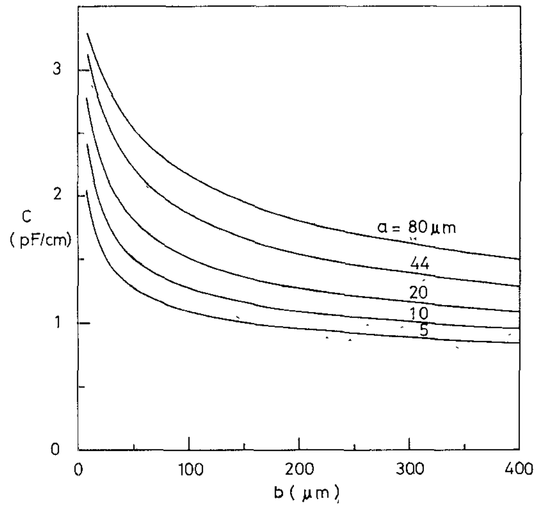

Fig. 3. Calculated capacitance between parallel-strip electrodes on Li–Nb–O_3 crystal ($\epsilon_x^* = 28$, $\epsilon_y^* = 43$, $h = 2$ mm).

where

$$Q = \int_0^\infty f(x)\,dx. \tag{5}$$

The function $\tilde{g}(\beta)$ is found to be

$$\tilde{g}(\beta) = \frac{1}{\epsilon_0\beta}\cdot\frac{\tanh\left[(\epsilon_x^*/\epsilon_y^*)^{1/2}\beta h\right] + (\epsilon_x^*\epsilon_y^*)^{1/2}}{(1+\epsilon_r^*\epsilon_y^*)\tanh\left[(\epsilon_x^*/\epsilon_y^*)^{1/2}\beta h\right] + 2(\epsilon_x^*\epsilon_y^*)^{1/2}}. \tag{6}$$

It is noted here that the Green's function in the transformed domain $\tilde{g}(\beta)$ for multilayer structures can also be derived easily. Approximate values of C are obtained by suitably choosing $f(x)$ to minimize the integral (4). The modulation bandwidth is then given by $(\pi RC)^{-1}$ where R is a parallel load resistance [1].

III. NUMERICAL RESULTS

The case of Li-Nb-O_3 crystal ($\epsilon_x^* = 28$, $\epsilon_y^* = 43$, $h = 2$ mm) has been treated as an example. Calculated capacitance values are shown in Fig. 3 where $f(x)$ in the first-order approximation has been assumed to be constant on both electrodes. The narrower gap between the electrodes is the better to minimize the modulation power for a constant electric field in the crystal. On the contrary, the wider gap between the electrodes is the better to give uniform modulation effects in the cross section of the optical beam. Therefore, there must be an optimum value of b for a constant value of a to trade these requirements. The uniformity of the electric field in the optical beam can be estimated by taking the inverse transform of $\tilde{\Phi}(\beta,y)$.

The existence of the optical guide layer (about 50 μm) has been neglected in calculating the capacitance since the change of dielectric constant in this region is considered to be negligible. However, it is possible, if necessary, to take into account this layer by using $\tilde{g}(\beta)$ of multilayer structures.

ACKNOWLEDGMENT

The authors wish to thank Prof. T. Okabe for his helpful advice.

REFERENCES

[1] I. P. Kaminow, J. R. Carruthers, E. H. Turner, and L. W. Stulz, "Thin-film $LiNbO_3$ electro-optic light modulator," *Appl. Phys. Lett.*, vol. 22, pp. 540–542, May 1973.
[2] E. Yamashita and S. Yamazaki, "Parallel-strip line embedded in or printed on a dielectric sheet," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 972–973, Nov. 1968.
[3] E. Yamashita, "Variational method for the analysis of microstrip-like transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 529–535, Aug. 1968.

Power Transfer of a Parallel Optical Fiber Directional Coupler

H. KUWAHARA, J. HAMASAKI, AND S. SAITO

Abstract—**This letter describes experimental results of a simple optical fiber directional coupler which picks up a small portion of the transmitted power in a main optical fiber transmission line without affecting the characteristics of the main line. This directional coupler consists of two fibers closely parallel in a certain coupling length; an index matching liquid, Si-oil, fills the coupling region. A 50-dB power coupling and 21-dB directivity are measured. Insertion loss is almost negligible. The measured power coupling is much larger than that expected by the simple coupling theory.**

For monitoring the power or the waveform in an optical fiber transmission line, a directional coupler which picks up a small portion of the power from the main optical fiber without disturbing its transmission characteristics is often needed. This letter describes experimental results of a directional coupler which can be constructed without breaking off the main line. The experimental directional coupler is constructed by using a multimode fiber of a normalized frequency [1] $V = 25.58$. The core glass of $n_1 = 1.620$ and the cladding glass of $n_2 = 1.518$ have the diameter of 9 μm and 13 μm, respectively. As shown in Fig. 1, two fibers are loosely twisted in order to keep the separation as small as possible and fixed on a microscope slideglass by adhesive. A few drops of index matching silicon oil of $n = 1.510$ fill the coupling region between the two fibers.

