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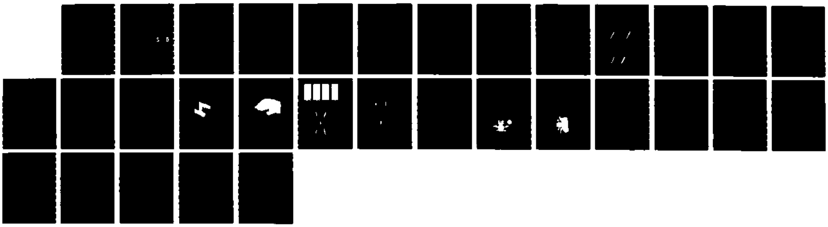

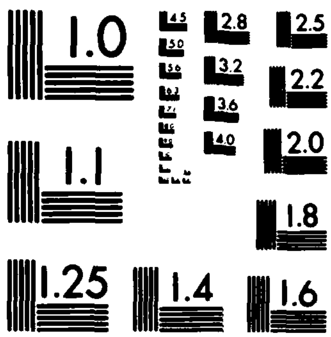

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INTEGRATED OPTIC MODULES FOR MULTICHANNEL DEFLECTION/SWITCHING AND SIGNAL PROCESSING

FINAL TECHNICAL REPORT

Chen S. Tsai, Principal Investigator

and Professor of Electrical Engineering

July 30, 1986

U.S. Army Research Office

Contract No. DAAG29-81-K-0060

University of California

Irvine, California 92717

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Integrated Optic Modules, Multichannel Deflection/Switching/Signal Processing, Tilted-Electrodes, Electrooptically Controlled Total Internal Reflection (TIR), Optical Switching Networks/Matrices, Crossed Channel Waveguide Acoustooptic Modulator/Deflector, Anisotropic Acoustooptic Time-Integrating Correlator, Titanium-Indiffused Proton-Exchanged (TIPE) Process, TIPE Microlens and Microlens Array.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the investigation and realization of a number of new hybrid integrated optic device modules in $LiNbO_3$ waveguides under the sponsorship of the Army Research Office. All of these device modules possess the desirable characteristics of very large bandwidth (GHz or higher), very small substrate size along the optical path (typically 1.5 cm), single-mode optical propagation, and low drive power requirement. The devices utilize either acoustooptic or electro-optic effects in planar or channel waveguides and, therefore, act as efficient

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20. Abstract (continued)

interface devices between a light wave and temporal signals. Major areas of application lie in wideband multichannel optical real-time signal processings, communications, and computing. Some of the specific applications include correlation of RF signals, fiber-optic sensing, optical systollic array computing and multiport switching/routing, and analog-to-digital conversion of wideband RF signals.

I. FOREWORD

It has been well recognized that the most immediate and important applications of integrated/fiber optics lie in the areas of wideband multichannel communications (for both military and civilian systems) and signal processings (for military hardware such as radars). Various kinds of high-performance active optical devices such as high-speed multichannel deflectors/switches and modulators are needed for the realization of these two areas of application. For example, one of the important functions of an optical receiver terminal is the routing or fanning-out of incoming optical signals to a large number of separte channels or users. Integrated optic device modules, aside from being smaller and lighter, can potentially perform this function in a simpler manner, at a faster speed, and at lower cost. Thus, the general objectives of this AROD-sponsored research are to discover and study novel concepts and devices based on electrooptic and acoustooptic effects in planar and channel optical waveguides and to develop and realize related integrated optic modules for such applications. As a result of this research effort a number of such integrated optic device modules have been realized.

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IV. BODY OF REPORT

A. STATEMENT OF THE PROBLEMS STUDIED

This Army Research Office-sponsored research program was concerned with guided-wave electrooptic and acoustooptic devices and modules for very high-speed multichannel light beam deflection/switching and RF signal processing. Specific research tasks are: (1) to study in detail a number of novel device concepts and relevant device parameters, (2) to advance the performance characteristics of the resulting devices, (3) to realize and study integrated optic modules based on these concepts and devices, and (4) to identify specific applications of such modules in integrated/fiber optic systems and electronic/optical computers. The ultimate goal is to advance the capability of wideband multichannel optical systems relating to Army Technology. The six specific subjects that have been studied are:

1. Very High-Speed Electrooptic Multiport Deflector/Switch Using Tilted-Electrode Structure
2. High-Speed Multiport Deflector/Switch Using Electrooptic Phased-Array Structure
3. Light Beam Deflector/Switch/Coupler Using Electrooptically Controlled Total Internal Reflection
    - i. Planar Waveguide Device
    - ii. Channel Waveguide Device With Taper-Horn Structure
    - iii. Channel Waveguide Device Without Taper-Horn Structure
4. Channel Optical Waveguide Switching Networks and Matrices
5. Acoustooptic Bragg Deflection in Crossed Channel Optical Waveguides
6. Integrated Optic Modules for Acoustooptic Time-Integrating Correlation.

