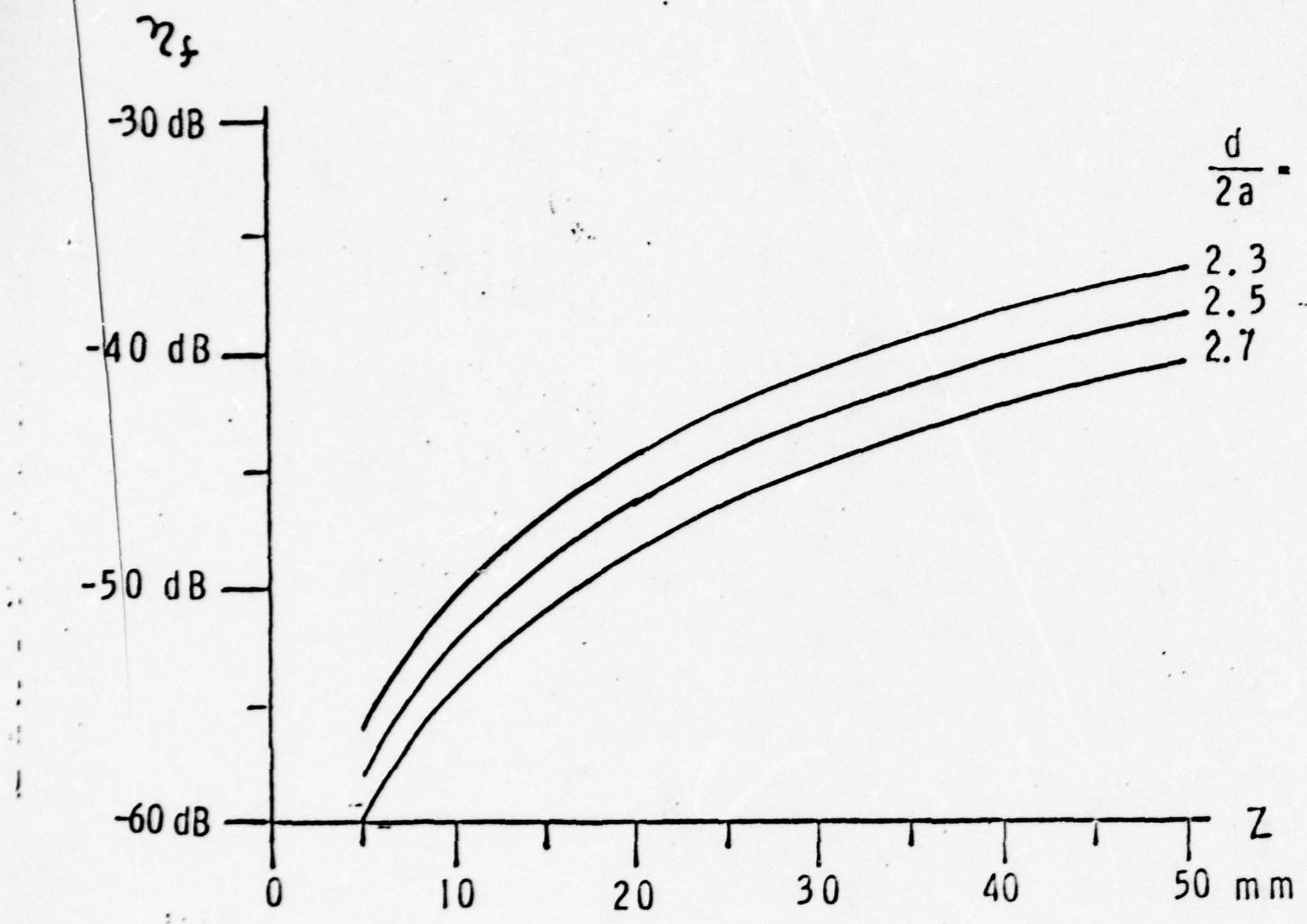


Fig. 10a, Theoretical maximum forward coupling ratio versus coupler length Z and spacing-to-core diameter ratio d/2a (for ITT step index fiber with a = 25 μm).

