High-performance acousto-optic guided-light-beam device using two tilting surface acoustic waves*

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An acousto-optic guided-light-beam device utilizing two surface acoustic wave interdigital transducers, which are staggered in their center frequency and tilted in their propagation direction, on an essentially single-mode optical guiding layer of a Y-cut $LiNbO_3$ substrate has been shown to be capable of providing a very wide bandwidth. Detailed measurements on the diffraction efficiency and the deflection angle of the light beam versus the frequency of the driving signal, using a 6328-Å He-Ne laser light, are presented. The measured -3 dB bandwidth of the device is close to 200 MHz, which is more than an order of magnitude larger than that obtained in previous devices, with the measured electric driving power of 200 mW at 50% diffraction efficiency. The new device configuration introduced here should be very useful for wide-band applications such as a guided-wave acousto-optic rf spectrum analyzer and high-speed multiport switches for fiber/integrated optics.

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Acousto-optic guided-light-beam devices will certainly serve important functions such as modulation, switching, and deflection of a laser beam in future thin-film and fiber optics systems. In accordance with this expectation, there has been a very active interest in this type of device in recent years.[1-10] However, to the best of our knowledge, all of the various forms of acousto-optic guided-light-beam devices, namely, modulators, switches, and deflectors which had been studied experimentally heretofore, employed only a single surface acoustic wave (SAW) interdigital transducer.[1-10] As a result, they suffer from either a relatively low diffraction efficiency or a relatively small device bandwidth. The inherent limitation with the device employing a single transducer and, therefore, a single acoustic beam is that in order to achieve a large device bandwidth (assuming an 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.[11] A further limitation of which a single interdigital transducer suffers is its relatively small acoustic bandwidth.[12] Under such an unfavorable condition a device with both large 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 device configurations which are capable of relieving these limitations.

In this paper the experimental results of an acousto-optic guided-light-beam device utilizing a new device configuration which is capable of significantly relieving these limitations are presented. The main idea behind this device configuration is the utilization of multiple tilting SAW 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. The approximate tilting angle between the adjacent transducers is determined by the difference in the Bragg angles at their center frequency. In the results to be presented below the device utilizes two tilting surface acoustic waves propagating on a Y-cut $LiNbO_3$ substrate. Y-cut $LiNbO_3$ substrates were chosen because of their large electromechanical coupling coefficient, moderate

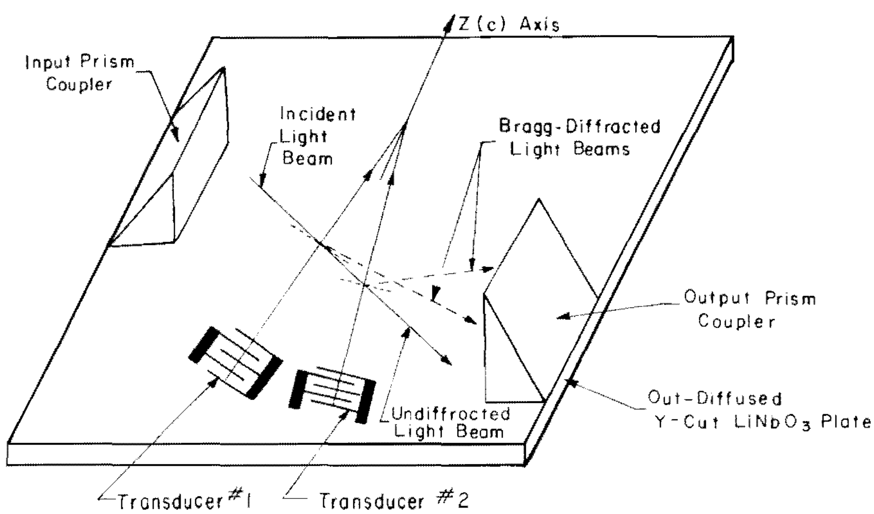


FIG. 1. Guided-wave acousto-optic Bragg diffraction from two tilting surface acoustic waves.