Some very significant results have been obtained in each subject.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

1. Very High-Speed Electrooptic Multiport Deflector/Switch Using Tilted-Electrode Structure

This research was concerned with a novel scheme to greatly increase the number of channels for high-speed optical switching. The scheme utilizes a number of basic tilted-electrode EO(1) deflectors (Fig. 1) which are successively increased in apertures and are arranged in tandem (along the optical path) and driven independently with discrete voltages. For example, for a deflector which uses a $LiNbO_3$ waveguide and 4 stages with each stage capable of 9 resolvable channels, the total number of resolvable channels would be 125. The discrete drive voltages required for each stage can be as low as a few volts per resolvable channel. However, as indicated in the original proposal, the main task was to integrate such deflectors/switches with wavegide lenses to form hybrid integrated optic modules. Consequently, it was necessary to study and determine the viability of existing waveguide lenses. The accomplishment that has resulted from this endeavor is described in the following subsection.

2. High-Speed Multiport Deflector/Switch Using Electrooptic Phased-Array Structure

As in the first research subject, the main task was to incorporate waveguide lenses to form hybrid integrated optic modules with applications to the schemes (Fig. 2) for multiport deflection/switching(1,2) and A/D conversion(2) that had been explored under the preceding Army Research Office (ARO) -sponsored research grant. Consequently, a great deal of effort was made to study and determine the viability of existing planar waveguide lenses. As a result of this endeavor, the titanium-indiffused proton-

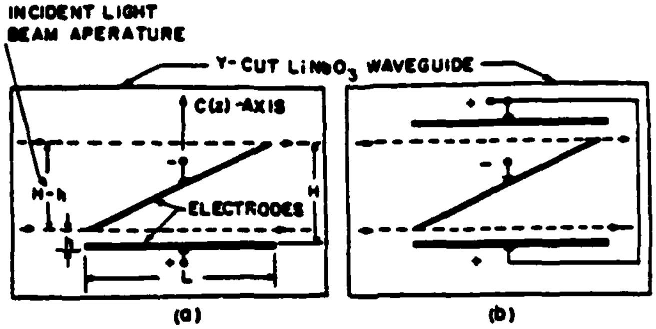
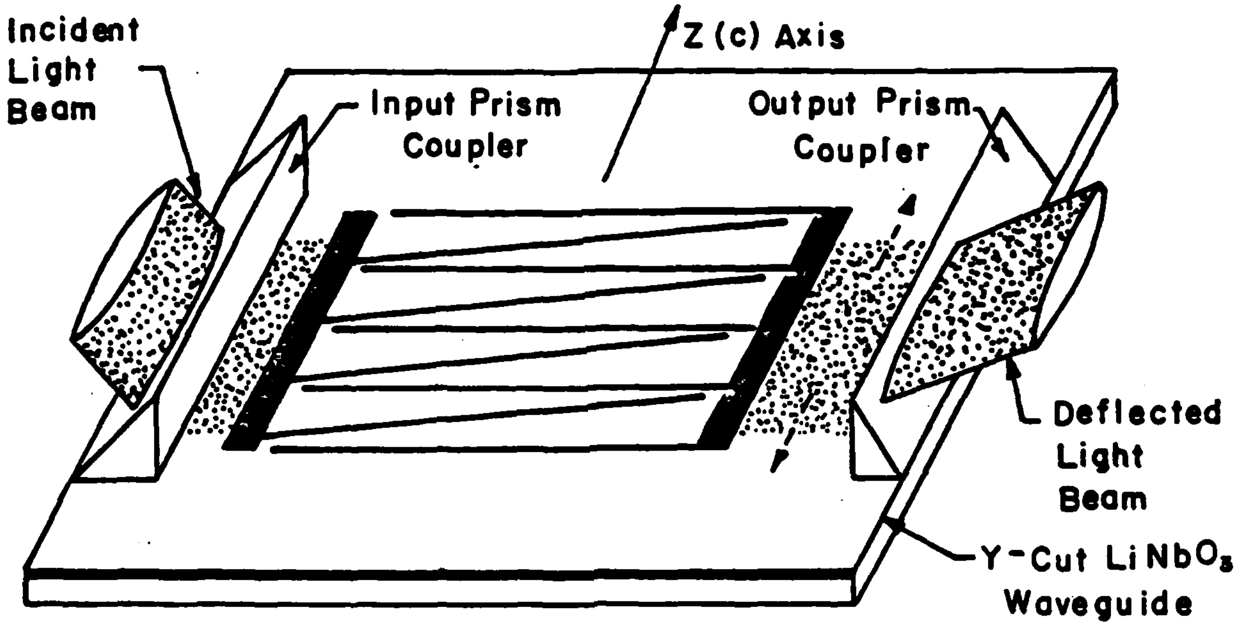


FIG.1a. Guided-wave electro-optic prismlike deflectors using the tilted electrodes on Y-cut $LiNbO_3$ waveguides. (a) Basic prism deflector; (b) two basic prism deflectors in parallel.



