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DARPA-NRL INTEGRATED OPTICS PROGRAM
QUARTERLY TECHNICAL REPORT TO DEFENSE
ADVANCED RESEARCH PROJECTS AGENCY

William K. Burns, et al

Naval Research Laboratory

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December 1974

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**DARPA-NRL Integrated Optics Program
Quarterly Technical Report**

to

Defense Advanced Research Projects Agency

September 1, 1974 - December 1, 1974

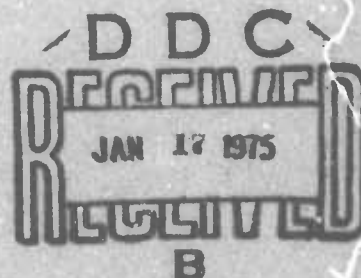
DARPA Order No. 2327

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December 1974



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The ARPA-NRL Integrated Optics program is concerned with the development of infrared integrated optics technology and with the development of a single-mode optical data bus. This report summarizes the NRL in-house progress in the area of indiffused LiNbO ₃ waveguides, separating waveguides for the data bus, and single-mode optical data bus planning. In particular, the results of a theoretical study of separating waveguides are presented.		

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QUARTERLY TECHNICAL REPORT

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TECHNICAL SUMMARY

TECHNICAL STATUS

This report summarizes the results of two journal papers on separating waveguides (references 3 and 4) which we recently submitted for publication.

OBJECTIVES

The main aim of this study is to develop and characterize an electro-optic branching waveguide switch in a LiNbO_3 optical waveguide system. Such a switch could be devised in several ways: as a single electro-optically controlled branch, or by two 3-db couplers (branches or otherwise) connected by an active phase shifter in one arm. Also operation with planar waveguides or three-dimensional channel waveguides could be considered.

THEORETICAL STUDIES

A. Mode Conversion in Branching Waveguides

Branching waveguides have previously been studied experimentally only for cases of very slow tapers and asymmetric branches.⁽¹⁾ It is expected that under more general conditions of arbitrary tapers and symmetry input modes will undergo mode conversion to other guided and radiation modes as they propagate through the branch. This problem of mode conversion in branching waveguides has been extensively studied theoretically under this contract. Using quasi-normal modes and a step transition model to approximate the taper, coupled amplitude equations that describe mode conversion were derived and programmed. This allowed us to study mode conversion as a function of taper slope and mode synchronism, which is adjusted by branch asymmetry. When the taper slope is large in a near symmetric structure, considerable mode conversion will occur and the structure will act as a power divider (Fig. 1b). Incident power concentrated in the upper and lower parts of the structure will end up in the upper and lower arms of the branch, respectively. This behavior is usually required for conventional evanescent couplers. However, in a more asymmetric structure with smaller taper slope, mode conversion is negligible and the structure will act as a mode splitter (Fig. 1a). Mode power is then transferred to one arm of the branch or the other. By using more conventional coupled mode theory we were then able to approximately define the transition boundary between a mode splitter and a power divider by:

$$\Delta\beta/\theta\gamma \lesssim .43$$

Here $\Delta\beta$ is the difference in mode propagation constant for large waveguide separation, θ is the taper slope, and γ is the decay constant of the field in the separating region. Fig. 2 is a plot of computer

calculated, mode converted amplitudes vs. the calculated parameter $\Delta\beta/\theta\gamma$. This result will allow the quantitative design of branching or separating waveguides, operating as mode splitters or power dividers as desired, without requiring further computer calculations.

B. Tapered Velocity Coupler

The analysis described in A has also been applied to the problem of tapered velocity couplers, which are expected to be useful for fiber-film coupling and also possibly for the construction of 3-db couplers (50-50 power dividers). Tapered velocity couplers are capable of nearly 100% power transfer between two guiding regions, without the requirement to provide mode synchronism over a critical coupling length. Mode synchronism need only be achieved at a single point somewhere in the middle of the coupler. The operation of a tapered velocity coupler (Fig. 3) depends on the absence of mode conversion in the device. Power is coupled into mode i, which is primarily in waveguide a, and as the thickness of waveguide a is decreased mode i is transferred to waveguide b. Power is thus transferred from waveguide a to waveguide b as long as there is no power transfer from mode i to mode j. By adapting our approximate theory of mode conversion in branching waveguides, we have been able to estimate mode conversion between the modes i and j in the tapered velocity coupler in terms of the maximum permissible slope in mode synchronism, $d\Delta\beta/dz$, and the coupling constant, K, between the two guiding regions. The desired adiabatic passage of the modes i or j will occur whenever

$$\frac{d\Delta\beta}{dz} < 5.9 KK^* .$$

Again this result allows the design of tapered velocity couplers and related devices without the need for computer calculations.

