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Electro-optic scanning of light coupled from a corrugated $LiNbO_3$ waveguide[a)]

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Light diffracted from a grating output coupler in a Ti-diffused $LiNbO_3$ waveguide is scanned electro-optically. Using a coupling length of 2.5 mm in our arrangement we have demonstrated a scanning capability of one resolved spot per 3 V/μm applied field.

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Periodic perturbations of dielectric waveguides have been used extensively for reflection,[1] coupling,[2] and deflection.[3] In the latter case Bragg diffraction of light from a variable wavelength acoustic wave was used for scanning the light beam.[4,5]

In this paper we report on a method of beam scanning in which the direction of light diffracted from a grating output coupler in a dielectric waveguide is controlled, via the electro-optic effect, by an applied electric field. The principle of the device was demonstrated using a $LiNbO_3$ waveguide in the manner sketched in Fig. 1. Consider a waveguide mode with a propagation constant along the x-axis β which is incident on a grating coupler with a period Λ. The wave will be diffracted into air with an angle ϕ with respect to the x axis. The angle ϕ is determined with the help of the subdiagram in Fig. 1

$$\beta - 2\pi/\Lambda = k\cos\phi , \tag{1}$$

where $k = 2\pi/\lambda$ and λ is the vacuum wavelength. If we define an effective-mode index n_{eff} by $\beta \equiv k n_{eff}$, then Eq. (1) becomes

$$n_{eff} - \lambda/\Lambda = \cos\phi . \tag{2}$$

For a given λ and Λ, the diffraction angle ϕ depends on the index n_{eff}. The angle of deflection corresponding to a small change of index is then

$$\Delta\phi = -\Delta n_{eff}/\sin\phi . \tag{3}$$

The number of resolvable spots N in the angle of deflection is obtained by dividing the magnitude of $\Delta\phi$ by the angular divergence $\delta\phi$ of the coupled wave. In a structure with uniform waveguide and grating parameters this angular divergence is diffraction limited by the finite coupling length L

$$\delta\phi = \lambda/(L\sin\phi), \tag{4}$$

where L is the shorter of the grating length or the $1/e$ folding distance for the waveguide mode intensity along the grating. Thus from Eqs. (3) and (4)

$$N = |\Delta n_{eff}| L/\lambda . \tag{5}$$

The number of resolvable spots N is thus independent of the choice of ϕ or Λ.

To estimate Δn_{eff}, we chose both the direction of the

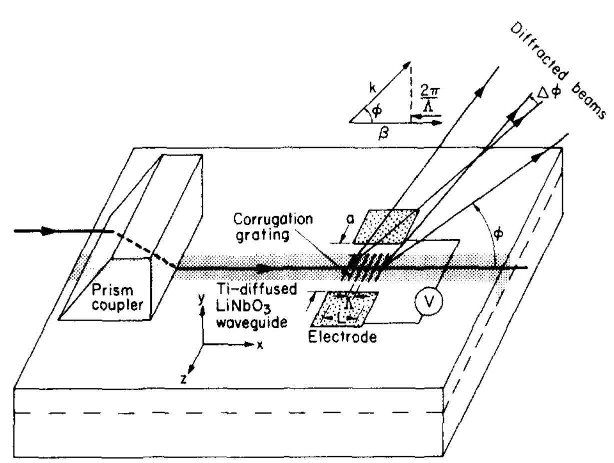

FIG. 1. Schematic diagram of the electro-optic beam scanner.

