A WIDEBAND ACOUSTOOPTIC GUIDED-LIGHT BEAM DEFLECTOR USING TILTING SURFACE ACOUSTIC WAVES*

C. S. Tsai, Le T. Nguyen and M. A. Alhaider
Department of Electrical Engineering
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

ABSTRACT. The experimental results on a new guided-wave acoustooptic beam deflector utilizing multiple surface acoustic wave (SAW) interdigital transducers, which are staggered in their center frequency and tilted in their propagation direction, are presented. The results have demonstrated that such a device configuration is capable of providing simultaneously both large diffraction efficiency and large bandwidth. For example, in one of the deflectors being studied, two tilting SAW transducers having center frequencies of 255 MHz and 382 MHz were fabricated on an essentially single-mode optical guiding layer of a Y-cut $LiNbO_3$ plate. The measured -3db bandwidth of the device is close to 200 MHz with measured electric driving power of 200 mw at 50% diffraction efficiency using a 6328 Å He-Ne laser light. This performance figure is at least one order of magnitude better than those having been achieved with previous devices. The 200 MHz device bandwidth will provide for 575 resolvable spot diameters with a transit time of 2.8 microseconds for a light beam aperture of 1 cm. It is clear that further increase in the device bandwidth can be achieved by adding more transducers at the appropriate center frequency and tilting angle. It has also been demonstrated that this device configuration is relatively easy to design and to fabricate. As a result of the development of this wideband technique a number of wideband system applications using guided-wave acoustooptic deflectors become very attractive. Applications with acoustooptic rf spectrum analysis and multiport beam switching for integrated and fiber optic terminals are briefly discussed.

I. INTRODUCTION

Guided-wave acoustooptic devices are based on the interactions between guided-light waves and surface acoustic wave. Some of the more obvious advantages of the guided-wave acoustooptic devices over their bulk-type counterparts are: (1) since the energies of both the guided-light waves and the surface acoustic waves are concentrated in a thin layer and since the guided-light waves spread (by diffraction) only in one dimension the efficiency of the guided-wave devices may be one to a few orders of magnitude higher than that of their bulk-type counterparts, (2) the dispersion properties of [illegible] the guided-light waves and the surface acoustic waves enable the phase matching conditions to be fulfilled for [illegible]nge of acoustic diffraction efficiency and large bandwidth requires a large rf driving power which in turn may easily result in the failure of the interdigital transducer. Consequently, it is desirable to study wideband techniques which are capable of relieving this limitation. This paper reports a wideband technique[6,8] for this purpose and presents some experimental results. In addition, some of the potential applications using wideband guided-wave acoustooptic beam deflectors will be described. This paper will limit the discussion to coplanar noncollinear beam deflection and switching as these are particularly useful for the potential applications to be described.

frequency and, therefore, a wider device bandwidth is inherent with guided-wave devices, (3) guided-wave devices have smaller size and weight and their isolation and alignment problems are less critical than their bulk-type counterparts. Consequently, guided-wave acoustooptic devices are expected to serve important functions such as deflection, switching, modulation and signal processing for future fiber and integrated optics systems. In accordance with this expectation, there have been very active research and development efforts with this type of devices in recent years.[1-8)

All of the various forms of noncollinear coplanar guided-wave acoustooptic devices, namely, modulators, switches and deflectors which has been studied experimentally heretofore involved isotropic Bragg-diffraction and employed only a single surface acoustic wave interdigital transducer.[1-7] As a result, they suffer from either a relatively low diffraction efficiency or a relatively small device bandwidth. The inherent limitation with devices employing a single transducer and, therefore, a single acoustic beam is that in order to achieve a large device bandwidth (assuming a transducer acoustic bandwidth sufficiently larger than the Bragg bandwidth) the aperture of the transducer must be chosen very small which in turn results in a drastic decrease in the diffraction efficiency.[9] A further limitation of which a single interdigital transducer suffers is its relatively small acoustic bandwidth. Under such an unfavorable condition a device with both large

* This work was supported jointly by the ONR and the NSF, 1973 Ultrasonics Symposium Proceedings, IEEE Cat. #74 CHO 896-1SU.