C. Optical Waveguide Power Dividers

A power divider or 3-db coupler is an essential component of any amplitude modulator constructed with optical waveguides which operates by interfering two phase shifted guided waves. One possibility for such a device (Fig. 4) follows from the tapered velocity coupler and can be designed with the analysis described in B. The advantages of requiring synchronism only at a point and a non-critical device length carry over. Fig. 4 depicts a cross-section of a two-dimensional slab waveguide. An input mode from the left, confined to arm #1, propagates to the point $z = 0$ where synchronism between the two guides is abruptly introduced. At this point the symmetrical (a) and anti-symmetrical (b) modes of the coupled structure are excited, each with one-half of the input power. Synchronism is then slowly removed by tapering the overlay to zero so that mode a selects arm #1, while mode b selects arm #2. The device should be reciprocal, and split incident modes from either direction.

EXPERIMENTAL WORK

We have built and are testing Ni diffused LiNbO_3 optical waveguides as reported by Schmidt and Kaminow.⁽²⁾ Low loss multimode guides have been obtained and efforts are being directed towards achieving single mode operation. The work in LiNbO_3 is being complimented by additional diffusion work in glasses. This glass work is aimed at perfecting fabrication procedures for forming single mode channel waveguide structures.

Under a related program, we (G. B. Hocker and W. K. Burns) have produced a theory that fully describes light guiding in diffused waveguides of arbitrary index profile. A universal chart was developed which allows us to obtain relevant waveguide parameters without any additional numerical computation.

We also are planning to build the optical waveguide power divider shown in Fig. 4 in a SiO_2 -glass waveguide system to test the theoretical branching waveguide predictions. To date construction of a fast taper (1 micron in 5) has been achieved in an SiO_2 film. This was done by sputter etching a photolithographically delineated Al_2O_3 mask. With most of the analysis and design work completed, we plan to concentrate our efforts in the next quarter on the various experimental aspects of separating and indiffused guides.

MISCELLANEOUS

The material on mode conversion in branching waveguides will be published in J. Quantum Electronics.⁽³⁾ The material on the tapered velocity coupler has been submitted to Applied Optics,⁽⁴⁾ and was also partially supported by the Office of Naval Research.

In collaboration with ONR (Code 411) a development plan entitled, "Integrated Optics and Single Mode Fiber Development Plan," was written in which future plans are discussed for demonstrating a shipboard single mode optical data bus and a switchboard. This development plan is designed to take advantage of ARPA and ONR developed integrated optics technology and apply this technology to a meaningful Naval data transfer system.