L=1.3cm, H=150μm, h=5μm, Total Aperature = 600μm

Fig.1b. Actual Design Of The Deflector

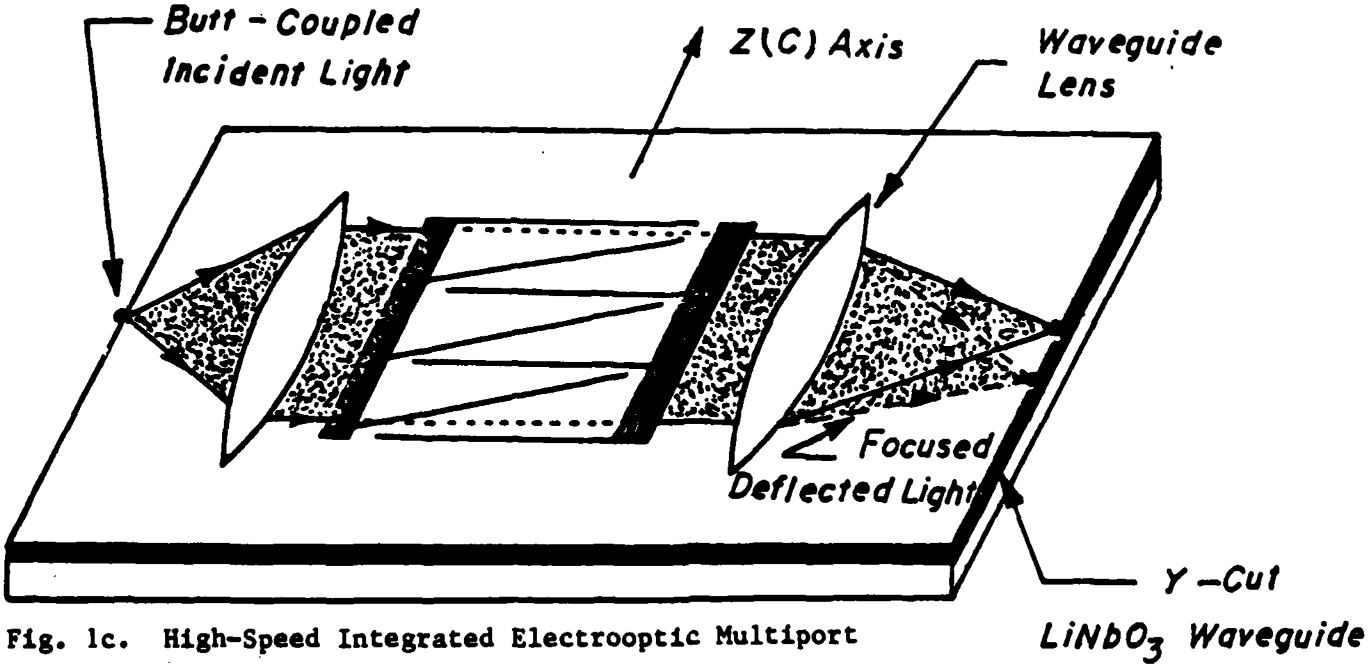


Fig. 1c. High-Speed Integrated Electrooptic Multiport Deflector/Switch Module

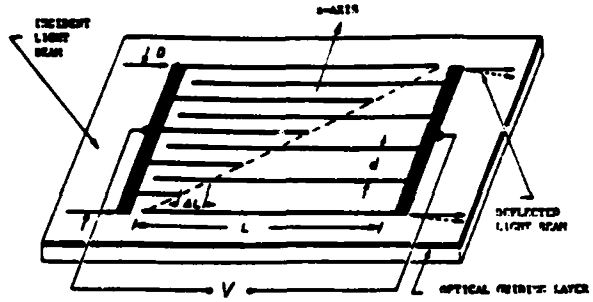


FIG 2a Guided-wave beam deflector/switch and modulator using apodized-electrode array structure on Y-cut $LiNbO_3$ waveguide.

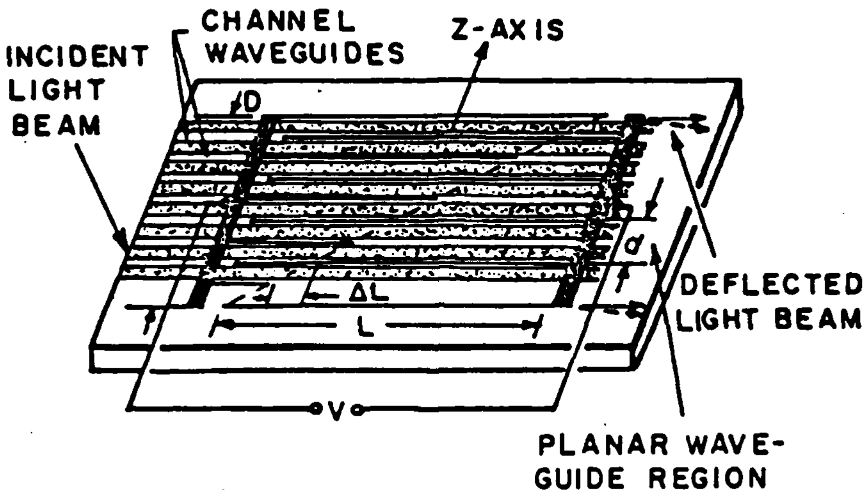


FIG. 2b
LIGHT BEAM DEFLECTOR USING APODIZED-ELECTRODE ARRAY STRUCTURE IN CHANNEL OPTICAL WAVEGUIDE.