II. DEVICE PARAMETERS FOR GUIDED-WAVE ACOUSTOOPTIC DEFLECTORS

The underlying interaction mechanism between the guided-light waves and the surface acoustic waves is analogous to that of bulk-type acoustooptic interactions.[9,10] With coplanar interactions the guided-light waves are diffracted as a result of the grating created in the guiding layer by the surface acoustic waves. A typical device configuration is shown in Ref. 2. The optical guiding structure can be either of a graded-index layer such as an out-diffused layer of $LiNbO_3$[11] or a step-index layer such as glass and As_2S_3 films on a suitable substrate.[1,2] Depending on the wavelength and the beam width of the acoustic wave and the wavelength of the light wave, the diffraction can be in either the Raman-Nath regium or the Bragg regium. The diffraction is in the Raman-Nath regium and consists of a number of side orders when the parameter $Q \equiv 2\pi\lambda_o L/n\Lambda^2$ is less than unity, in which λ_o and Λ designate the wavelength of the light wave (in free space) and the acoustic wave; n the index of refraction of the medium and L the aperture of the acoustic wave. In the other extreme the diffraction is in the Bragg regium and consists of mainly one side order when Q is larger than 10. The relevant phase-matching condition between the incident, diffracted light waves and the surface acoustic wave is shown in Ref. 2 for the case in which the diffracted light wave is of different waveguide mode than the incident light wave. The diffracted light wave may also be in the same waveguide mode as that of the incident light wave and may have a polarization orthogonal to that of the incident light wave.

Surface acoustic waves are generated by interdigital finger transducers[12] and propagate either on the top of the optical guiding structure or in the interface between the guiding layer and the substrate.

The device parameters of the guided-wave acousto-optic devices with applications to beam deflection and switching are: 1). diffraction efficiency, 2). number of scannable spot diameters, and 3). switching time. It has been shown that the diffraction efficiency η (for a relatively low diffraction efficiency, say below 60%) depends linearly on the acoustooptic figure of merit, overlap-intergral and total acoustic power flow as well as the ratio between the aperture of the surface acoustic wave and the effective depth of the optical guiding layer.[2] Since with guided-wave devices the ratio can be much larger than that with bulk-type devices, a correspondingly higher diffraction efficiency is inherently possible. The number of scannable spot diameters N is equal to the product of the transit time τ and the device bandwidth Δf. The switching time t_s is just the transit time of the surface acoustic wave across the incident light beam aperture D.

The device bandwidth Δf is determined by both the acoustic bandwidth of the transducer and the Bragg bandwidth as imposed by the Bragg-condition (phase-matching condition), namely, Δf is lower than the smaller of the two bandwidths. It is seen that for a fixed device configuration a large N can be achieved by having a large D and/or a large Δf. However, a large D necessarily imply a large transit time and, therefore, a slower switching speed. In addition, as a result of the acoustic attenuation, a large D may possibly cause nonuniformity in the beam profile of the diffracted light and, therefore, causes some reduction in N. Consequently, in order to achieve a large N it is more desirable to achieve it through a large Δf than a large D.

utilizes two tilting surface acoustic waves propagating on a Y-cut $LiNbO_3$ substrate. The configuration of the device being studied is shown in Fig. 1. An optical waveguiding layer having one or two TE modes was formed on a Y-cut $LiNbO_3$ plate using the out-diffusion technique.[11] Two interdigital transducers having the designed center frequencies of 255 MHz and 382 MHz, respectively, and a tilting angle of approximately 0.3 degrees were fabricated on the top of the waveguide to generate two tilting acoustic beams propagating approximately along the z-axis of the $LiNbO_3$ crystal. Each of the two transducers consists of two and a half pairs of interdigital finger electrodes and, therefore, can provide a large acoustic bandwidth. The apertures of the two transducers are 1.66 and 1.11 mm, respectively, each being large enough to insure the individual diffraction to be in the Bragg regime. The two transducers were connected in parallel and their combined electrical capacitance was tuned out with an inductance. The measured frequency response of the Bragg diffraction efficiency with two acoustic beams exicted simultaneously, together with that of the two acoustic beams excited separately are shown in Fig. 2b and 2a. Similar frequency responses with the resultant device bandwidth varying from 155 MHz to 195 MHz were also obtained as the incident angle of the light beam was varied by approximately $\pm$ 25' from the optimum Bragg condition. It is seen that a resultant bandwidth close to 200 MHz has been achieved. From Figs. 2a and 2b it is seen that this resultant device bandwidth is slightly larger than the sum of the device bandwidth using acoustic beam #1 alone (85 MHz) and the device bandwidth using acoustic beam #2 alone (75 MHz). It should also be observed that the diffraction efficiency peaks in a neighborhood of the transducer center freqnencies, namely, 255 MHz and 382 MHz as expected. A flat response, instead of a dip, between the two peaks would be expected if the center frequencies of the two transducers were separated by a smaller amount than the one implemented.

