Electro-optic scanning of light coupled from a corrugated LiNbO\(_3\) waveguide\(^a\)

C. S. Hong and A. Yariv

California Institute of Technology, Pasadena, California 91125

B. Chen

Hughes Research Laboratories, Malibu, California 90265
(Received 10 February 1978; accepted for publication 14 March 1978)

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/\(\mu\)m applied field.

PACS numbers: 42.80.Ks, 78.20.Jq, 42.80.Fn, 42.80.Lt

Periodic perturbations of dielectric waveguides have been used extensively for reflection,\(^1\) coupling,\(^2\) and deflection.\(^4\) 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 \(\beta\) which is incident on a grating coupler with a period \(\Lambda\). The wave will be diffracted into air with an angle \(\phi\) with respect to the \(x\) axis. The angle \(\phi\) is determined with the help of the subdiagram in Fig. 1.

\[
\beta = 2\pi/\Lambda = k \cos \phi, \quad (1)
\]

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

\[
n_{\text{eff}} = \lambda/\Lambda = \cos \phi. \quad (2)
\]

For a given \(\lambda\) and \(\Lambda\), the diffraction angle \(\phi\) depends on the index \(n_{\text{eff}}\). The angle of deflection corresponding to a small change of index is then

\[
\Delta \phi = -\Delta n_{\text{eff}}/\sin \phi. \quad (3)
\]

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 \(L\)

\[
\Delta \phi = \lambda/(L \sin \phi), \quad (4)
\]

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)

\[
N = |\Delta n_{\text{eff}}| L/\lambda. \quad (5)
\]

The number of resolvable spots \(N\) is thus independent of the choice of \(\phi\) or \(\Lambda\).

To estimate \(\Delta n_{\text{eff}}\), we chose both the direction of the

\[\text{FIG. 1. Schematic diagram of the electro-optic beam scanner.}\]
applied electric field and that of the mode polarization
as parallel to the z (optic) axis of LiNbO$_3$. The electro-
optic index change $\Delta n$ is given by

$$\Delta n = -\frac{1}{2} n_0^2 \frac{\partial E}{\partial z}.$$ (6)

If the waveguide mode is well confined, then we can, to a high degree of accuracy, approximate $\Delta n_{\text{eff}}$ by $\Delta n$ with $E_z$ given by

$$E_z = \frac{Q}{\pi} V(a),$$ (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 photosensitive film
and then developing the photosensitive film and trans-
ferring 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. The resulting waveguide supported a TE$_0$
mode with an index $n_{\text{eff}} = 2.212$. 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 $\phi$ was calculated and measured to be
8°. The measured angular divergence was $\delta \phi \sim 0.15^\circ$, which
was larger than the calculated value $\delta \phi_{\text{ideal}} = 0.10^\circ$.
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. It supported a single mode ($\nu_{\text{eff}} = 2,210$) with a loss constant 1 dB/cm. The grating
parameters were $\Lambda = 4200$ Å and $L = 2.5$ mm, so $\phi \sim 45^\circ$
and $\delta \phi_{\text{ideal}} \sim 0.02^\circ$. 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 pro-
duced 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 $a = 33$ μm,
Figure 2(b), 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 re-
solved 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 ($E_z = 10$
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, $N = 5$ when
$V = 200$ V. The theoretical number is 8. The discrepan-
cies between the measured and the calculated values
are partly due to an overestimate of $\Delta n_{\text{eff}}$, and, partly,
to imperfections in the structure.
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.

The authors would like to thank J. D. Marshall for the titanium evaporation in the early stage of this work, and D. R. Armstrong for his technical assistance.