By using a fundamental mode He–Ne laser ($\lambda = 0.6328$ μm) as a light source, a directivity of 21 dB is measured when the reflected power at port 2 in Fig. 1 is kept minimum by immersing the port and an absorber in the index matching oil. Power transfer of 49 dB and 54 dB are measured for directional couplers of 4.6 cm and 2.3 cm coupling length, respectively. The insertion loss is very small because of the short fiber length.

When a propagating wave amplitude of the pth mode of the jth fiber is denoted $a_p^{(j)}$ ($j = 1,2$), and the wave propagates along the z-direction, according to Synder [2], the following equation describes the wave propagation:

$$da_p^{\left(\substack{1\\2}\right)}/dz + i\beta_p a_p^{\left(\substack{1\\2}\right)} = i\sum_q C_{pq} a_q^{\left(\substack{2\\1}\right)}$$

where β_p is the propagation constant of the pth mode and C_{pq} is the coupling coefficient.

Assuming only the HE_{1m} modes are excited in the fibers, the coupling coefficient C_{pq}, the complete power transfer length $l = \pi/2C_{pq}$ and power transfer $\sin^2 C_{pq}z$ are calculated by a numerical integration method. They are shown in Table I. When the main fiber is excited by a pure HE_{11} mode, from this table the coupling power of the same mode in the secondary fiber should be too small to observe. Assuming that the pth mode of the main fiber is predominantly coupled with the qth mode of the secondary fiber, $C_{pq} = 0.077$ m is obtained from the experimental results. Since only weak power is transfered to the secondary fiber, its mode power distribution is unclear. Though it qualitatively agrees with the experimental data, a more resaonable explanation of the experimental power transfer still has to be investigated.

In conclusion, the power transfer of the present directional coupler is smaller but much larger than that predicted by a simple coupling theory. It has a simple construction and can be used in extracting a small amount of power from an optical fiber transmission line.

Manuscript received March 27, 1974; revised July 24, 1974.
H. Kuwahara is with the Fujitsu Laboratory, Kawasaki, Japan.
J. Hamasaki and S. Saito are with the Institute of Industrial Science, University of Tokyo, Tokyo, Japan.

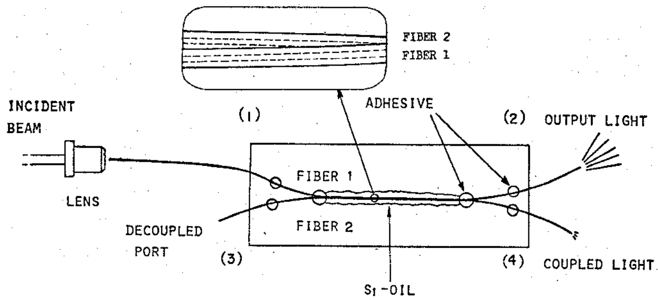

Fig. 1. Directional coupler made up of two parallel fibers.

TABLE I
CALCULATION OF THE COUPLED POWER

MODE	COUPLING COEFFICIENT C_{PP} (M^{-1})	COMPLETE POWER TRANSFER LENGTH $\ell = \pi/2C_{PP}$ (M)	POWER TRANSFER $\sin^2 C_{PP}Z$
HE_{11}	0.1199×10^{-7}	1.3100×10^{8}	2.500×10^{-19}
HE_{12}	0.9445×10^{-7}	1.6631×10^{7}	1.849×10^{-17}
HE_{13}	0.4882×10^{-6}	3.2175×10^{6}	5.018×10^{-16}
HE_{14}	0.2787×10^{-5}	5.6361×10^{5}	1.644×10^{-14}
HE_{15}	0.2157×10^{-4}	7.2823×10^{4}	9.848×10^{-13}
HE_{16}	0.2737×10^{-3}	5.7391×10^{3}	1.585×10^{-10}
HE_{17}	0.7852×10^{-2}	2.0005×10^{2}	1.304×10^{-7}
HE_{18}	$0.1333\times10^{+1}$	1.1801×10^{0}	3.756×10^{-3}

Z=0.046 M

ACKNOWLEDGMENT

The authors wish to thank Associate Prof. Fujii for his helpful advice and the members of the Fujitsu Laboratories, Ltd., for providing the fiber and the reviewers of this letter.