exchanged (TIPE) process which had been originally developed for fabrication of planar waveguides[3] was successfully utilized for the first time to form single-mode waveguide lenses in $LiNbO_3$ substrates.[4] For fabrication of the single-mode microlenses and microlens arrays the well-established TI process was first applied in a Y-cut $LiNbO_3$ substrate to form a planar waveguide that supports a single TE-mode and a single TM-mode of the lowest order. Subsequently, a masking material such as Si_3N_4 with a designed lens contour was deposited on the TI waveguide (Figure 3). The sample was then immersed in molten benzoic acid at 230^0C for six hours. As a result of the selective proton exchange, the region (the shaded area in Figure 3) without the masking material had its extraordinary refractive index increased by as much as 0.11 in comparison to the remaining TI region. Consequently, this PE region of appropriate contour will function as a planar waveguide lens. For example, using the Fermat principle the contour for a plano-convex lens depicted in Figure 1 has been shown to be an ellipse. A variety of basic (single) lenses with plano-convex and double-convex contours of various apertures and focal lengths have been fabriated and tested. The measured half-power (3 dB) width of the focal spot in light intensity was typically 2.0μm. The strength of the highest sidelobe was typically -12 to -16 dB lower than that of the mainlobe. The measured focal length of the lens agrees well with the design value. The average insertion loss of the lens was measured to be 1.5 dB which corresponds to a throughput efficiency of 71%. An angular field of view of 10-degree has been measured with the plano-convex lenses. In the case of double-convex lenses an angular field of view as large as 25 degree has also been measured.

A large number of the basic single-mode microlenses as described above but of much smaller dimensions in aperture and focal length has also been

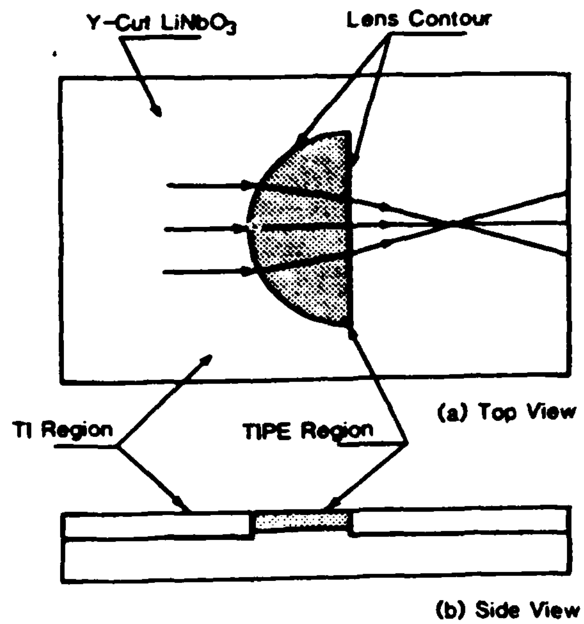


Fig. 3 Planar Waveguide Lens In $LiNbO_3$ Formed By Titanium Indiffused Proton Exchanged (TIPE) Technique

configured into a linear array in the $LiNbO_3$ substrate. For example, a 60-element linear microlens array with each lens element having a 60μm aperture and 200μm focal length has been successfully fabricated. The microlenses fabricated thus far have provided desirable properties such as very short focal length, large numerical aperture, focal spot size of a couple of microns for a wide range of focal length, large field of view, and low optical insertion loss. Subsequent study has demonstrated the viability of this TIPE process for fabrication of high-performance planar microlenses and microlens arrays using a single masking step.(5)

The microlenses and microlens arrays described above should facilitate realization of integrated optic device modules for applications in integrated- and fiber-optic signal processing and computing as well as communication systems.

3. Light Beam Deflector/Switch/Coupler Using Electrooptically Controlled Total Internal Reflection

Although three versions of the electrooptically controlled total internal reflection (TIR) devices(6-8) were mentioned in the original proposal, a study showed that the third version, namely, Channel Waveguide Devices without Taper-Horn Structure or Channel Waveguide Devices Using Straight Intersecting (Crossed) Waveguides in $LiNbO_3$ (Fig. 4)(8) possessed the highest merit. Therefore, subsequent effort was focused to this particular version.

Through a variety of designs in terms of the channel waveguide width, the intersecting angle, and the width and separation of the parallel electrode pair, a number of desirable features of the TIR channel waveguide devices have been demonstrated.(9-11) The desirable features include small substrate size