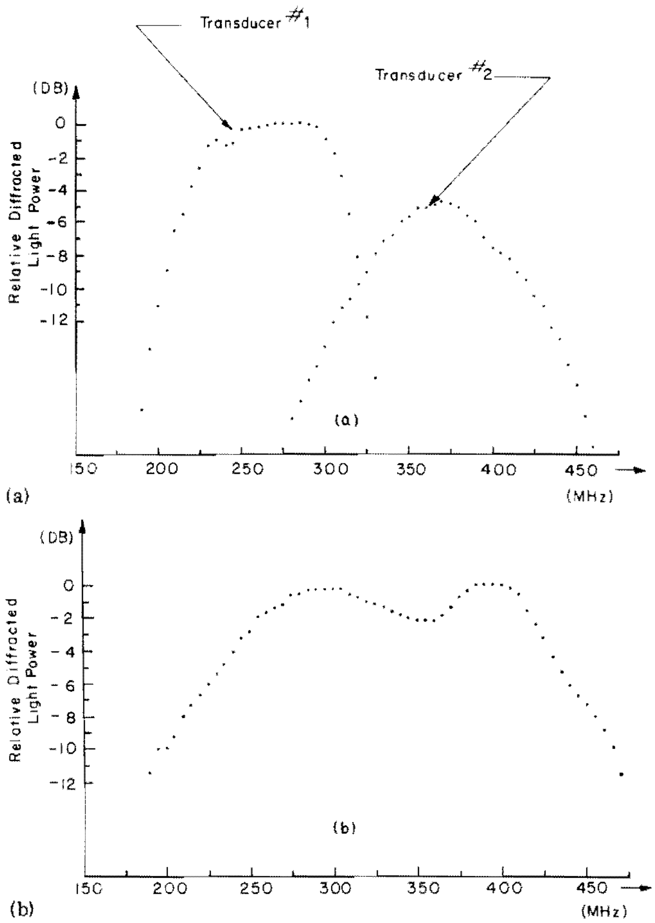
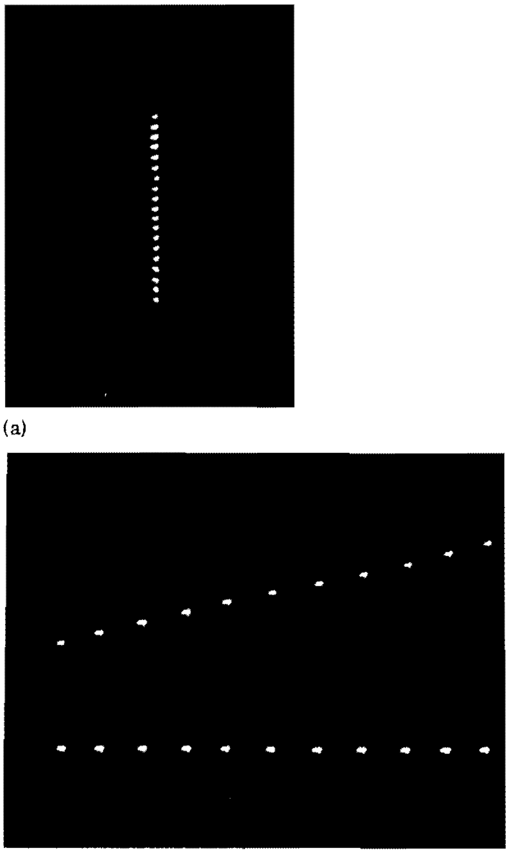


FIG. 2. (a) Frequency responses of the Bragg-diffracted light power for the individual acoustic waves. (b) Frequency response of the Bragg-diffracted light power for the combined acoustic waves.

acousto-optic figure of merit,[7] and the applicability of the out-diffusion technique for the fabrication of the optical waveguiding layer.[13] Detailed measurements for the device include the diffraction efficiency as well as the deflection angle of the light beam versus the frequency of the driving signal using a 6328-Å He-Ne laser light.