III. BRAGG-DIFFRACTION USING MULTIPLE TILTING SURFACE ACOUSTIC WAVES

To achieve a large device bandwidth Δf one must employ a transducer which generates surface acoustic waves efficiently over a large frequency band and in the meantime utilize an interaction configuration which allows the Bragg condition to be satisfied over the same large frequency band. As mentioned at the beginning of this paper, beam deflectors using a single surface acoustic wave and involving isotropic Bragg-diffraction has a rather limited Δf. Three techniques which are in principle capable of providing a large Δf are: A). Bragg-diffraction using optimized anisotropic configuration,[7,13] B). Bragg-diffraction using frequency scanning surface acoustic array,[14,15] C). Bragg-diffraction using multiple tilting surface acoustic waves.[6,8] To the best of our knowledge, the first technique has not been studied experimentally and will not be discussed in this paper. Although both the second and the third techniques are being studied at C-MU, only the third technique will be described in detail, together with experimental results in this paper.

The main idea behind the third wideband technique is the utilization of multiple tilting surface acoustic wave transducers, which are staggered in their center (operating) frequency and tilted in their propagation direction, to simultaneously achieve both a large diffraction efficiency and a large bandwidth.[8]

IV. EXPERIMENTAL RESULTS

In the results to be presented below the device

In beam deflection and switching applications a 200 MHz device bandwidth will provide 575 resolvable spots with a transit time of 2.8 microseconds using a light beam aperture of 1 cm. Fig. 3 shows the photograph of the deflected spots as the frequency of the driving signal was varied from 240 MHz to 420 MHz for a light beam aperture of about 0.1 cm. From the photograph the number of resolvable spot diameters as defined by the Rayleigh criterion is estimated to be 48 which agrees well with the calculated value of 51. The frequency variation required for one resolvable spot diameter was measured to be 3.8 MHz which also agree with the theoretical value. In the device being studied a light beam aperture of 0.4 cm with some non-uniformity in light intensity was achievable after the light beam has propagated through the input and output prism couplers. At this light beam aperture close to 200 resolvable spot diameters would be obtained. Improvement of the surface condition of the prim couplers and $LiNbO_3$ plate and the contact between them should result in a larger uniform light beam aperture. The through-put coupling efficiency, after propagating through the input and output prism couplers, is on the order of 20%.

The rf driving power of the device for a 50% diffraction efficiency was measured to be 200 mw. Optimization of both electrical and acoustical parameters of the device should further reduce the rf driving power. In addition, further increase in the device bandwidth can be achieved by adding more transducers at the appropriate center frequency and tilting angle.

V. CONCLUSION

In conclusion, we have experimentally demonstrated, for the first time, that a substantial increase in the bandwidth of an acoustooptic guided-light beam deflector/switch can be achieved by employing multiple tilting surface acoustic waves which are staggered in their operating frequency and tilted in their propagation direction. It has also been demonstrated that this device configuration is both relatively easy to design and to fabricate. The new technique introduced here will be essential for applications involving very wide bandwidths[16] such as guided-wave acoustooptic rf spectrum analysis[16,17] which requires a very large bandwidth and high-speed multiport beam switching for integrated/fiber optics terminals[16,18] as well as signal processing in two dimensions.[19]

