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Radiation Patterns from Parallel, Optical Waveguide Directional Couplers—Parameter Measurements

By V. RAMASWAMY and R. D. STANDLEY

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A new method for measuring the parameters of optical, parallel, waveguide directional couplers is presented. Basically, we observe the changes in radiation pattern obtained by placing a high, refractive, index coupling prism on the coupled guides as a function of position along the coupler. For a coupler, in a Z cut, Ti-diffused $LiNbO_3$ substrate with 3-μm guides and 3-μm separation, the transfer length is about 1.8 mm at 7266 Å.

I. INTRODUCTION

Parallel coupled waveguides are the basic building block for a number of integrated optical devices; these include switches,[1–6] modulators, and channel dropping or adding filters.[7] The techniques used to measure coupling parameters are often visual in nature. The simplest approach is to observe the energy exchanges between the parallel guides from the surface scattering of these guides viewed through a microscope. However, this is not always feasible; e.g., operation at longer wavelengths away from the visible, with low-loss surface scattering guides, and in cases where the energy at the surface is rather low, as it happens with Ti diffused guides in $LiNbO_3$. In such cases, the technique developed by Ostrowsky et al.[8] is quite useful. They observed the fluorescence from RhB-doped polyurethane film over the strip guides pumped by an argon laser.

In this paper, we present a method found useful in measuring the parameters of such couplers. Basically, the method consists of observation of the interaction length dependence of the coupling via radiation pattern measurements;[9] the radiation patterns are obtained by moving an output coupling prism along the coupled waveguide region.

II. THEORY

2.1 Synchronous couplers

Figure 1 depicts two coupled parallel waveguides where a is the guide width, c is the guide spacing, and L is the length over which the guides are coupled; i.e., the interaction length. We consider the ideal case which assumes that the guides are identical in width and thickness so that perfect synchronism of the unperturbed propagation constants exists; for this case, the normalized field amplitudes in the two guides as a function of length z can be shown to be[10]

$$\begin{aligned} R &= \cos \kappa z \\ S &= j \sin \kappa z, \end{aligned} \tag{1}$$

where R is the field amplitude in the initially excited guide, S is that of the auxiliary guide, and κ is the coupling strength per unit length. We are interested in determining the coupling strength κ per unit length for a coupler of known physical parameters; knowledge of κ permits the selection of L for a coupler of desired overall coupling strength. If, at some point z along the parallel coupled region, we place a prism whose refractive index is higher than that of the waveguides, then power will be radiated from the two waveguides. Thus in the far field we observe a radiation pattern due to the interference of the fields from the coupled waveguides over the coupling length of the prism coupler. If we keep the prism coupling length small compared to $1/\kappa$, say, less than a millimeter, then the far-field radiation pattern would truly be representative of the pattern from two slits separated by a distance of d having relative amplitudes given by eq. (1).

If we assume constant transverse field amplitudes, as seen from Fig. 2, the expression for the radiation pattern is

$$|E|^2 = \frac{\sin^2 u}{u^2}\left(1 + \sin 2Z \sin 2u\frac{d}{a}\right), \tag{2}$$

where

$$Z = \kappa z$$

$$u = \frac{\pi a}{\lambda}\sin\theta$$

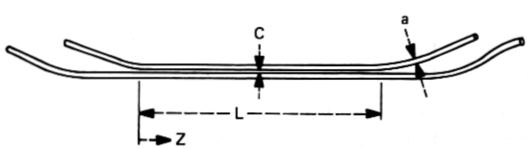
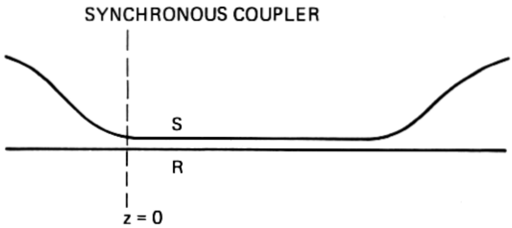
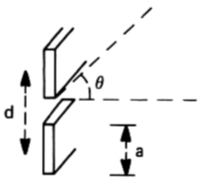