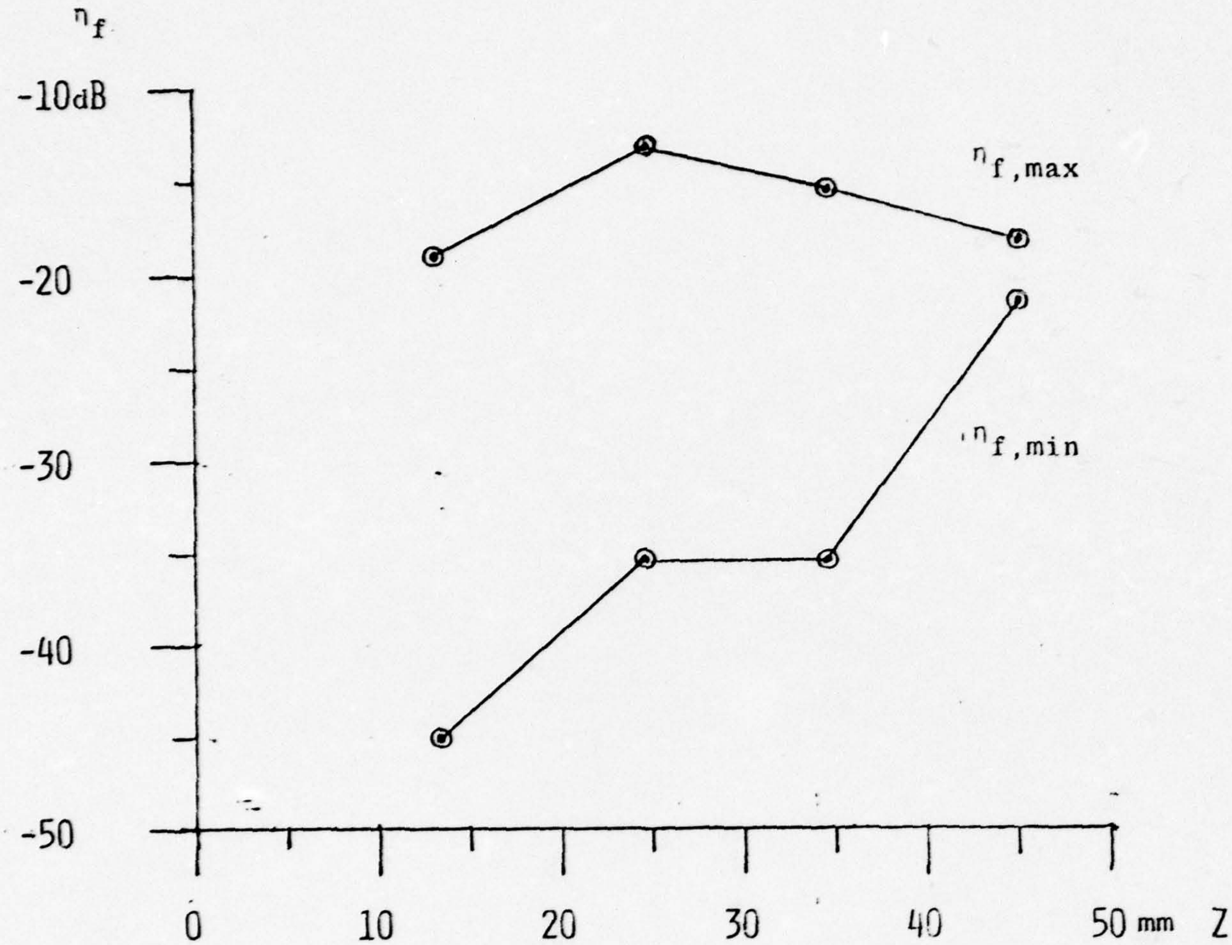


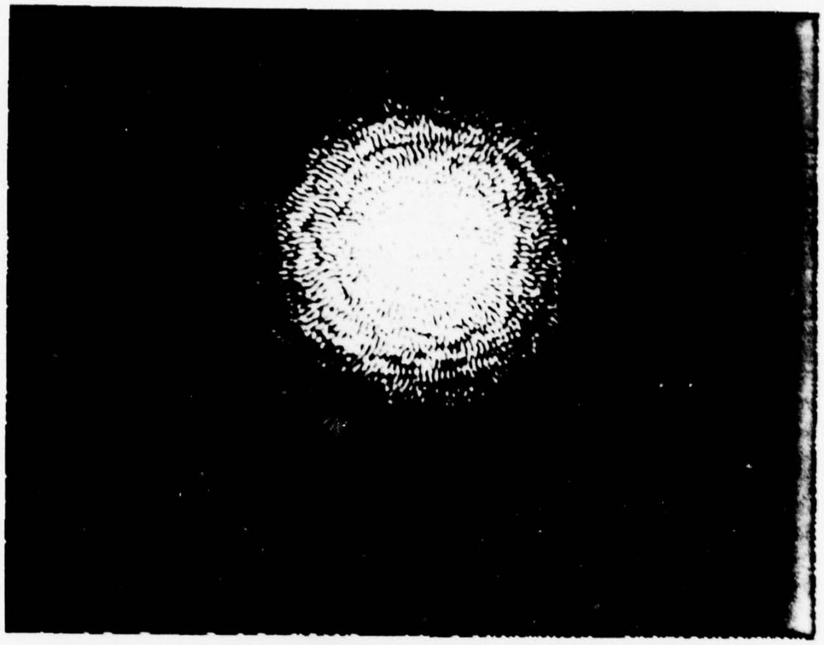
Fig. 10b. Experimental Forward Coupling Ratio versus Coupler Length z.
(ITT graded index fiber; 30 m input length; 20x objective)

$d/za = 2.5$. This decrease in η_f at $z = 34$ mm indicates that some of the energy coupled from the main fiber into the side fiber is recoupled back into the main fiber.