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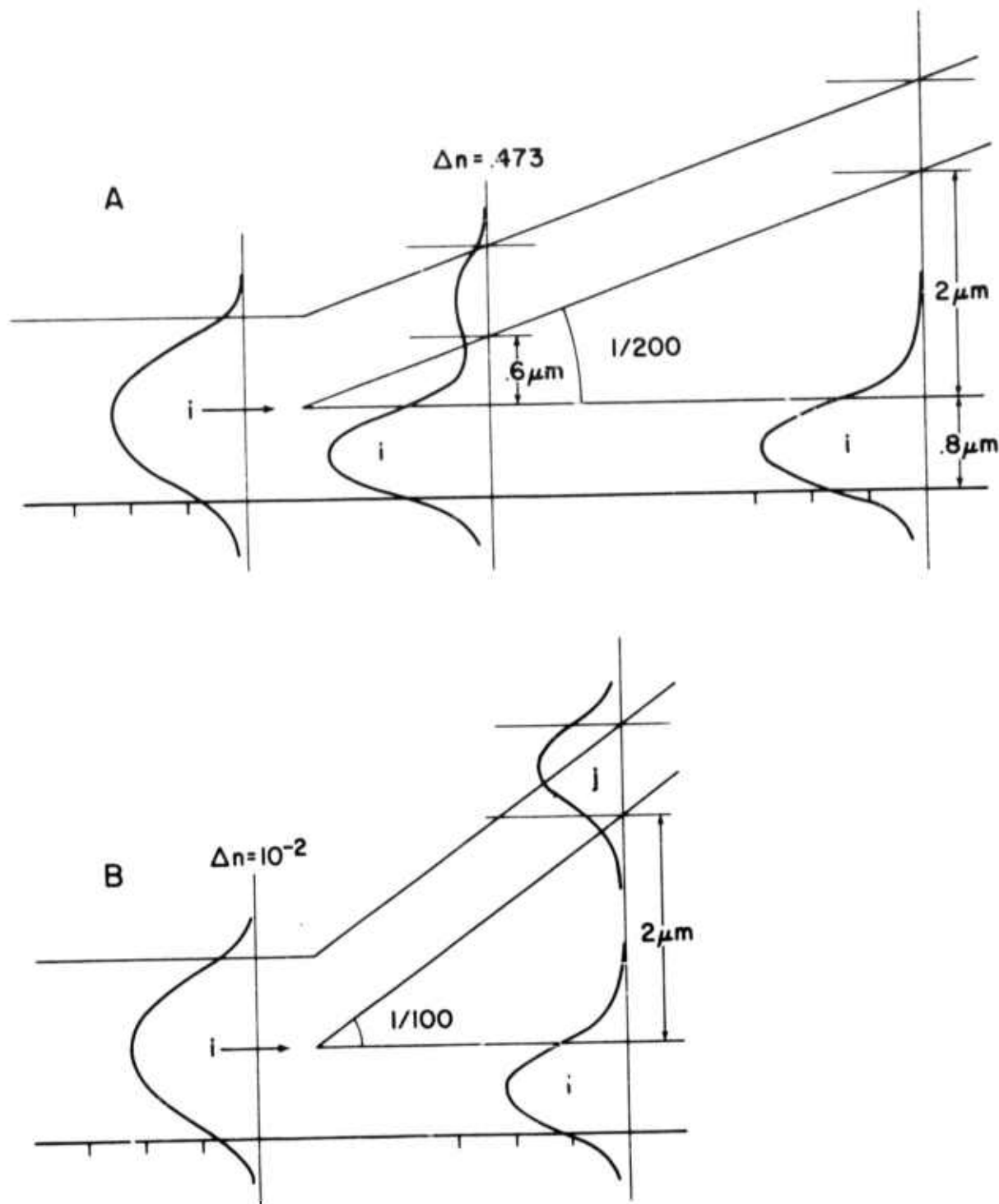


Fig. 1 — Mode conversion in a branching or separating waveguide depicting operation as a mode splitter (1a — essentially no mode conversion), and a power divider (1b — significant mode conversion). (Mode synchronism varies as the refractive index difference between the top and bottom cladding layers, Δn).