REFERENCES

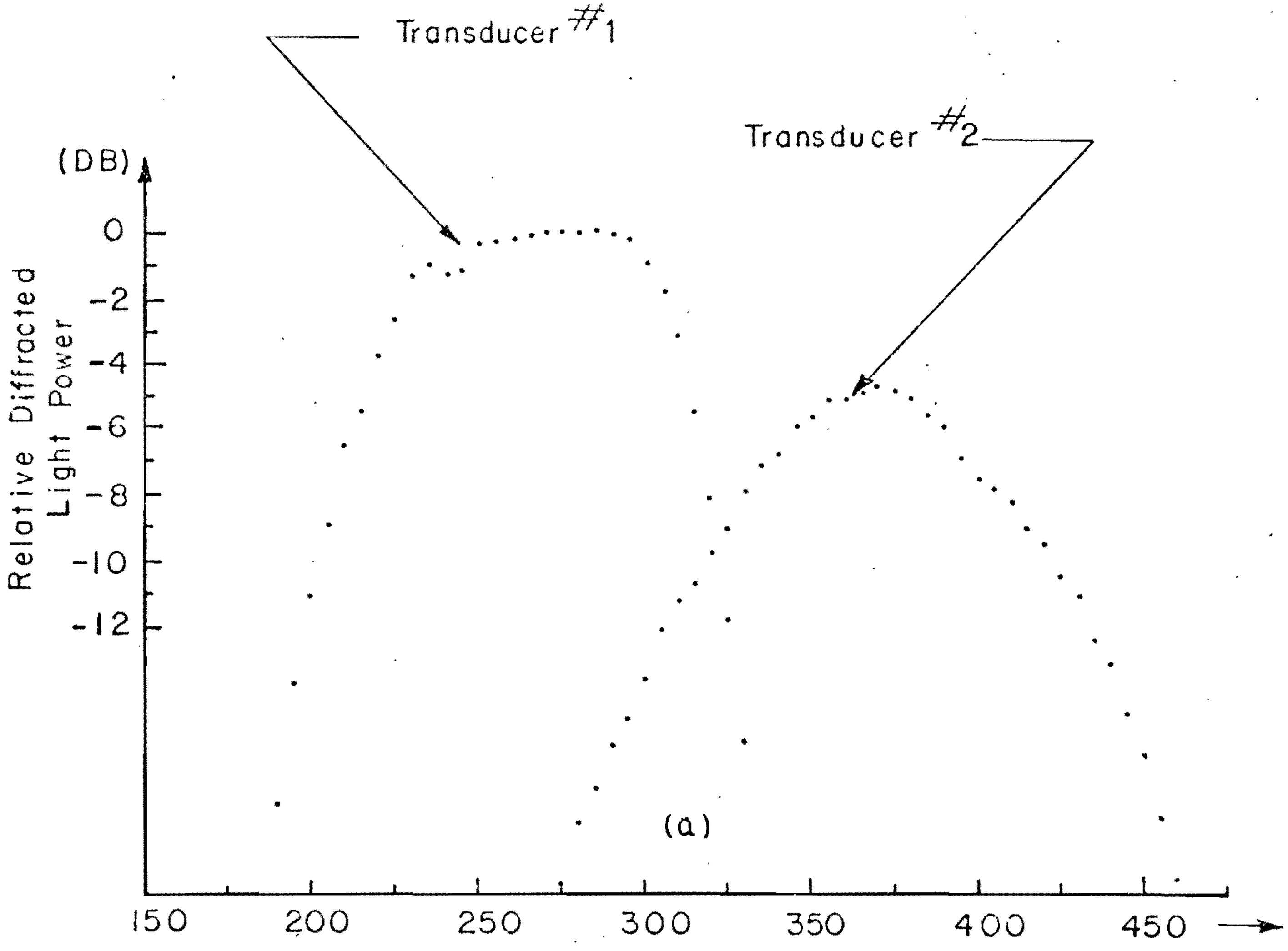
1. L. Kunh et al., Appl. Phys. Lett., 17, 265 (1970).
2. Y. Ohmachi, J. Appl. Phys., 44 3928 (1973).
3. R.V. Schmidt et al., Appl. Phys. Lett., 23, 417 (1973).
4. J.F. Weller et al., "Light Deflection in Single and Multimode Waveguides Using the Acoustooptic Interaction", Topical Meeting Integrated Optics, Paper WA9-1, Jan. 21-24, 1974, New Orleans, Louisiana.
5. D.A. Wille and M.C. Hamilton, Appl. Phys. Lett., 24 159 (1974).
6. C.S. Tsai, "Thin-Film Acousto-Optic Surface Wave Interactions," presented at the ONR-ARPA Electrooptics Review, Paper V3, Arlington, Virginia, Oct. 2-4, 1973.
7. T.G. Giallorenzi and A.F. Milton, J. Appl. Phys., 45, 1962 (April 1974).
8. C.S. Tsai, S.K. Yao and M.A. Alhaider, "A High Performance Acoustooptic Guided-Light Beam Device Using Intersecting Surface Acoustic Beams," Post Deadline Paper, D12, Integrated Optics and Fiber Optics Communications Conference, Naval Electronics Laboratory Center, San Diego, California, May 13-14, 1974 (unpublished).
9. E.I. Gordon, Appl. Opt., vol. 5, 1629 (Oct. 1966).