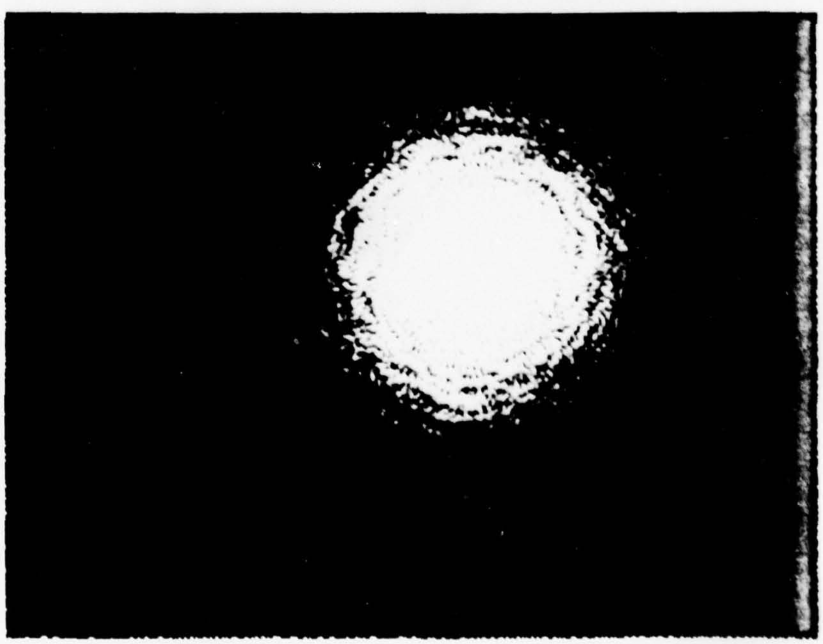
Two different explanations were advanced to explain this increased η_f and the recoupling. The first was that the modes are not all uniformly excited but instead mostly higher orders are excited. This would increase the theoretical η_f. Conversely, if only lower order modes were excited, then the theoretical values would be less than that shown in Figure 10. This was investigated by observing the mode patterns of the side fibers (P_2) in the far field. This is shown in Figure 11a for the case when P_2 was maximum (η_f maximum). If only higher order modes were present, then a characteristic "doughnut" pattern would have been observed. However, the peak of intensity in the center, as shown in Figure 11a, indicates that a large number of lower order modes is still present.

Conversely, if only lower order modes were present, then η_f should be lower than the theoretical values shown in Figure 10a. This condition was approximated by maximizing P_1, and the resulting mode pattern of P_2 is shown in Figure 11b. Here the number of lower order modes is much greater than in Figure 11a since the intensity in the center is increased. However, the experimental η_f was still greater than the theoretical value of Figure 10a.

The second theory of the increased coupling is that of perturbed boundary conditions where the fibers are in contact, similar to frustrated total internal reflection. Using ray theory, as shown in Figure 12, any ray in the main fiber which strikes the contact line will enter the side fiber. Other rays will be contained within the fiber until, after multiple reflections, they also strike the contact line. Since the higher order



a)



b)

Fig. 11 a) Mode pattern of P_2 when P_2 is maximized (η_f maximized)

b) Mode pattern of P_2 when P_1 is maximized (η_f minimized)

(ITT step index fibers, 45mm interaction length, 50m input length)

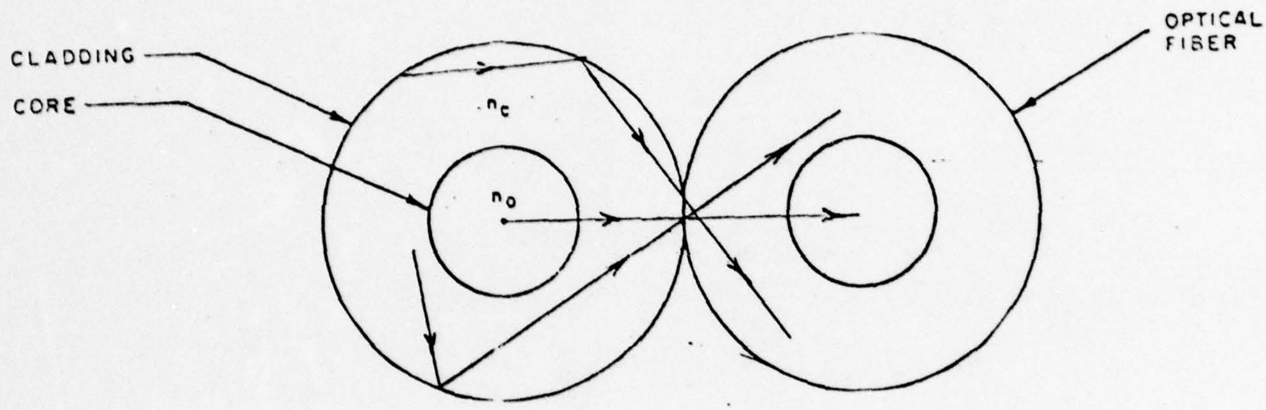


Fig. 12. Coupling of meridional and skew rays from main to side fiber by frustrated total internal reflection.

modes have larger ray angles with respect to the center line, they will have more reflections/unit length and will couple more strongly than lower order modes. In theory, the fibers touch only in a line. However, the fibers are in close proximity on either side of this line and energy will be coupled through frustrated total internal reflection. Increased pressure on the alignment rods will increase the pressure on the fibers and will increase this contact area leading to increased η_f.