Fig. 1—Parallel waveguide directional coupler where a is guide width, c is the guide spacing, and L is the interaction length.



$$R = \cos \kappa z \;;\quad S = j \sin \kappa z$$



$$E = \left(S + R e^{\frac{j2\pi d}{\lambda}\sin\theta}\right)\frac{\sin u}{u}$$

$$E^2 = \frac{\sin^2 u}{u^2}\left(1 + \sin 2\kappa z \sin \frac{2ud}{a}\right)$$

$$u = \frac{\pi a}{\lambda}\sin\theta$$

Fig. 2—Radiation field amplitudes under far-field conditions due to a pair of sources of width a, separated by a distance d. θ is measured in the plane perpendicular to the plane containing the waveguides.

$$d = a + c$$

θ is radiation angle.

Figure 3 shows computed plots of $|E|^2$ as a function of u for the case $d/a = 2$ with Z as the parameter. Except when all of the energy is in one guide, e.g., at $Z = o$, the radiation pattern is asymmetrical about $\theta = o$. This is true even for the case when $Z = \pi/4$, when the field amplitudes in both guides are equal, and differ by a phase shift of 90 degrees. When Z is increased from $\pi/4$ to $\pi/2$ in specific increments, the patterns remain the same as Z is varied from $\pi/4$ to 0, for the same shape, i.e., for example, identical patterns are observed for the cases when $Z = \pi/16$ and $7\pi/16$, $\pi/8$ and $3\pi/8$, $3\pi/16$ and $5\pi/16$, etc. At $Z = Zo = \pi/2$, complete energy transfer occurs. When Z is varied from $\pi/2$ to $3\pi/4$ and back to π, the graphs shown in Fig. 3 can be used with change in sign of abscissa. The whole series of patterns repeat themselves in this manner with increasing Z.

2.2 *Asynchronous couplers*

If the waveguides differ in width, thickness, or refractive index, their propagation constants will differ. This could occur as a result of errors in the fabrication process. For such asynchronous couplers, complete power transfer from one guide to the other is not possible. If we define

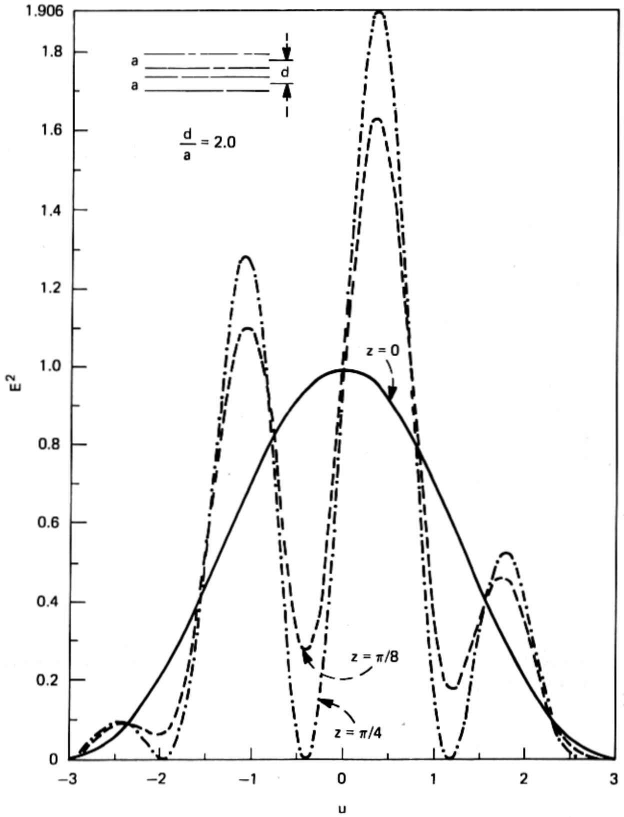


Fig. 3—Computer plots of energy distribution as a function of normalized radiation angle u for the case $d/a = 2$, with $Z = \kappa z$ as the parameter.