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. Two interdigital SAW transducers having the designed center frequencies of 255 and 382 MHz, respectively, and a tilting angle of approximately 0.3° were fabricated on the top of the waveguide to generate two tilting acoustic waves propagating approximately along the z axis of the $LiNbO_3$ crystal. Since it is desirable for the transducers to provide an acoustic bandwidth which is as wide as possible and since the fractional acoustic bandwidth of an interdigital transducer is inversely proportional to the number of interdigital finger electrode pairs, two and a half finger pairs was chosen for each of the two transducers. The apertures of the two transducers are 1.66 and 1.11 mm, respectively, each being large enough to ensure that the individual diffraction is 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 responses of the Bragg diffraction with the two transducers excited separately are shown in Fig. 2(a) and that with the two transducers excited simultaneously is shown in Fig. 2(b). From Figs. 2(a) and 2(b) it is seen that the resultant device bandwidth (~190 MHz) is larger than the sum of the device bandwidth using acoustic wave No. 1 alone (85 MHz) and the device bandwidth using acoustic wave No. 2 alone (75 MHz). It is also seen that the Bragg diffraction peaks in a neighborhood of the transducer center frequencies, namely, 255 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. As a matter of fact an additional peak, located between the two peaks, was observed in an earlier design in which the separation of the two center frequencies, 170 and 200 MHz, was considerably smaller.[14] In this earlier version a resultant device bandwidth of 60 MHz was obtained. Similar frequency responses with the resultant device bandwidth varying from 155 to 195 MHz was also obtained as the incident angle of the light beam was varied by approximately ±25′ from the optimum Bragg condition. Thus, a resultant device bandwidth close to 200 MHz has been achieved. Measurement of the strengths of the two surface acoustic waves, using a laser beam probe at normal incidence to the substrate, as a function of frequency indicates that the resultant device bandwidth is mainly limited by the acoustic bandwidths of the two transducers. Thus, a resultant device bandwidth larger than 200 MHz may be expected by inserting a wide-band electric matching network between the signal generator and the two transducers. A further increase in the resultant device bandwidth should be possible by adding more transducers at the appropriate center frequency and tilting angle.

In beam deflection and switching applications the relation $N=(D/v_s)\Delta f$ prevails, where N designates the number of resolvable beam diameters, D the aperture of the light beam, v_s the velocity of the surface acoustic wave, and Δf the device bandwidth. Figure 3(a) shows the photograph of the diffracted light spots at the far field as the frequency of the driving signal was varied from 240 to 420 MHz for a light beam aperture of about 0.1 cm. Figure 3(b) shows the corresponding undiffracted and diffracted light spots at the near field. With such a relatively small light beam aperture no degradation of either the undiffracted or the diffracted light beam was observed. From Fig. 3(a) the number of resolvable spot diameters as defined by the Rayleigh certerion is estimated to be 48, which agrees well with the calculated value of 51. In the device being studied a light beam aperture of 0.4 cm with slight nonuniformity in light intensity was achievable after the light beam has propagated through the input and output prism couplers. Improvement of the surface condition of the prism couplers and the $LiNbO_3$ plate and the contact between them should result in a larger light beam aperture. Thus, the device should be able to deflect a light beam of 1-cm aperture into 575 resolvable spot diameters with a transit time of 2.8 μsec. (The relevant surface



(a)

(b)

FIG. 3. (a) Diffracted light spot positions at the far field as the frequency the driving signal is varied. (b) Diffracted and undiffracted light spot positions at the near field as the frequency of the driving signal is varied.

acoustic wave velocity is 3.5×10^5 cm/sec.) The through-put coupling efficiency, after propagating through the input and output prism couplers, is approximately 20%. From Fig. 3(b) it is also seen that the mode structure of the diffracted beam is the same as that of the undiffracted beam. We, therefore, conclude that no observable mode conversion was generated during the acousto-optic interaction with the device being studied.

The rf driving power of the device for a 50% diffraction efficiency was measured to be 200 mW, corresponding to an estimated acoustic power of at most 50 mW. This estimation is based on the assumption of a -3 dB electric-acoustic conversion loss and an additional -3 dB insertion loss as a result of the bidirectional property of the interdigital transducer. Exact determination of the acoustic power was not possible because no receiving transducer was fabricated in the device being studied. For the earlier version of the device, referred to in Ref. 14, the corresponding rf driving power and the estimated acoustic power are 140 and 35 mW, respectively, with a device bandwidth of 60 MHz. This driving power requirement is slightly lower than that of a comparable device (at $\lambda = 1.15$ μ) described in Ref. 5. The very efficient diffraction achieved with our device is attributed to a close match of the penetration depths, estimated to be about 10 μ,[13] between the lowest-order mode guided-light waves and the surface acoustic waves. Optimization of both electrical and acoustical parameters of the device should further improve its performance.

In conclusion, we have experimentally demonstrated, for the first time, that a substantial increase in the bandwidth of an acousto-optic guided-light-beam deflector or switch can be achieved by employing multiple tilting surface acoustic waves which are staggered in their operating frequency and tilted in their propagation direction. The measured performance figure of the device being studied, which employs two tilting surface acoustic waves, is among the best of those having been achieved in recent years. It has been demonstrated that such a device configuration is relatively easy to design and easy to fabricate. The new technique introduced here should be very useful for applications involving very wide bandwidths, such as a guided-wave acousto-optic rf spectrum analyzer which requires a bandwidth of approximately 500 MHz[9] and high-speed multiport switches for integrated/fiber optics terminals.

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