An attempt was made to calculate η_f theoretically using ray theory. This was based on a method of Cherin and Murphy and involved calculations coupling loss for each possible ray angle, both for meridianal and skew rays[8]. This involved a search and summing technique which proved to be a very inefficient program and exceeded the alloted computer time. It was not possible to streamline the program and complete this work during the contract period. A method of calculating the coupling between fibers using numerical methods based on mode theory has been developed by Yeh and appears applicable to the present coupler[9].

The conclusion concerning the coupling mechanism is that the boundary condition is altered at the line of contact between the two fibers, allowing energy to leak only through this altered boundary while still guiding the energy in the remainder of the fiber volume.

6.0 DEPENDENCE OF COUPLING UPON FIBER TYPE

In the previous research, the couplers constructed used fibers from only one manufacturer - ITT step and graded index (see Table III). These were W-type or doubly clad fibers, as shown in Figure 13, which have a thin intermediate layer of lower index of refraction between the core and cladding. The purpose of this layer is to confine the modes of the fiber

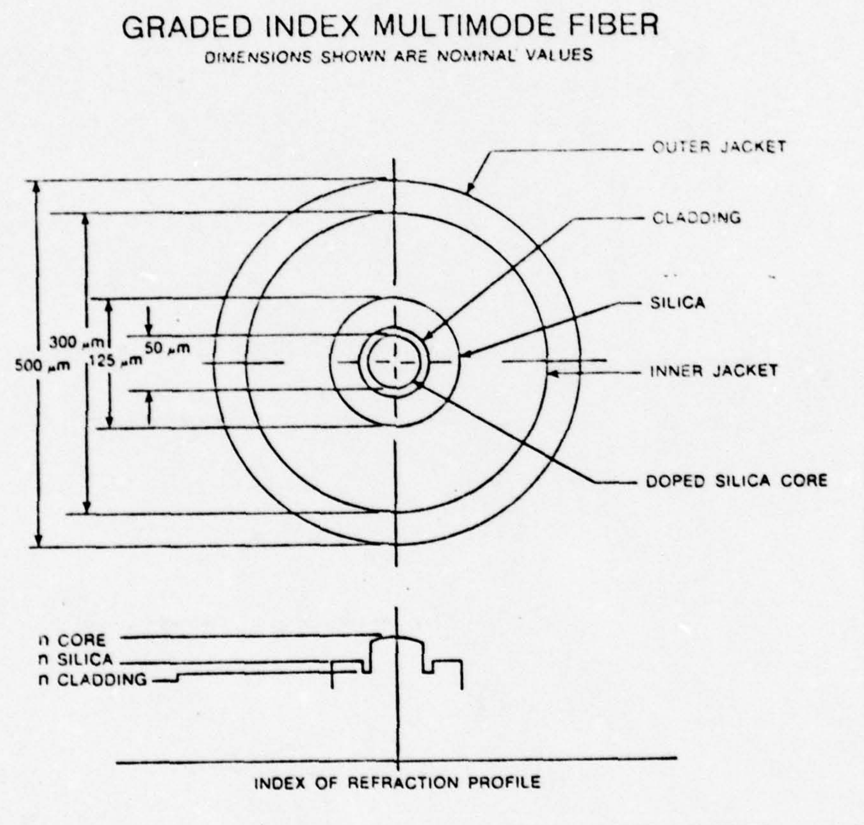


Fig. 13 Dimensions and Index of Refraction Profile of a W-Type Fiber (Courtesy of ITT Electro-Optical Products Division).

more strongly within the core. However, Maeda and Yamada have shown that if this layer thickness is not carefully controlled (±0.5 m), its presence may lead to leaky modes being propagated on the fiber for distances greater than 1 km[10].

In the present research, couplers were constructed from fibers from ITT and two other manufacturers. The results are summarized in Table VI.

TABLE VI

Forward Coupling Coefficient for Different Fibers (see Table III)
(45 mm coupling length; 1-3 m fiber length; 20x objective)

	Manufacturer			
	ITT[11]	ITT[11]	Corning[12]	Valtec[13]
Type of index gradient:	Step	Graded	Graded	Graded
Type number:	GS-02-08	GG-02-08	1054	MG05-01
η_f, min (dB):	-37.21	-21.3	-58.1	-20.8
η_f, max (dB):	-10.2	-17.7	-44.1	-7.8
d_{core}:	50 μm	50 μm	63 μm	51.3 μm
N:	1,924	962	1,078	857
N.A.:	0.25	0.25	0.21	0.23
Loss (dB/km)	5.33	3.90	9.1	9.56

There is no clear correlation between the experimental η_f and the physical parameters of the fibers listed here. There is a weak dependency of η_f upon NA: a higher NA gives higher coupling. Initial results with the Valtec fiber showed results similar to those of the Corning fiber, but the protective coating of the Valtec fiber had not been completely removed. Complete removal of the protective coating with a Teflon stripper increased the coupling to the value shown in Table VI. The other fibers were also checked for coating removal but showed no change in performance.