the difference in unperturbed propagation constants in the two guides as $\Delta\beta$, then the normalized field amplitudes[6] as a function of z become

$$R' = \cos\alpha - j\frac{\gamma}{\sqrt{\gamma^2+1}}\sin\alpha$$

$$S' = j\frac{\sin\alpha}{\sqrt{\gamma^2+1}}, \tag{3}$$

where

$$\gamma = \Delta\beta/2\kappa$$

$$\alpha = \sqrt{\gamma^2+1}\,\kappa z.$$

Here, again, R' is the field amplitude in the initially excited guide and S' is that of the auxiliary guide. With these field amplitudes, the radiation pattern is given by

$$|E'|^2 = \frac{\sin^2 u}{u^2}\left(1 + \frac{\sin 2(\gamma^2+1)^{1/2}Z}{(\gamma^2+1)^{1/2}} \sin\left(2u\frac{d}{a}\right) - \frac{\gamma}{(\gamma^2+1)}\left[1 - \cos 2(\gamma^2+1)^{1/2}Z\right] \cos\left(2u\frac{d}{a}\right)\right). \quad (4)$$

The power in the coupled guide is obtained by squaring eq. (3) and is given by

$$|S'|^2 = \frac{\sin^2[(\gamma^2+1)^{1/2}Z]}{(\gamma^2+1)}$$

and (5)

$$|R'|^2 = 1 - |S'|^2.$$

We find the maximum value for the coupled power to be $(\gamma^2 + 1)^{-1}$ at $Z = (m\pi/2)(\gamma^2 + 1)^{-1/2}$. Plots of $|E'|$ show the expected result that the information content in the radiation patterns decreases rapidly with increasing asynchronism. However, useful information is obtained by recognizing the transfer period as indicated by all the power being present in the input guide.

III. COUPLER FABRICATION AND MEASUREMENT TECHNIQUE

The procedures used in the fabrication of the experimental couplers are described. Z-cut lithium niobate substrates were coated with polymethyl-methacrylate (PMMA) electron resist approximately 0.5 micron in thickness. A thin layer of aluminum (100 Å) is evaporated onto the

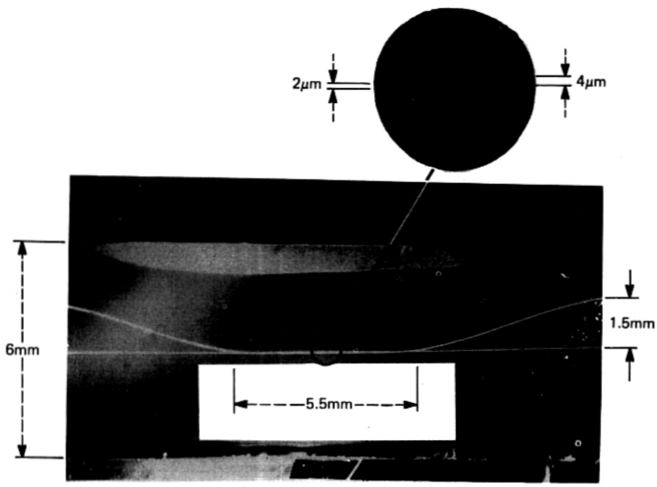


Fig. 4—Guide tracks defined in PMMA after electron beam exposure and development.

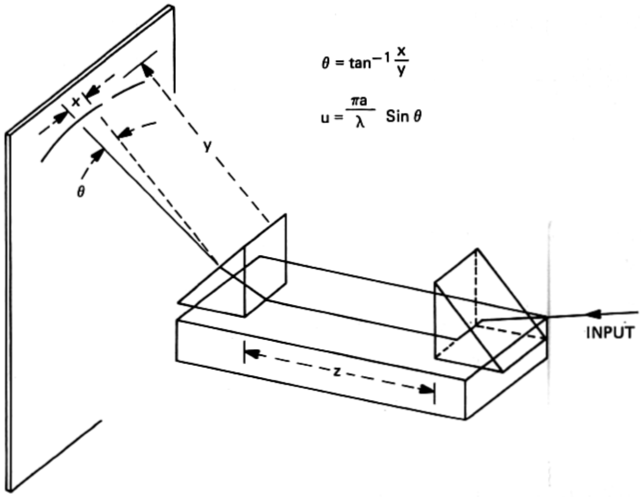


Fig. 5—Illustration of the setup to measure the coupler radiation pattern.