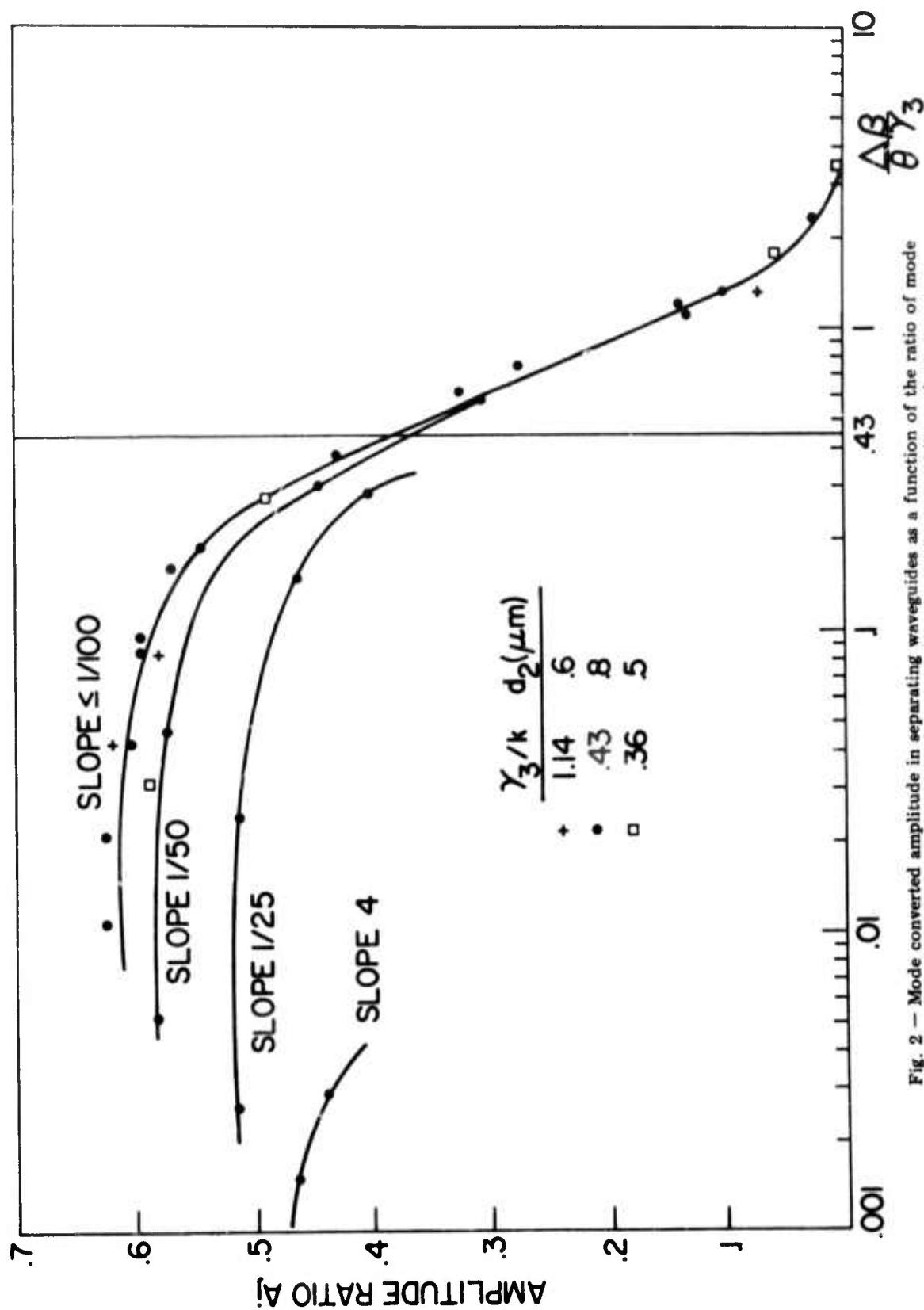


Fig. 2 — Mode converted amplitude in separating waveguides as a function of the ratio of mode synchronism ($\Delta\beta$) to taper slope (θ). Devices to the left of the vertical line behave as power dividers, to the right as mode splitters.