The only conclusion that can be drawn from this part of the investigation is that the coupling effect is heavily dependent upon the particular fiber used and somewhat dependent upon the numerical aperture. The coupling efficiency apparently has no dependency whether the fiber is step or graded index or is W-type.

7.0 EFFECT OF INPUT FIBER LENGTH

The previous research tentatively indicated a dependence of the forward coupling efficiency upon the length of the input fiber[1,2]. The experiments there showed a decrease in coupling ratio for a He-Ne laser source when the input length was changed from approximately 0.5 m to 240 m for ITT step index, and from 0.7 m to 100 m for ITT graded index fiber. The difference between η_f (max) and η_f (min) also decreased. Similar results were shown for GaAlAs LED sources. These results were explained by assuming that some of the leaky modes on the fiber were of a type known as tunneling leaky modes, which may persist for hundreds of meters[14]. In this portion of the present investigation, a series of couplers was constructed from ITT step index fiber using the same alignment rods each time but with a different input fiber length each time. The results are shown in Figure 14 for both $\eta_{f,\,min}$ ($P1_{max}$) and $\eta_{f,\,max}$ ($P2_{max}$). The results show a length dependence when higher order modes are deliberately excited for $\eta_{f,\,max}$. The data point of $\eta_{f,max}$ = +1.4 dB at 1 meter occurred when the input fiber was tilted as well as offset to maximize P_2. This clearly shows that the coupling effect is primarily due to higher order modes which are known to be more highly attenuated with length than