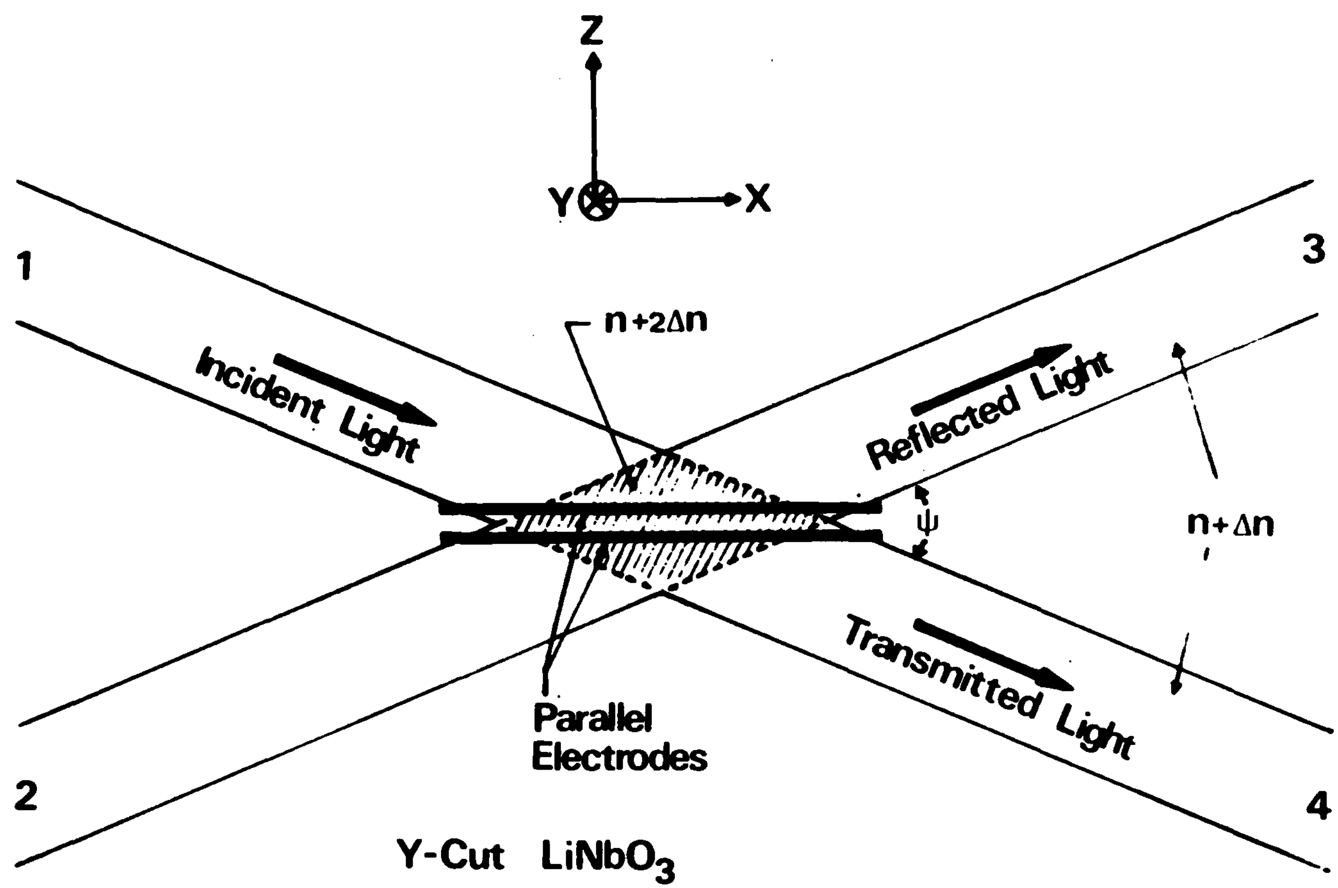


Fig.4 Optical Channel Waveguide Double-Pull-Double-Throw Switch/Coupler Using Total Internal Reflection

per unit device and thus high packing density, large base bandwidth, relatively low drive voltage requirement, and relatively low crosstalk. As a demonstration of wideband capability, a 8.5 GHz bandwidth single-mode modulator and switch operating at 0.79 μm wavelength was realized in a Y-cut $LiNbO_3$ substrate (Fig. 5(a)).[12]

The resulting wideband TIR modulator/switch module (Fig. 5(b)) should constitute a desirable modulator or switch that provides a multigigahertz bandwidth for microwave communication and radar systems. Also, the resulting optical switching networks or matrices (to be described in the following subsection) are expected to provide a variety of high-speed operations such as multiport routing and multiplexing in single-mode fiber optic communication and signal processing systems as well as residue-based optical computing.[13,14]

4. Channel Optical Waveguide Switching Networks And Matrices

A simple 4 x 4 switching matrix/network having a total device length as small as 0.75 cm which consists of five basic TIR switches of multigigahertz bandwidth on the same $LiNbO_3$ substrate have been realized (Fig. 6).[9,10] A simple scheme which involves cascade of identical devices (Fig. 7) for reduction of the crosstalk by a factor of two in db, namely from -15db to -30 db, has also been devised and verified experimentally.[11] As indicated in the preceding subsection, the resulting optical switching networks and matrices are expected to provide a variety of high-speed operations such as multiport routing and multiplexing in single-mode fiber optic communication and signal processing systems as well as residue-based optical computing.[13,14].