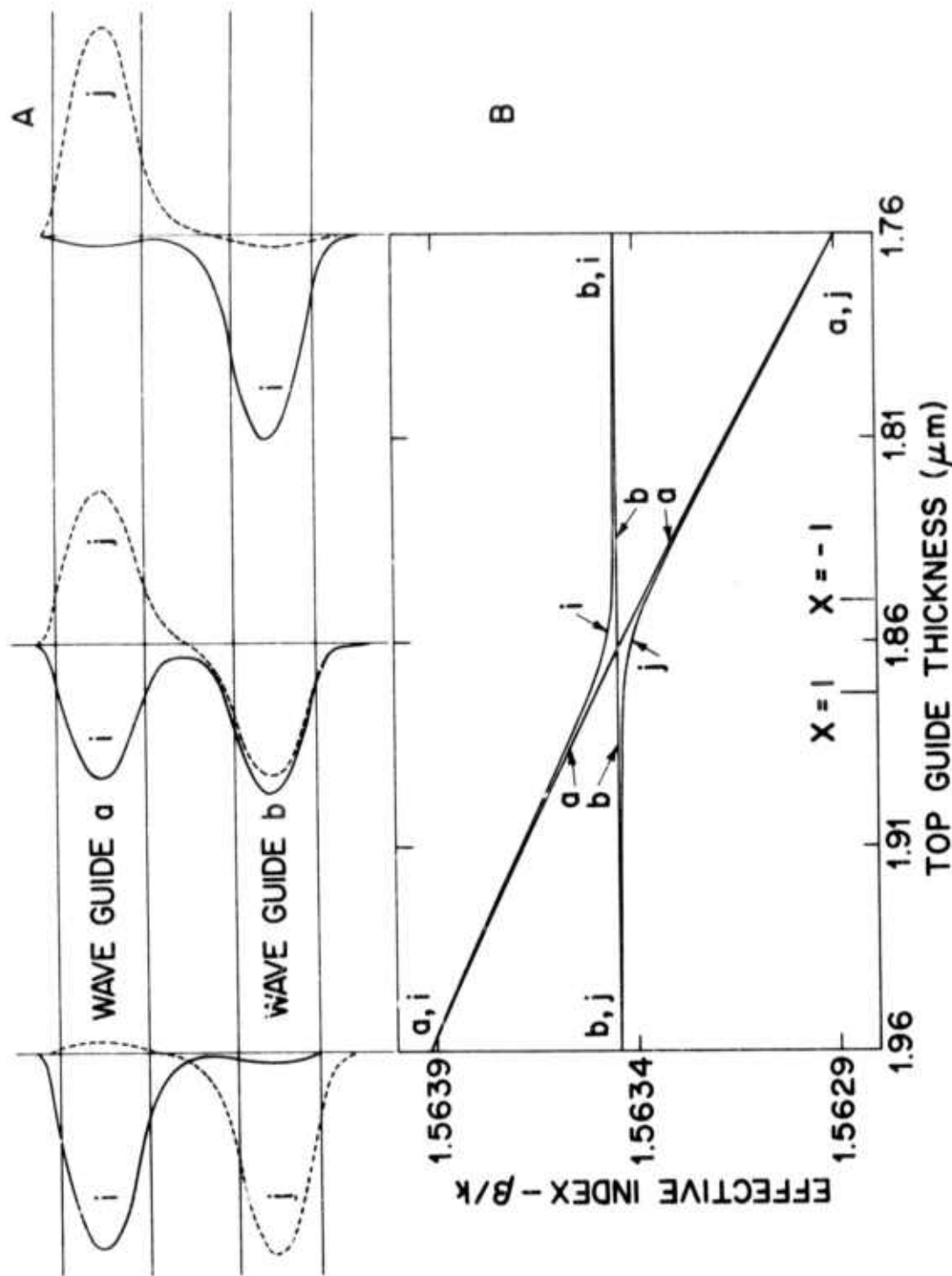


Fig. 3 — (a) A tapered velocity coupler composed of two guiding layers with a linear decrease in the thickness of the top guiding layer. Mode electric field profiles are plotted at various positions along the coupler. (b) Effective index (β/k) for the various modes as a function of position along the tapered velocity coupler of (a). Curves labeled i and j represent the local normal modes; a and b represent the conventional modes of the two three layer waveguides taken separately.

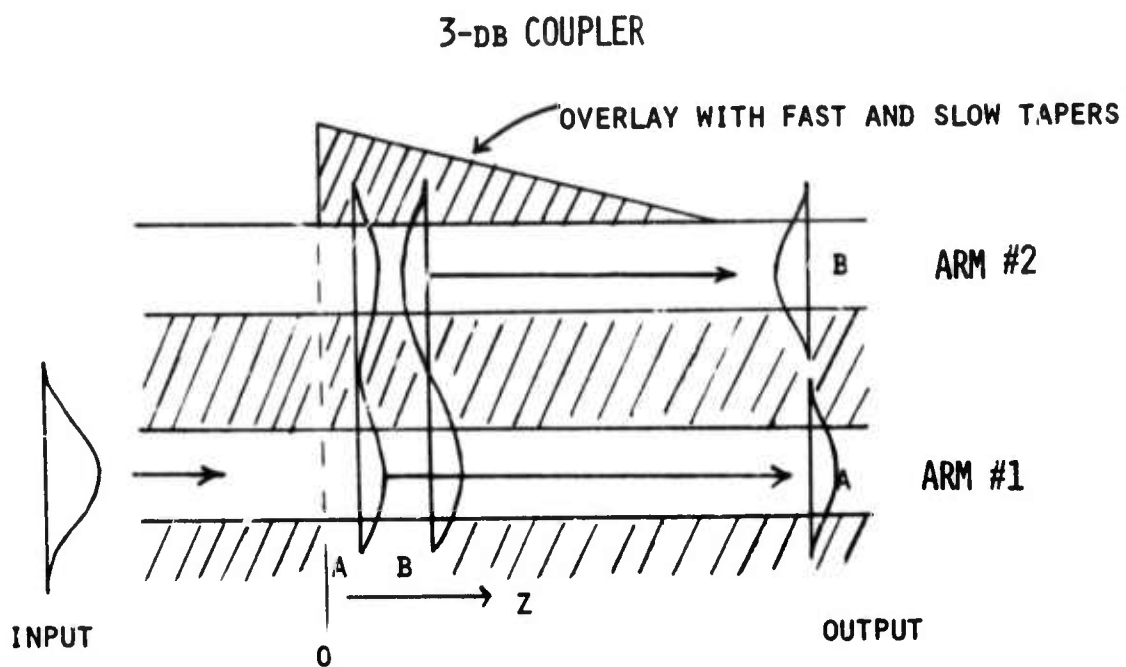


Fig. 4 — A 3-dB coupler or 50-50 power divider which utilizes the modal evolution of local normal modes. Synchronism is required only at the point $z = 0$.