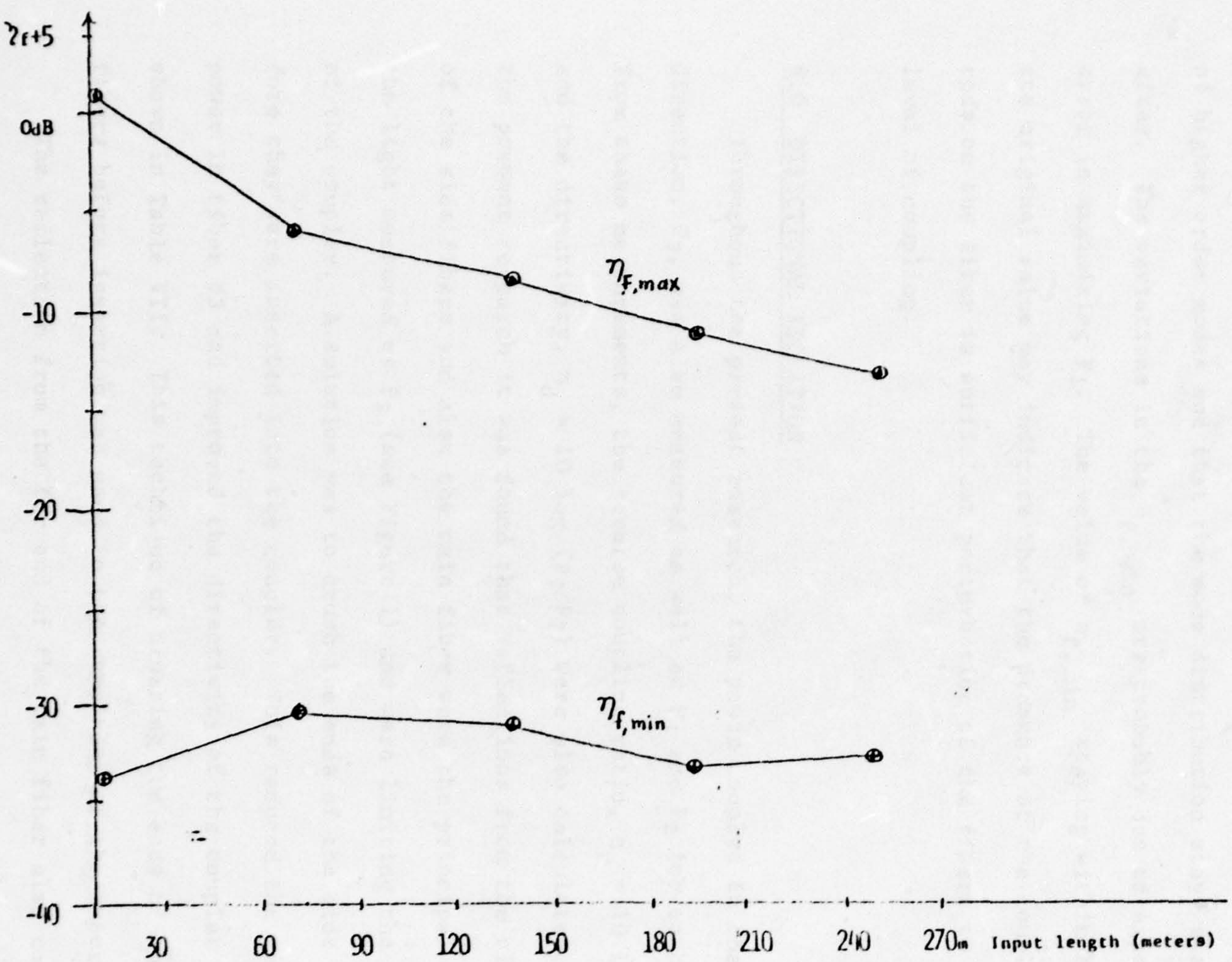


Fig. 14. Dependence of maximum and minimum forward coupling ratios, $\eta_{f,max}$ and $\eta_{f,min}$ upon the input fiber length. (ITT step index fiber; 35 mm interaction length; 20x objective).

the lower order modes. The minimum coupling, $\eta_{f,min}$ shows no length dependence indicating that the input conditions have minimized the number of higher order modes and that the mode distribution stays stable thereafter. The variations in the $\eta_{f,min}$ are probably due to experimental error in maximizing P_1. The value of $\eta_{f,min}$ staying within a few dB of its original value may indicate that the presence of the coupler alignment rods on the fiber is sufficient perturbation of the fibers to yield this level of coupling.

8.0 DIRECTIONAL ISOLATION

Throughout the present research, the power coupled in the reverse direction, P_3, was also measured as well as P_1 and P_2 for each coupler. From these measurements, the reverse coupling ratio, $\eta_r = 10 \log (P_3/P_1)$ and the directivity, $\eta_d = 10 \log (P_3/P_2)$ were also calculated. Early in the present research it was found that reflections from the cleaved ends of the side fibers and also the main fiber were the principal sources of the light measured as P_3 (see Figure 1) and were limiting the directivity of the coupler. A solution was to crush the ends of the side fibers before they were inserted into the coupler. This reduced the reflected power in fiber #3 and improved the directivity of the coupler greatly as shown in Table VII. This technique of crushing the ends of the side fibers before insertion was used in the remainder of the experiments.

The reflection from the far end of the main fiber also contributed to the light coupled into P_3. This reflection could be reduced by terminating the far end of the main fiber in index matching fluid, thereby reducing η_r and increasing η_d by a few dB. In some couplers, the reverse coupled power, P_3, was below the measuring ability of the apparatus (~1nwatt).

TABLE VII

Improvement in Directivity of Coupler
(ITT graded index; 34 mm interaction length, 40x objective)

	Power Maximized	η_r(dB)	η_d(dB)
Before crushing	P_1	-49.1	10.6
side fiber ends	P_2	-36.0	20.7
After crushing	P_1	-60.6	21.8
side fiber ends	P_2	-45.7	29.7

In all of the preceding sections of this report, only the coupling of light out of the main fiber has been considered. A potential use of the three-fiber coupler is to couple light from a side fiber into the main fiber. Several experiments of this type were performed and typical arrangement and results are shown in Figure 15 for P_1 maximized. This indicates that this type of coupler could also be used as a data input port.

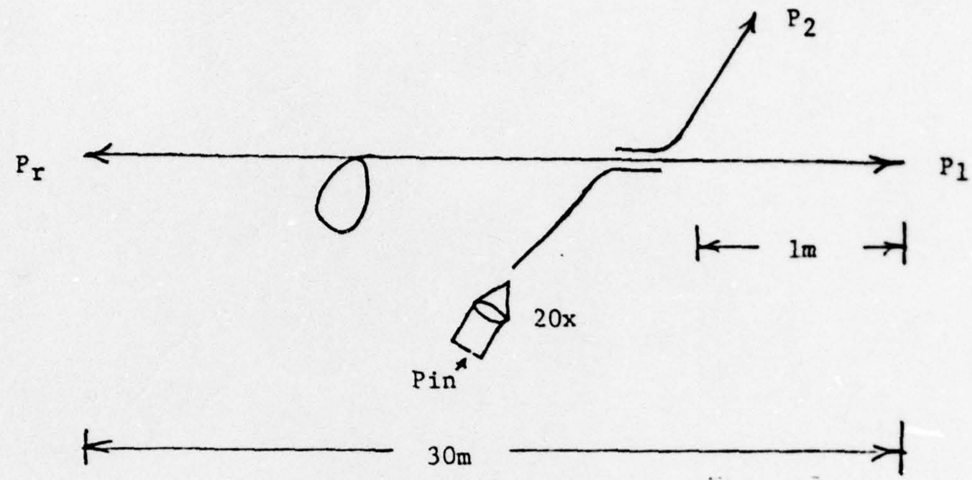
9.0 SUMMARY AND CONCLUSIONS

This investigation of the three-fiber multimode coupler has produced the following results:

1) The forward coupling ratio, η_f, was shown to increase for gross perturbations of the surface of the alignment rods (i.e. threads), but only for higher order mode launching input conditions.

