packages, these are relatively small. Therefore, it would be a useful exercise to derive a lumped element equivalent circuit (based on the average of the results obtained using the galvanomagnetic technique), possibly consisting of a ladder type of structure.

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Tapered Block Coupling and Mode Conversion in Integrated Optics

G. A. TEH, V. C. Y. SO, AND G. I. STEGEMAN

Abstract—**High-efficiency power transfer between two planar waveguides on separate substrates has been achieved via the tapered velocity mechanism. The method is simple and easily repeatable. The same setup can also be used as a mode converter as well as a mode filter.**

THE CURRENT EFFORT in integrated optics has resulted in numerous discrete thin-film devices [1]. The original aim [2] was to have all the components on a single substrate in the form of an integrated optical circuit. While such a development would no doubt be highly desirable, it may be some years before the objective is realized. In the meantime, a quasi-integrated optical system can still be obtained by interconnecting the various devices using couplers [1], [3], [4]. The tapered block coupler is proposed to serve such a function.

A tapered optical directional coupler with close to 100-percent coupling efficiency has been demonstrated in a multilayer structure [5]. Theory shows that this type of coupler has greatly improved tolerance properties and does not, in particular, suffer from the severe tolerance restriction placed on velocity synchronism in conventional uniform couplers. Hsu and Chang [3] introduced the concept of block coupling between two near-identical thin films on different substrates. Transfer efficiencies of up to 70 percent were obtained by cutting a single waveguide in half and pressing the two surfaces together. The 70-percent coupling efficiency is limited by phase mismatch [3]. A grating has also been used to exchange energy between

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G. A. Teh is with the Department of Physics, University of Toronto, Toronto, Ont., Canada, on leave from Nanyang University, Singapore.

V. C. Y. So and G. I. Stegeman are with the Department of Physics, University of Toronto, Toronto, Ont., Canada.

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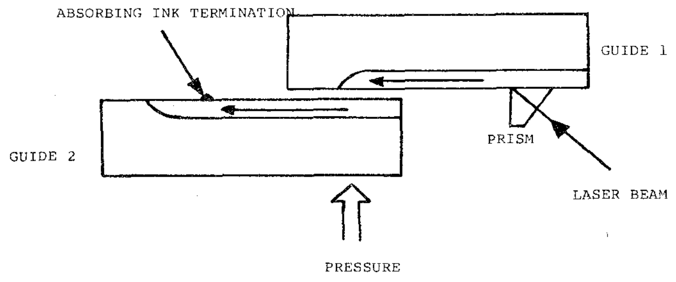

Fig. 1. A schematic diagram of tapered block coupling between ion-diffused waveguides.

nonsynchronous waveguides [6], [7] with about 27-percent efficiency [6]. Both these schemes require dimensional precision and careful alignment. In this paper, we report the successful combination of the block coupler's simplicity with the tapered coupler's tolerance advantages to produce a coupling system with greater than 90-percent coupling efficiency and at the same time obtain a device that is extremely simple to fabricate and operate. High-efficiency tapered coupling was obtained between two ion-diffused waveguides and between two glass films on different substrates.

Ion-exchanged waveguides can be fabricated easily by soaking soda–lime microscope glass slides in a silver nitrate bath [8]. Tapers are formed naturally around the air–salt boundaries. Our guides support typically 3–4 modes. A wedge was used to press the tapered section of one waveguide against the uniform region of a second guide. A schematic representation of the experimental arrangement is shown in Fig. 1. A laser beam ($\lambda = 6328$ Å) is excited in an ion-diffused waveguide (guide 1) that ends in a taper. In the absence of guide 2, the guided light would radiate into the substrate after cutoff at the taper. However, when guide 2 is pressed against guide 1 as indicated in Fig. 1, then the optical energy in guide 1 could be almost entirely transferred to guide 2 if a cross-over in the propagation coefficients of the two guides occurs. This phenomenon is shown in Fig. 2 where the streak of light continues from guide 1 into guide 2 and is terminated along guide 2 by an absorbing ink marking. Similar experiments have been repeated with various other ion-diffused waveguides. In each instance, at least 90 percent of the light has been coupled with minimal effort via the tapered velocity mechanism. However, when two uniform waveguides were pressed together, negligible power transfer was observed.

Coupling between glass films was also studied. Power transfer was obtained from a Corning 7059 glass film on fused quartz to a 7059 film on soda–lime glass and vice versa. In one of the cases that we have studied, a TE_0 mode of a quartz substrate guide (β/k tapering from 1.5512 to 1.457) was efficiently coupled to a TE_1 mode of

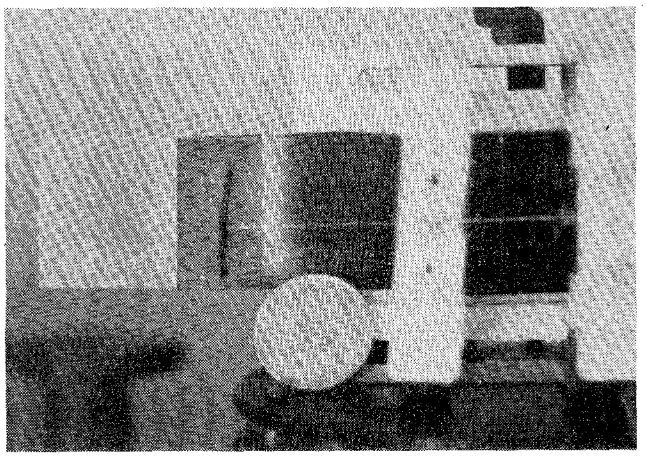

Fig. 2. Light is coupled into guide 1 through a prism coupler on the right; at the taper it is coupled into guide 2. An ink marking terminates the guided light in guide 2.

the soda–lime substrate guide ($\beta/k = 1.5440$). Negligible coupling occurs between the two TE_0 modes as the propagation coefficient $\beta(\beta/k = 1.5539)$ of the latter guide is always higher than that of the former guide.

The above example suggests that the tapered coupler can also be used as a mode filter and/or converter. This is a distinct advantage of the tapered coupler over the tapered connector demonstrated by Tien *et al.* [9] where power transfer must occur completely between the same mode orders. In addition, the tapered coupler allows the retention of power in the original guide and does not require physical isolation of the waveguides after coupling as in the case of the conventional coupler [5]. Phase mismatch can be used to cease power exchange.

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