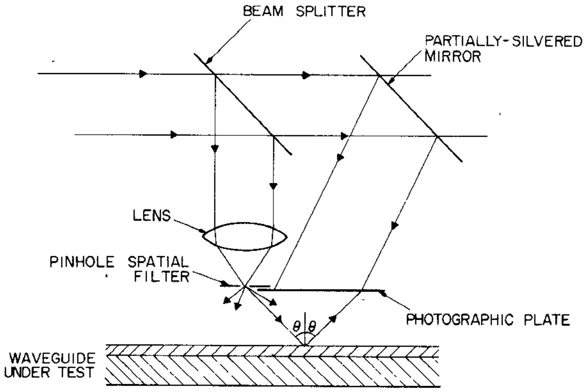

Fig. 2. Proposed setup for obtaining the phase information of the reflection coefficients.

shown, for instance, in Fig. 2. Using a beam splitter, collimated light from a laser is split into two beams, one of which is focused to generate a point source using a converging lens and a pinhole spatial filter. Rays diverging from this point source impinge on the waveguide surface at different incident angles as sketched in the diagram. After reflection, these rays are then made to interfere with a reference beam derived from the second beam via the use of a partially silvered mirror. The intensity of the reference beam may be controlled either by appropriately choosing the transmittance of the partially silvered mirror or via the insertion of an optical attenuator along the path of the beam.

The hologram formed in this manner contains the phase information on $\rho_0(\theta)$ for all $\theta_a < \theta < \theta_b$, where θ_a and θ_b are angles determined by the physical arrangement of the measurement system. This phase information can be extracted from the knowledge of the intensity distribution in the hologram via the use of a photodensitometer. This method has been successfully used by Stigliani *et al.* [2] for processing holographic recordings.

One restriction in this method is that the distance from the pinhole filter to the surface of the waveguide should be greater than $l \approx 2D^2/\lambda$ where D is the diameter of the pinhole. However, for $\lambda = 0.6\ \mu m$ and $D = 10\ \mu m$, the minimum value of l is 0.3 mm which is easily attained. It should be emphasized once again that the method outlined above is only a proposed one and has yet to be verified experimentally.

Finally, it should be noted that the method presented in this letter is quite general and is equally well applicable to nonplanar geometries, e.g., optical fiber waveguides.

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Distributed Capacitance of a Thin-Film Electrooptic Light Modulator

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***Abstract*—An analytical method is described which determines the distributed capacitance of a thin-film electrooptic light modulator with parallel-strip electrodes. The capacitance is expressed in a variational form. The anisotropy of the crystal and the presence of surrounding air are considered. Numerical examples for the case of Li–Nb–O_3 are given.**

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I. INTRODUCTION

The development of active thin-film components is very important in constructing integrated optical devices. An electrooptic light modulator with parallel-strip electrodes made with the out-diffusion technique [1] appears to be a practical structure.

This letter describes an analytical method to determine the distributed capacitance, as a basic circuit parameter, of the above thin-film light modulator based on a variational method [2], [3].

II. A THIN-FILM ELECTROOPTIC LIGHT MODULATOR AND ITS DISTRIBUTED CAPACITANCE

The cross-sectional view of a thin-film light modulator reported by Kaminow *et al.* [1] is shown in Fig. 1. An important circuit parameter of this structure is the capacitance between the electrodes which limits the modulation bandwidth. Since the electrooptical crystal like Li–Nb–O_3 is anisotropic and the electric line of force between the parallel-strip are not straight, this anisotropy should be taken into account in the analysis of the capacitance. A similar structure with isotropic media as shown in Fig. 2 has been treated by a variational method in a previous paper [2] which we apply to the present case with some modification.

Suppose the electrodes are very long and thin compared with a and b. Then a basic equation to govern the potential distribution $\phi(x,y)$ is the two-dimensional Laplace's equation,

$$\epsilon_x \frac{\partial^2 \phi}{\partial x^2} + \epsilon_y \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad (1)$$

The charge density distribution on the electrodes can be approximated as

$$\rho(x,y) = f(x)\delta(y) \qquad (2)$$

where $\delta(y)$ is Dirac's delta function.

By applying the Fourier transform

$$\tilde{\phi}(\beta,y) = \int_{-\infty}^{\infty} \phi(x,y) \exp(j\beta x)\, dx \qquad (3)$$

to the potential in each medium and using continuity conditions, we can obtain the solution of $\tilde{\phi}(\beta,y)$. Instead of carrying out the inverse transform, the capacitance per unit length is expressed in a variational form in the transformed domain [3],

$$\frac{1}{C} = \frac{1}{\pi Q^2} \int_0^{\infty} [\tilde{f}(\beta)]^2 \tilde{g}(\beta)\, d\beta \qquad (4)$$

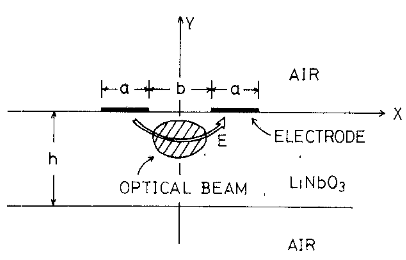

Fig. 1. An electrooptic light modulator structure proposed by Kaminow *et al.* [1].

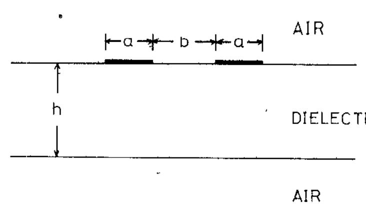

Fig. 2. Parallel-strip line printed on a dielectric sheet [2].

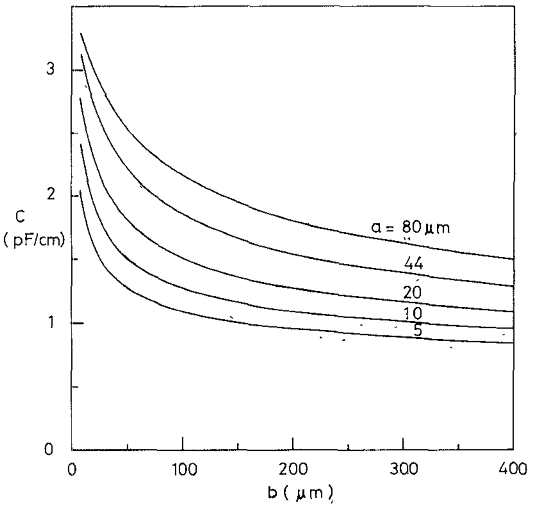

Fig. 3. Calculated capacitance between parallel-strip electrodes on Li–Nb–O_3 crystal ($\epsilon_x^* = 28$, $\epsilon_y^* = 43$, $h = 2$ mm).

where

$$Q = \int_0^\infty f(x)\, dx. \quad (5)$$

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

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

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

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Power Transfer of a Parallel Optical Fiber Directional Coupler

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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:

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

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.

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