Design Conference, San Francisco, California, Nov. 5-7.

18. S.F. Miller et al., "Research Toward Optical-Fiber Transmission Systems." Proc. IEEE Vol. 61, 1703 (Dec. 1973); C.M. Stickley et al., "Anticipated Uses of Fiber and Integrated Optics in the Defense Department," Paper WB1-1, Topical Meeting on Integrated Optics, Jan. 21-24, 1974, New Orleans, Louisiana; R.A. Andrews, "Integrated Optics Technology," Naval Research Reviews, Jan. 1973.
19. R. Shubert and J.H. Harris, IEEE Trans. MIT-16, 1048 (December 1968).

10. R.W. Damon et al., Physical Acoustics, edited by W.P. Mason (Academic, New York, 1970), Vol. 7, Chapter 5; N. Uchida and N. Niizeki, Proc. IEEE, Vol. 61, 1073 (1973).

11. I.P. Kaminow and J.R. Carruthers, Appl. Phys. Lett., Vol. 22, 326 (1973).
12. W.R. Smith et al., IEEE Trans. MIT-17, 865 (1969).
13. R.W. Dixon, IEEE J. Quantum Electron QE-3, 85 (1967); E.G.H. Lean et al., Appl. Phys. Lett., Vol. 10, 48 (Jan. 1967); A.W. Warner et al., J. Appl. Phys., Vol. 43, 4489 (Nov. 1972); N. Uchida and N. Niizeki, Proc. IEEE Vol. 61, 1073 (Aug. 1973).
14. See for example, A Korpel et al., Proc. IEEE, Vol. 54, 1429 (1966); D.A. Pinnow, IEEE Trans. SU-18 209 (1971); C.S. Tsai, Thin-Film Acousto-Optic Surface Wave Interactions," Presented at ARPA-ONR Electrooptics Review, Paper V3, Arlington, Virginia, Oct. 2-4, 1973.
15. R.M. De LaRue, et al., Electron Lett., Vol. 9, 32 326 (July 26, 1973); C.S. Tsai and Le T. Nguyen, "Surface Acoustic Wave Array Transducers and Their Applications," Symposium on Optical and Acoustical Microelectronics, Paper X5, Polytechnic Institute of New York, New York City, April 16-18, 1974.
16. C.S. Tsai, "Wideband Guided-Wave Acoustooptic Devices and Their Applications," 1974 Electrooptics Systems Design Conference, San Francisco, California, Nov. 5-7.
17. M.C. Hamilton, et al., "Acoustooptic Diffraction in $LiNbO_3$ Waveguides," 1973 Electrooptics Systems



Transducer #1
Transducer #2
(DB)
Relative Diffracted Light Power
0
-2
-4
-6
-8
-10
-12
150
200
250
300
350
400
450

(a)