2) η_f is increased by placing additional pressure on the alignment rods, but again only for higher order mode launching conditions.

3) The forward coupling ratio increased with increasing length of the alignment rods, but showed an anomoly at 34 mm length. This was possibly due to a reverse coupling.



$$\eta_f = 10 \log (P_1/P_{in}) = -22.8\text{dB}$$

$$\eta_r = 10 \log (P_r/P_{in}) = -46.8\text{dB}$$

$$\eta_d = 10 \log (P_1/P_r) = +31.1\text{dB}$$

Where P_{in} = 2.4mW from He-Ne Laser.

Fig. 15 Three-fiber coupler used as an input port to main fiber (ITT graded index, 34mm interaction length)

4) The forward coupling ratio depends strongly upon the presence of higher order modes in the main fiber. However, appreciable power can be coupled out of the main fiber even for a mode distribution of mostly lower order modes.

5) The forward coupling ratio depends strongly on the fiber manufacturer, and is somewhat influenced by the numerical aperture of the fiber.

6) The forward coupling ratio decreases with an increase in the fiber length between source and coupler, but only for higher order mode launching conditions. For lower order modes, a minimum value is always present and is relatively constant with length.

7) The directivity of the coupler was greatly improved by reducing the reflections from the cleaved ends of the side and main fibers.

8) The three-fiber coupler can be used as an input port as well as an output port.

The performance of this type of coupler can be maximized by constructing the coupler from Valtec graded index fiber with 45 mm long threaded alignment rods held together with a single sleeve of heat shrink tubing. The forward coupling ratio is expected to be between -8 to -20 dB depending upon the source and launching condition. For an LED or ILD source, a higher coupling ratio is expected.

10.0 SUGGESTIONS FOR FURTHER RESEARCH

The first step to continue this research would be to measure the coupling ratios for LED and ILD sources. These are appearing as the sources of choice in most fiber-optic communications systems, and higher coupling ratios are expected. Secondly, the influence of stress on the coupling ratio should be investigated more thoroughly. This work is already in progress[6]. The influence of the periodic perturbations upon the coupling coefficient should be studied to determine if changing the period of the perturbation (the number of threads/unit length) will increase the coupling. Lastly, since the presence of a discontinuity in the fiber, such as a connector, increases the coupling ratio, this type of coupler should be tested in a fiber system of several km length where the main fiber of the coupler is placed in the system with electric arc fused connections.

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APPENDIX A

PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH REPORT

PRINCIPAL INVESTIGATOR:

Dr. Marvin D. Drake
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Florida Institute of Technology
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Education: Ph.D. in Electrical Engineering, The John Hopkins University, 1970

Thesis Title: "Binary Light Beam Deflection in Single Crystal Barium Titanate"

B.S. in Electrical Engineering (cum laude), University of Toledo, 1960

Employment: Associate Professor, Department of Electrical & Computer Engineering, Florida Institute of Technology, 1979 to present
Assistant Professor, 1975 to 1979

Faculty Associate, 1977 USAF/ASEE Summer Faculty Research Program

Consultant, DBA Systems, Inc., Melbourne, Florida

Consultant, Harris Semiconductor, Melbourne, Florida

Consultant, Digital Equipment Corporation, Maynard, Massachusetts

Associate Principal Research Engineer, Harris Corporation, Melbourne, Florida, 1971-1974

Member of Technical Staff, Systems Group of TRW, Inc., Washington Operations, McLean, Virginia, 1970-1971

Research Staff Assistant, Carlyle Barton Laboratory, Institute for Sponsored Research, The John Hopkins University, Baltimore, Maryland, 1962-1970

Publications & Presentations: "A Multimode Fiber-Optic Coupler with Low Insertion Loss," Applied Optics, October, 1978.

"PLZT Matrix-Type Block Data Composers," Applied Optics, February, 1974. Also presented as Paper 18.5 at the 1973 Conference on Laser Engineering and Applications.

"PLZT Block Data Composers Operated in Differential Phase Mode," (with D. E. Klingler), paper 30/3 presented at the 1973 WESCON Convention.

"Characteristics of Wide Aperture PLZT Electrooptic Shutters," presented at Winter Meeting, Florida Section of Optical Society of America, January 29, 1977.

"FAA Lightning Protection Study: Lightning Protection Requirements for Wilcox I/D Instrument Landing System," Report No. FAA-RD-77-102, May, 1977 - Contract No. DOT-FA WA I-356.

Publications & Presentations (Continued):

"FAA Lightning Protection Study: Lightning Protection Requirements for Runway Visual Range Systems," (with A. W. Revay, Jr., and R. M. Cosel), Report No. FAA-RD-75-181, June, 1975 - Contract No. DOT-FA-72 WA I-356.