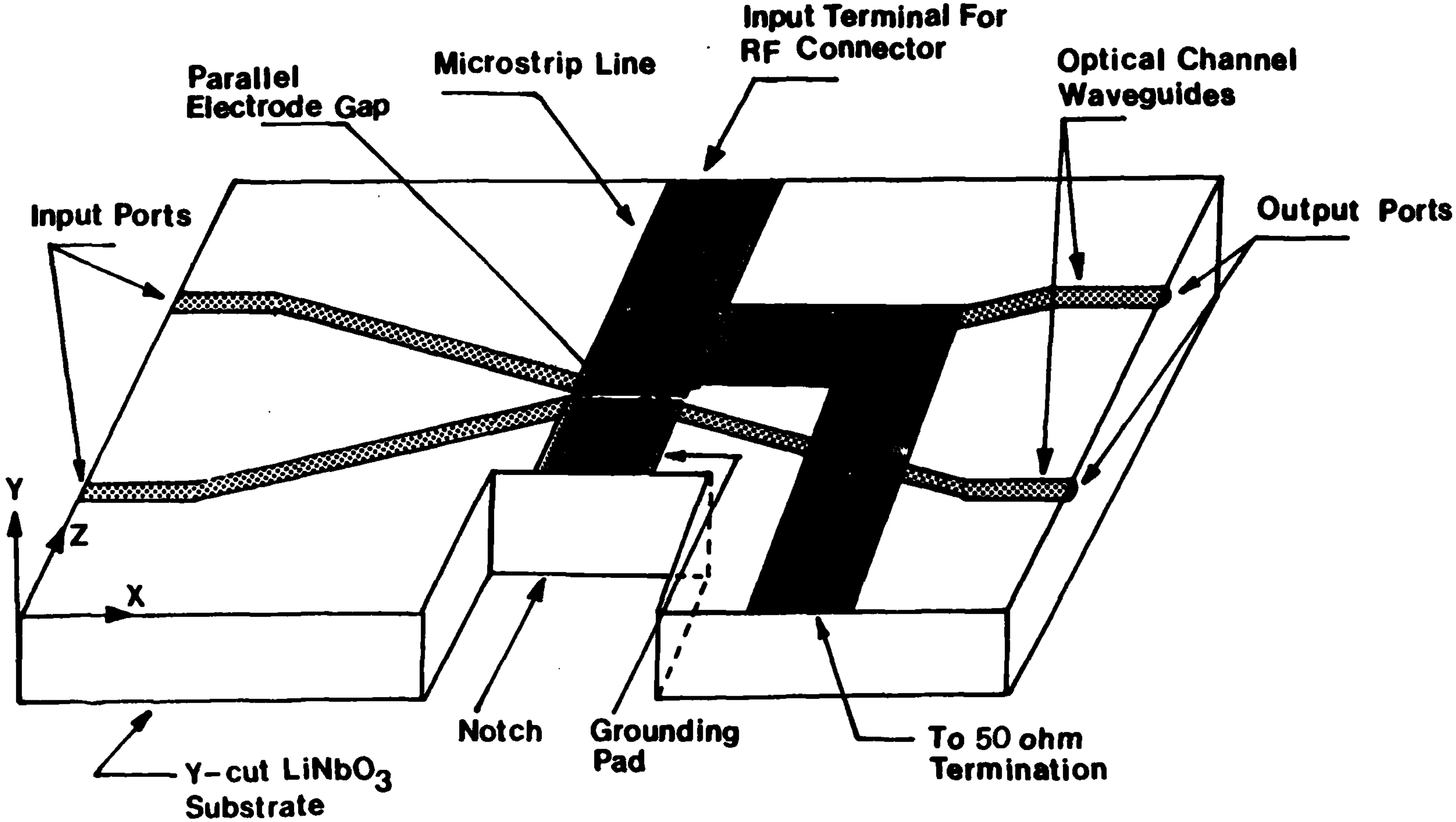


Fig. 5(a) Electrooptic Crossed Channel Waveguide Total Internal Reflection Modulator Incorporating A Notch For Multigigahertz Bandwidth Operation

Fig. 5(b) A Packaged Electrooptic Crossed Channel Waveguide Device Module Using a Traveling-Wave Coplanar Microstripline Structure With No. 70 Coaxial Cable and Flange-Mount SMA Connectors.