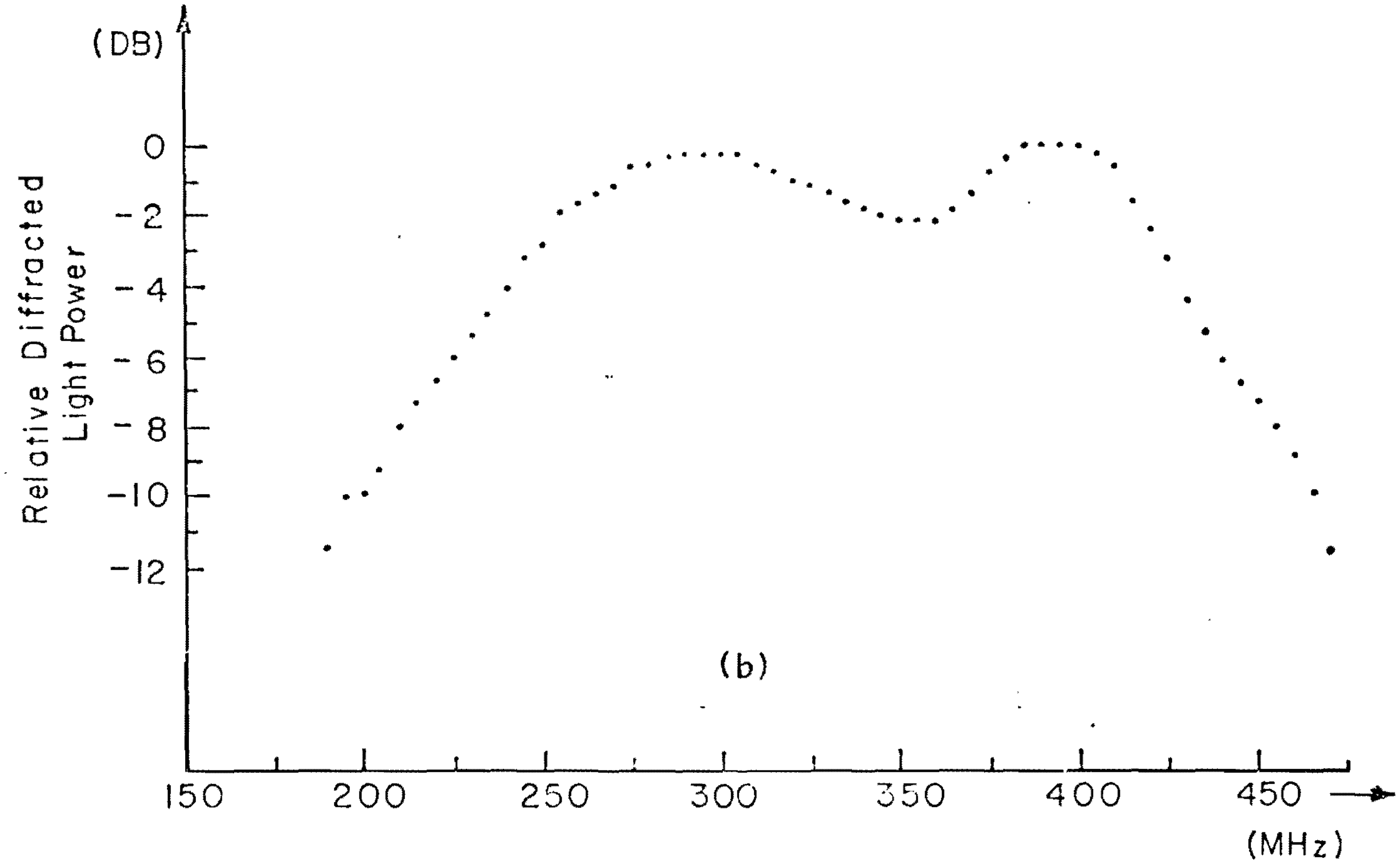


Figure 2. (a) Frequency Responses of the Bragg-Diffracted Light Power for the Individual Acoustic Waves,

(b) Frequency Response of the Bragg-Diffracted Light Power for the Combined Acoustic Wave.