"Binary Light Beam Deflection in Single Crystal Barium Titanate," (with R. I. Joseph and C. Harvey Palmer, Jr.), Journal of Applied Physics, April, 1971. Also presented at the IEEE Symposium on Applications of Ferroelectrics, June, 1971.

Air Force Technical Report AFAL-TR-70-197, "Binary Light Beam Deflection in Single Crystal Barium Titanate," August, 1970 (Air Force Avionics Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio).

Contributions to "Updated Optical Read/Write Memory System Components" prepared by Electro-Optics Operations, Harris Corporation, for George C. Marshall Space Flight Center, Huntsville, Alabama, under NASA Contract NAS-8-26672, Quarterly and Final Reports for 1972-1974.

Experience:

Research on low loss fiber optic couplers and fiber optic lenses.

Research and development of (Pb, La) (Zr, Ti) O_3 ferroelectric ceramic electro-optic input devices for holographic data processing and storage systems: Two-dimensional matrix addressed memory and one-dimensional non-memory block data composers.

Research on the electrode edge effects in PLZT electro-optic modulators. Study of the characteristics of wide aperture electro-optic shutters utilizing PLZT ceramics.

Research and development of acousto-optic devices. Theoretical comparison of expected performance of various acousto-optic materials in one-dimensional block data composers. Directed fabrication of 100 channel block data composers from SF-59 and As_2S_3 glasses.

Research on the properties and growth of several ferroelectric and electro-optic materials and their applications to optical data storage, processing and display systems.

Research on an electro-optic beam deflector using single crystal barium titanate.

Studies of the Lightning Protection Requirements for FAA Runway Visual Range System and Wilcox I/D Instrument Landing System.

Study on the use of Light Emitting Diodes for Flat Panel Display of Alphanumeric and graphical data.

Courses Initiated:

Introduction to Optical Electronics (Graduate course). Text: "Introduction to Optical Electronics," 2nd Edition, Amnon Yariv; Holt, Rinehart, and Winston, Pub., 1976.

Optical Fiber Communications (Short course presented at Patrick Air Force Base, Summer, 1978). Text: "A User's Manual for Optical Waveguide Communications," R. L. Gallawa, U.S. Dept. of Commerce.

Optical Communications (Graduate course). Text: "Fundamentals of Optical Fiber Communications," M. K. Barnoski, Ed., Academic Press, 1976.

Electro-optic and Acousto-optic Devices and Systems (Graduate course). Text: "An Introduction to Electrooptic Devices," I. P. Kaminow, Academic Press, 1975.

Introduction to Lasers (Undergraduate course). Text: "Introduction to Lasers and Their Applications," O'Shea, Callen and Rhodes, Addison-Wesley, 1977.

Other Courses Taught:

Physical Electronics and Electron Devices. Text: "Solid State Electronic Devices," B. G. Streetman, Prentice-Hall, 1972.

Electromagnetic Fields. Text: "Electromagnetic Fields and Waves," P. Lorrain and D. R. Corson, W. H. Freeman and Co., 2nd Edition, 1970.

Circuit Theory. Text: "Basic Circuit Theory with Digital Computations," L. P. Huelsman, Prentice-Hall, Inc., 1972.

Electronic Circuits. Text: "Electronic Analysis and Design," Hayt and Neudeck, Houghton Mifflin Co., 1976.

Direct Energy Conversion. Text: "Direct Energy Conversion," 3rd Ed., S. W. Angrist, Allyn and Bacon, Inc., 1976.

Communication Systems. Text: "Information Transmission, Modulation, and Noise," Mischa Schwartz, McGraw-Hill Book Co., 2nd Edition, 1970.

Master's Theses Supervised:

"Electrode Edge Effects in Electrooptic Modulators," Paul C. K. Chung, 1976.

"Pulse Dispersion and Information Capacity in Single-Mode Glass Fiber Waveguide," George P. Osolsobe, 1978.

"The Three Stub Alignment Method for Maximizing Transmission Through Optical Fiber Junctions," David F. Richards, 1978.

Research Interests:

Fiber-optic components and mode theory. Electro-optic, acousto-optic and ferroelectric materials and devices and their applications to optical data processing, communication, storage and display systems.

Patents Filed:

"Electro-Optical Birefringent Device," Filed April 15, 1974, Serial Number 460,741.

"Phase Modulated Electro-Optical Memory," (with D. E. Kingler), filed May 23, 1974, Serial Number 472,712.

Grants:

Research Equipment Grant, Florida Institute of Technology, December, 1978.

"Investigation of Multimode Fiber Optic Coupler," U.S. Air Force, Office of Scientific Research, AFOSR-78-3566, April 1, 1978.

APPENDIX B

ADVANCED DEGREES AWARDED

David F. Richards

Master of Science in Electrical Engineering, August, 1978

Thesis Title: The Three Stub Alignment Method for Maximizing Transmission through Optical Fiber Junctions.