PMMA to eliminate charging problems. The coated substrate is then mounted onto a scanning electron microscope (SEM) stub using a conducting silver paste. Using the appropriate scan generator, the first guide of the coupler is exposed. The scan generator output amplitude is then attenuated and the writing beam moved by electronic adjustment of the fine shift coil current; the auxiliary guide is then exposed. For exposure, a specimen current of 10^{-9} A is typically used with an exposure time of about 25 s to obtain 3-μm wide guides 15 mm in length. The sample is then removed from the SEM. A brief soak in dilute NaOH removes the aluminum layer. The PMMA is then developed for about 30 s in a 3-to-1

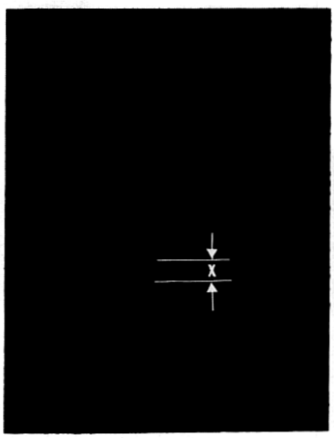


Fig. 6—A typical radiation pattern—in this case, the energy is very close to the position where all the energy is one of the guides.

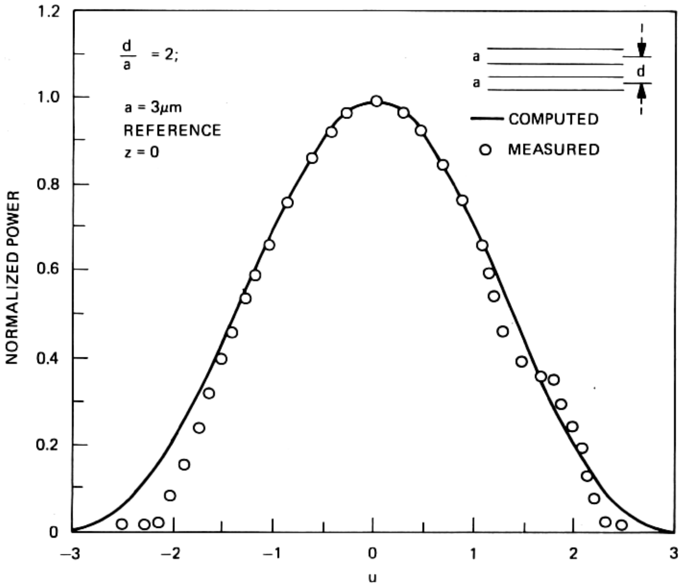


Fig. 7—Radiated power output as a function of normalized radiation angle u where all the energy is in one of the guides, $z = 0$. $d/a = 2$ for this coupler.

mixture of isopropyl alcohol and methylethyl ketone. The guide tracks are now defined in the PMMA (Fig. 4). The sample is blown dry with dry nitrogen and mounted in a sputtering system for deposition of a Ti layer usually about 300 Å thick. The PMMA and excess Ti are next removed by soaking the sample in acetone. At this point, we have a sample with Ti where we want the waveguides. The sample is next placed in an oven and brought to 1000°C in an argon ambient. Following the 1000°C soaking for about three hours, the furnace is turned off and the ambient changed to oxygen. The resulting guides exhibit single TE mode operation.