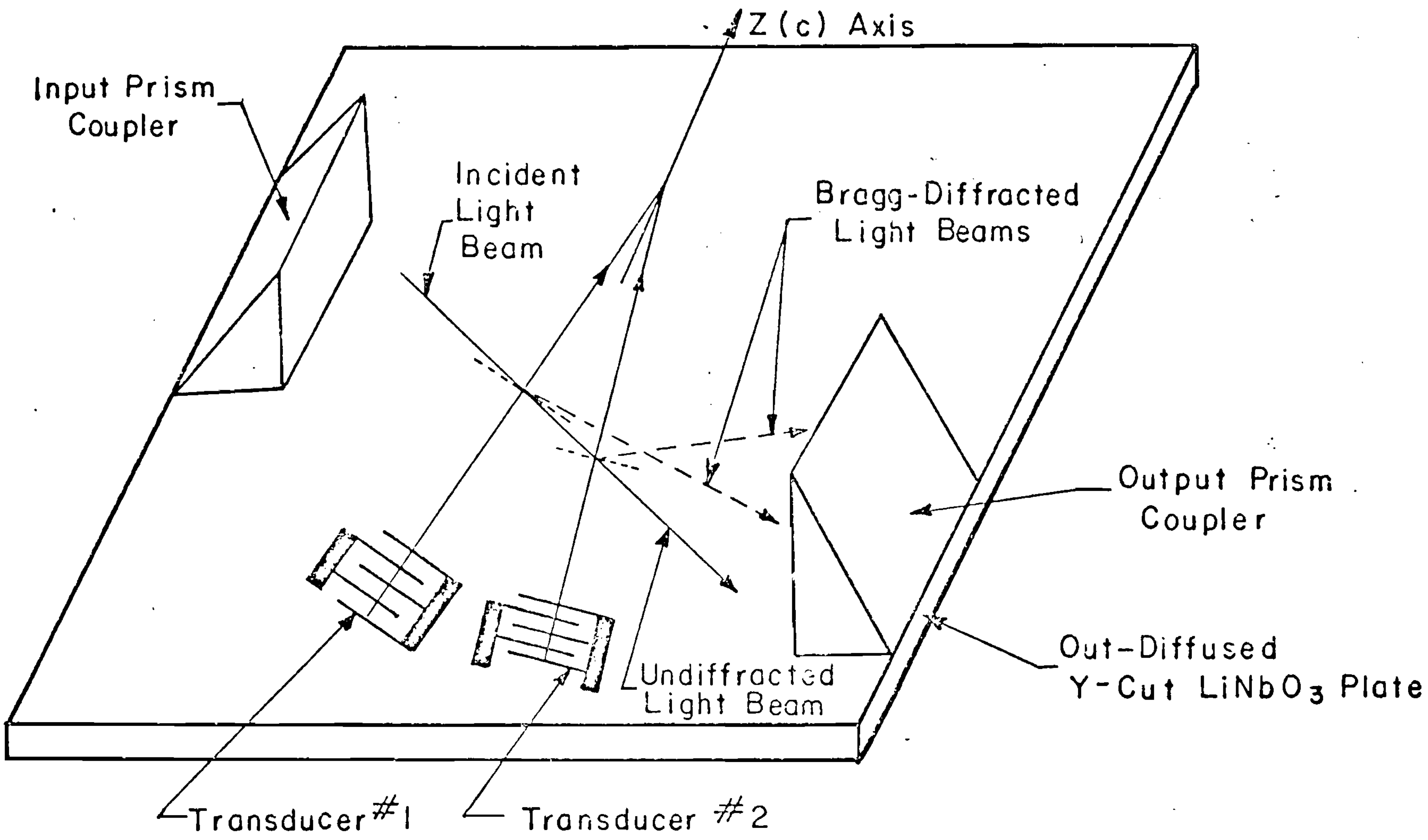


Figure 1. Guided-Wave Acoustooptic Bragg-Diffraction from Two Tilting Surface Acoustic Waves.

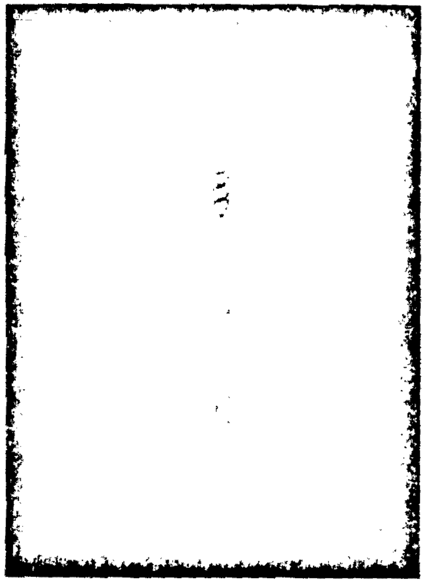


Figure 3. Diffracted Light Spot Positions at the Far-Field as the Frequency of the Driving Signal is Varied.

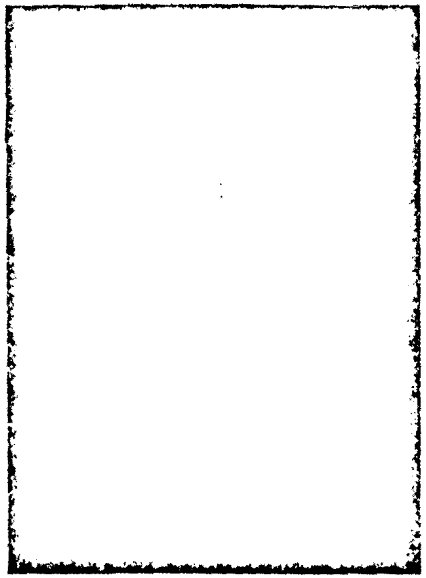


Figure 3. Diffracted Light Spot Positions at the Far-Field as the Frequency of the Driving Signal is Varied.