REFERENCES

[1] E. Snitzer, "Cylindrical dielectric waveguide modes," *J. Opt. Soc. Amer.*, vol. 51, pp. 491–498, May 1961.
[2] A. W. Snyder, "Coupling mode theory for optical fibers," *J. Opt. Soc. Amer.*, vol. 62, pp. 1267–1277, Nov. 1972.
[3] A. L. Jones, "Coupling of optical fibers and scattering in fibers," *J. Opt. Soc. Amer.*, vol. 55, pp. 261–271, Mar. 1965.
[4] N. S. Kapany, *Fiber Optics, Principles and Applications.* New York: Academic, 1967.

A Semi-Transparent Mirror-Type Directional Coupler for Optical Fiber Applications

H. KUWAHARA, J. HAMASAKI, AND S. SAITO

***Abstract*—A directional coupler for optical fiber applications is constructed of two pieces of optical fibers cut obliquely and a thin dielectric film. Coupling coefficient −20 dB to −10 dB depending on the refractive index of the dielectric film, insertion loss 1 dB, and directivity −20 dB are measured. They agree with the analytical results.**

In an optical fiber circuitry, a directional coupler which extracts an appreciable amount of power directly from the fiber into an outside detector is often needed. This letter describes results of experiments of a semi-transparent mirror-type directional coupler for multimode optical fibers.

Manuscript received March 27, 1974; revised July 29, 1974.
H. Kuwahara is with Fujitsu Laboratory, Kawasaki, Japan.
J. Hamasaki and S. Saito are with the Institute of Industrial Science, University of Tokyo, Tokyo, Japan.

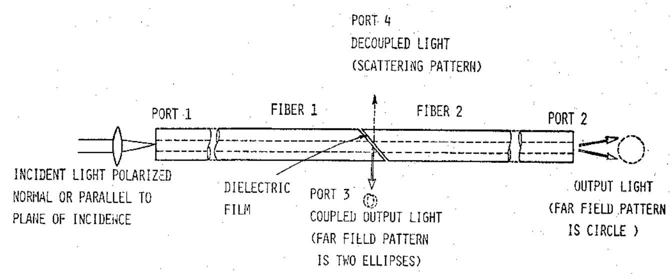

Fig. 1. The directional coupler by dielectric film and its far-field pattern.

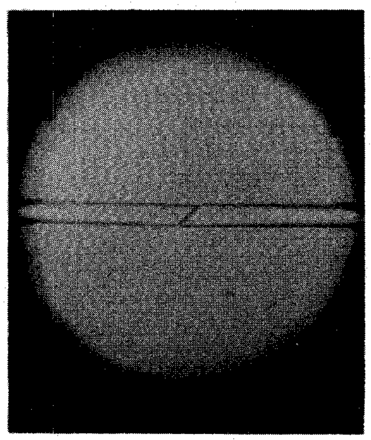

Fig. 2. The optical directional coupler observed in microscope.

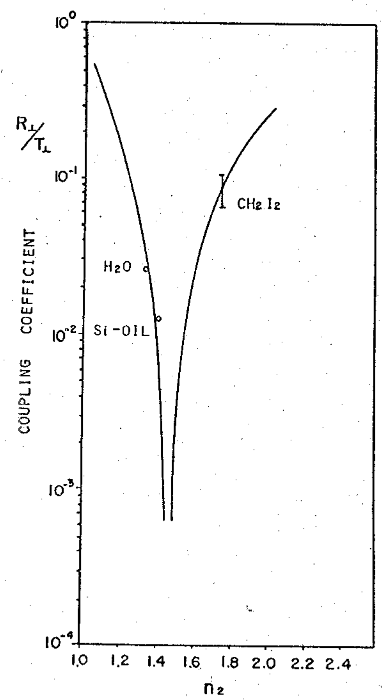

Fig. 3. Coupling efficiency versus refractive index of the dielectric film (n_2).

Fig. 1 shows the construction of the directional coupler. Two pieces of fibers are cut and polished at a 45° angle, and a dielectric film is inserted between the polished surfaces.

Since the diameter of the fiber is much larger than the wavelength of the guided light wave, the characteristics of the coupler are analyzed based on the superposition of plane waves which propagate almost parallel to the fiber axis [1]. The ratio R/T of the power