The experimental set-up used to measure the coupler radiation pattern is shown in Fig. 5. The lasers employed were He-Ne operating at 6328°A and a nile-blue dye laser covering the wavelength 6900°A to 7500°A. The latter source was pumped by the 6471°A line of a krypton laser. The prisms were made of rutile. The input prism was quite flat, allowing strong coupling, whereas the base of the output prism had a curvature in it to ensure the coupling region to be much less than that of a millimeter. Although the amount of energy coupled out is rather small, the resulting radiation pattern is primarily due to the energy of the guide at the output prism location and does not include the effects of long coupling lengths. As the output prism was moved along the guides, the radiation pattern was scanned using an iris. Figure 6 is a photograph of a typical nearly synchronous coupler radiation pattern. The pattern in Fig. 7 resulted from a coupler operating at 7266°A con-

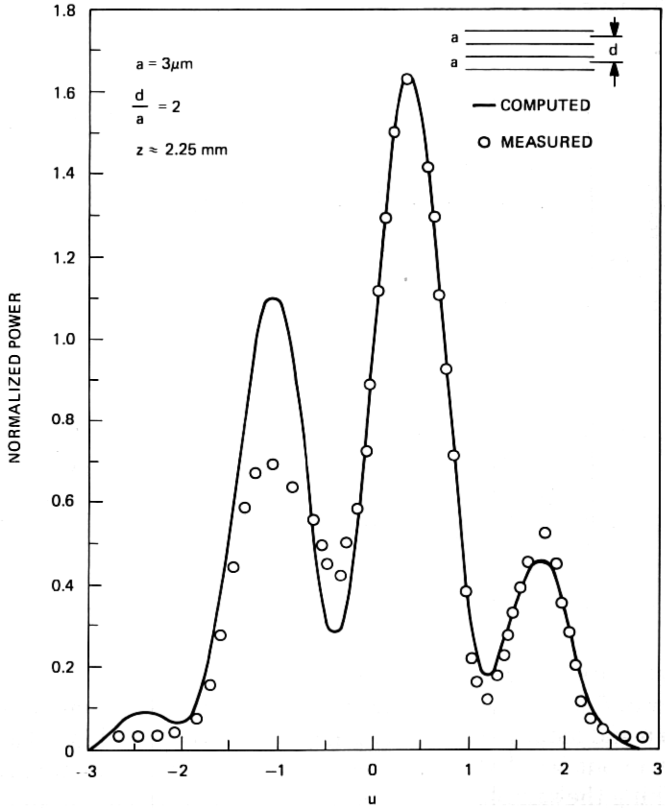


Fig. 8—Radiation pattern of the same coupler shown in Fig. 7, but at a different $z \simeq 5\pi/8$, past the location of complete energy transfer.

sisting of 3-μm guides. The measurement was made at a position $Z = 0$ along the coupler. Where all power was essentially in one of the guides, measured distribution agrees well with the theory. By moving the output prism to a place where all the energy is in the other guide, the transfer length can be measured. However, if the prism is not placed exactly at this location, one can infer this information by noting the nature of the asymmetry and measuring the radiation pattern. For example, Fig. 8 shows the output radiation pattern for the same coupler, but at a different longitudinal position $z = 2.25$ mm. In this case, the power in the two guides is nearly equal, resulting in sidelobe development in the observed radiation pattern. From Fig. 3 for $d/a = 2.0$, the separation Δu between minima is 1.6. At 7266°A, for $a = 3$ μm, this translates into a separation $\Delta x = 2.24$ cm between minima at a distance $y = 18$ cm from the output prism coupling position. This compares favorably with the measured value of 2.25 cm. By a series of observations on this coupler, we can infer an interaction length for full power transfer $L_o = \pi/2\kappa$; the best fit for curve in Fig. 8 occurs at $Z = \pi z/2L_o = 5\pi/8$, from which the transfer length L_o is inferred to be 1.8 mm for this coupler. The separation of the minima agrees very well, although the peaks do not. Considering that we analyze uniform distribution of energy in the waveguides, the agreement is rather good.

IV. CONCLUSION

We have described a method for measuring the coupling strength of synchronous optical waveguide directional couplers by observing the length dependence of the radiated signal. As indicated earlier, the technique is useful, with care in implementation, as a laboratory tool.

V. ACKNOWLEDGMENTS

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