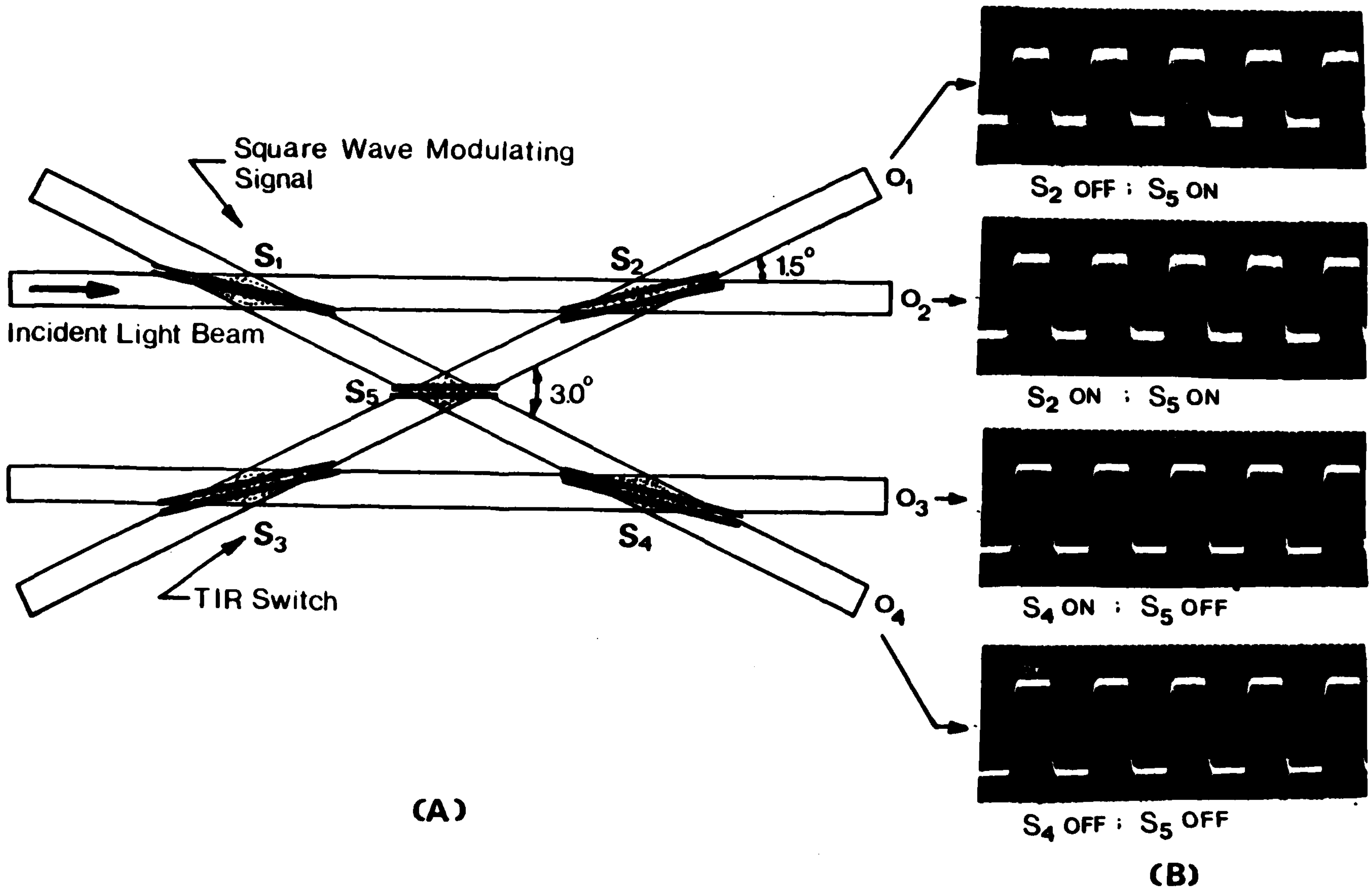
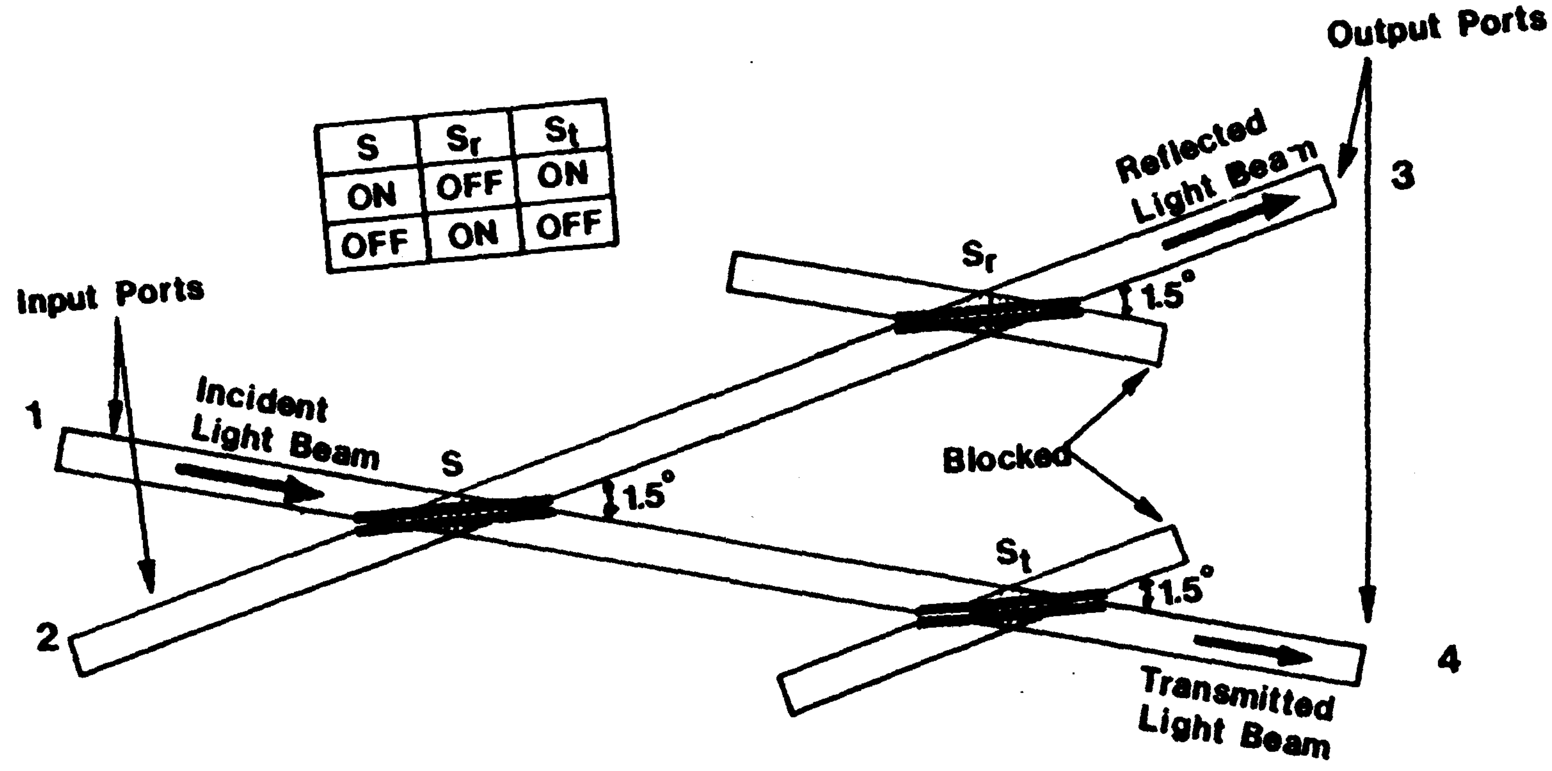