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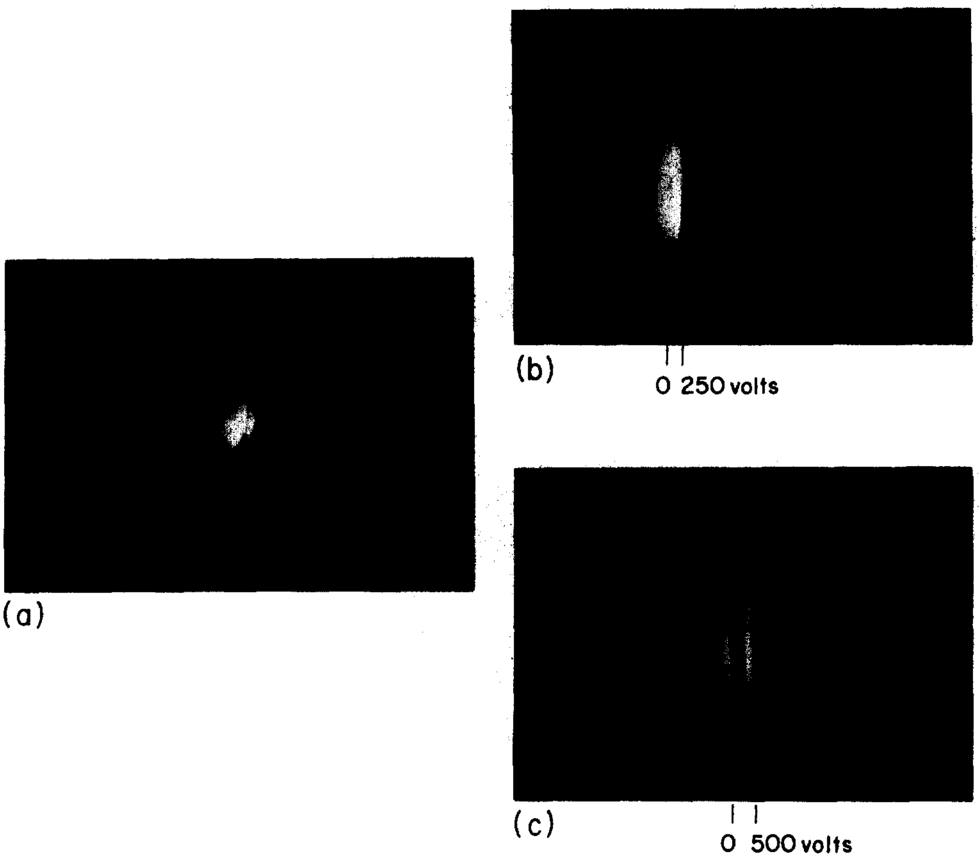

FIG. 2. (a) Typical far-field diffraction pattern of the coupled wave from a planar waveguide. (b) and (c) are photographs of the resolved spots corresponding to the applied voltages as indicated. $a = 33\ \mu$m.

applied electric field and that of the mode polarization as parallel to the z (optic) axis of $LiNbO_3$. The electro-optic index change Δn_e is given by[6]

$$\Delta n_e = -\tfrac{1}{2} n_e^3 r_{33} E_z . \tag{6}$$

If the waveguide mode is well confined, then we can, to a high degree of accuracy, approximate Δn_{eff} by Δn_e with E_z given by[7]

$$E_z = (2/\pi)(V/a) , \tag{7}$$

where V and a are the applied voltage and separation between the two electrodes, respectively.

In the experiment, both planar and channel Ti-diffused $LiNbO_3$ waveguides were used. The grating, which is in the form of a periodic surface corrugation, was fabricated by first recording an interference pattern (derived from a He-Cd laser at 3250 Å) in the photoresist coating and then developing the photoresist and transferring the pattern to the waveguide surface by ion-beam etching. We chose a shallow corrugation to ensure that the coupling length L was the geometrical length of the grating. The period and height of the grating rulings were determined using an Ar^+ laser line at 4579 Å. The TE_0 mode at $\lambda = 6328$ Å was excited in the waveguide by a rutile prism coupler and diffracted out to air by the corrugation grating.

A planar waveguide was formed by diffusing a 200-Å Ti metal film into a Y-cut $LiNbO_3$ substrate at 975 °C for 5 h.[8] The resulting waveguide supported a TE_0 mode with an index $n_{eff} = 2.212$. The corrugation grating with a period $\Lambda = 5180$ Å and a length $L = 2.5$ mm was then fabricated on top of the waveguide. A typical far-field diffraction pattern for the coupled wave is shown in Fig. 2(a). The angle ϕ was calculated and measured to be 8°. The measured angular divergence was $\delta\phi \sim 0.15°$, which was larger than the calculated value $\delta\phi_{ideal} = 0.10°$. A channel waveguide on a $LiNbO_3$ substrate was formed by, first, oxidation of a 4-μm wide and 200 Å-thick Ti film at 600 °C for 4 h, and then diffusion of the resulting oxide at 950 °C for 5 h.[9] It supported a single mode ($n_{eff} = 2.210$) with a loss constant 1 dB/cm. The grating parameters were $\Lambda = 4200$ Å and $L = 2.5$ mm, so $\phi \sim 45°$ and $\delta\phi_{ideal} \sim 0.02°$. A typical far-field diffraction pattern of the coupled wave from a 4-μm channel is shown in Fig. 3(a).

The electro-optically induced index change was produced by applying a voltage to a pair of parallel Al electrodes deposited photolithographically on top of the waveguide. In the case of the planar waveguide, the separation between the two electrodes is $a = 33\ \mu$m. Figure (2b), which is a double exposure, shows two states: without an applied voltage and with a voltage of 250 V which corresponds to a field of 5 V/μm applied. Figure 2(c) corresponds to $V = 500$ V where three resolved spots can be obtained. The number predicted by Eq. (5) is 6. Figure 3(b) shows the scanning of the beam coupled from a channel waveguide. The voltage of 150 V is applied to electrodes with a spacing of 10 μm ($E_z \simeq 10$ V/μm). The photograph in Fig. 3(c) shows three well-resolved spots corresponding to voltages of 0, 100, and 200, respectively. From the measurement, $N \simeq 5$ when $V = 200$ V. The theoretical number is 8. The discrepancies between the measured and the calculated values are partly due to an overestimate of Δn_{eff}, and, partly, to imperfections in the structure.

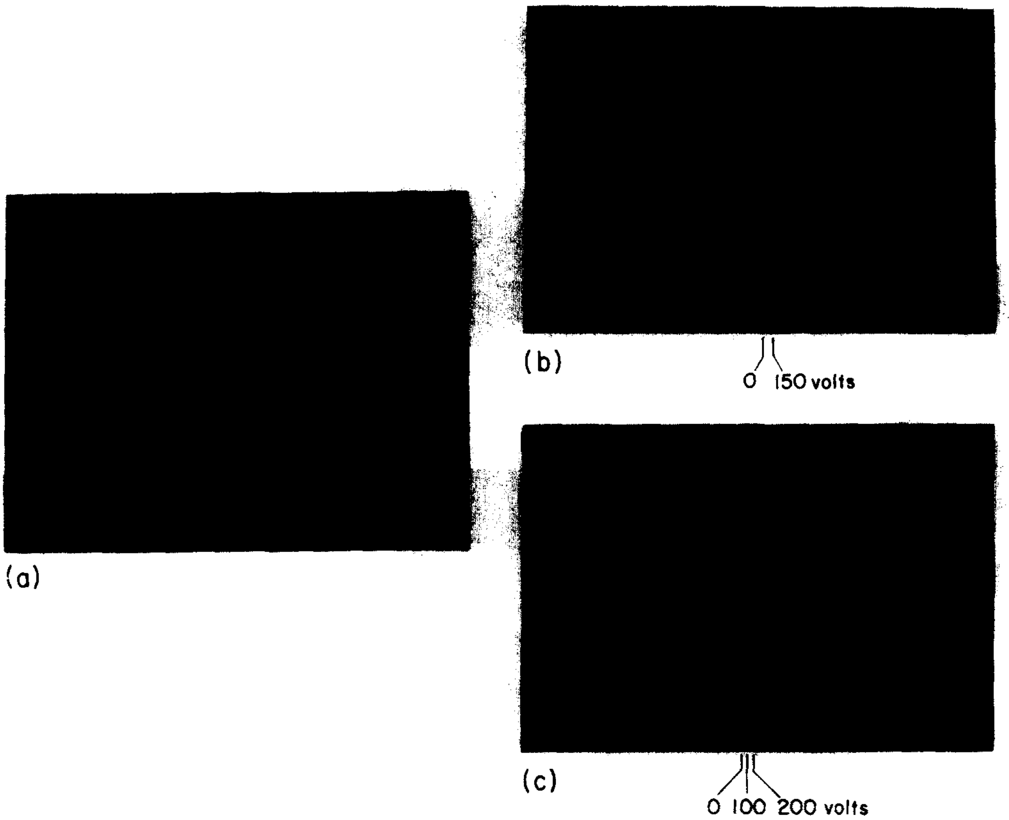

FIG. 3. (a) Typical far-field diffraction pattern of the coupled wave from a 4-μm channel waveguide. (b) and (c) are photographs of the well-resolved spots corresponding to the applied voltages as indicated. $a = 10\ \mu$m.

In this application we have used $\Delta n_e = (1-2)\times 10^{-3}$. A further reduction of the voltages required can be made by decreasing the separation between the two electrodes. The resolution can be improved by increasing the coupling length in the grating with a corresponding penalty of the switching speed.

In conclusion, we have demonstrated angular scanning of a beam coupled from a corrugated $LiNbO_3$ waveguide. This was done by using the electro-optic effect to modulate the index of refraction in the corrugated section of the waveguide. The number of resolution elements can be improved by increasing the coupling length in the grating and is only limited by the dielectric breakdown of the waveguide material. We have demonstrated the scanning capability of one resolved spot per 3 V/μm applied field. In principle, by using a grating of 1 cm length and an applied field of 40 V/μm in Fig. 1, the number of resolution elements should be ~100.

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