Fig. 6 **A 4×4 Optical Switching Network Using Channel Waveguide TIR Switches (A). And Output Waveforms (B)**



S	S_r	S_t
ON	OFF	ON
OFF	ON	OFF

Fig. 7 Cascading Of Channel Waveguide E-O TIR Switches For Crosstalk Reduction

5. Acoustooptic Bragg Deflection In Crossed Channel Optical Waveguides

This research project was concerned with realization of single-mode integrated optic device modules that utilize AO Bragg diffraction in $LiNbO_3$ crossed channel waveguides (Fig. 8).[15] A high diffraction efficiency acoustooptic (AO) deflector/modulator using single-mode crossed-channel waveguides in a Y-cut $LiNbO_3$ substrate has been successfully realized (Fig. 9).[15] Measurements at the center frequency of 320 MHz has demonstrated simultaneously a high diffraction efficiency and a large deflector bandwidth, namely, a 50% diffraction efficiency and a 13.4 MHz bandwidth requiring only 0.13 Watt of surface acoustic wave (SAW) power. This experiment has clearly indicated the possibility of realizing an integrated optic module with a 50-50 power split and a tunable frequency offset.[16] Such a module should find a variety of unique applicatons in future integrated and fiber optic systems. In the application for heterodyne detection the frequency-shifted light can be conveniently used as a reference signal (local oscillator) in connection with optical communications and fiber optic sensing.

6. Integrated Optic Modules For Acoustooptic Time-Integrating Correlation

Some significant progress has been made on a novel interaction configuration that utilizes anisotropic AO Bragg diffraction in a planar waveguide (Fig. 10).[17,18] This novel scheme has resulted in an AO correlator module (Fig. 11) which is not only much smaller in dimension along the optical path (in comparison to that which utilizes the conventional isotropic AO Bragg diffraction) and capable of providing a larger time window and a lower optical insertion loss, but also easier to be implemented in integrated optic format. A brief description of the basic device

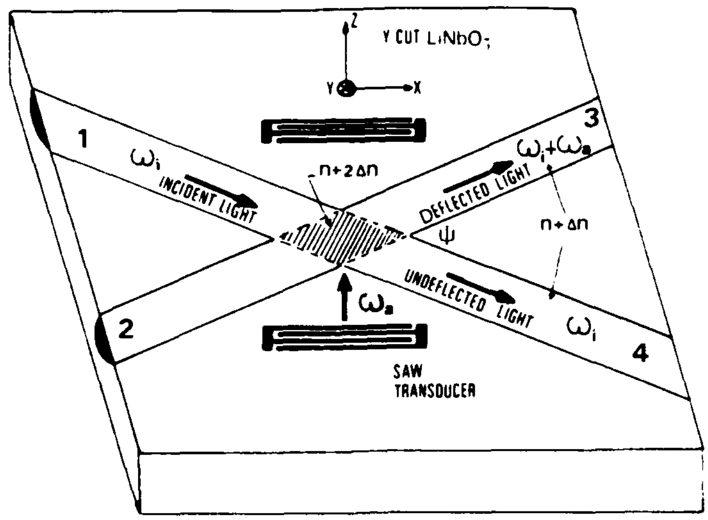


Fig. 8 Acoustooptic Diffraction From Surface Acoustic Wave in Crossed-Channel Waveguides

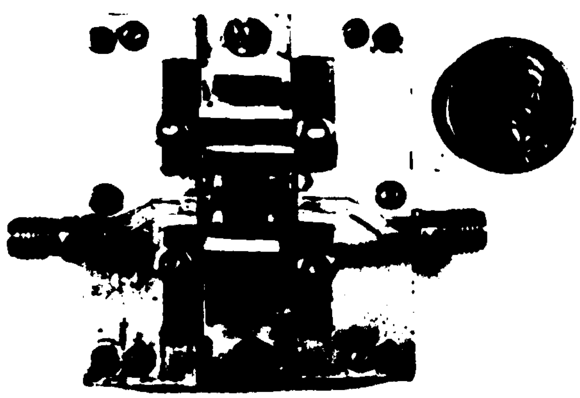


Fig. 9 Single-Mode Crossed-Channel Waveguide Acoustooptic Modulator Module in $LiNbO_3$ Substrate

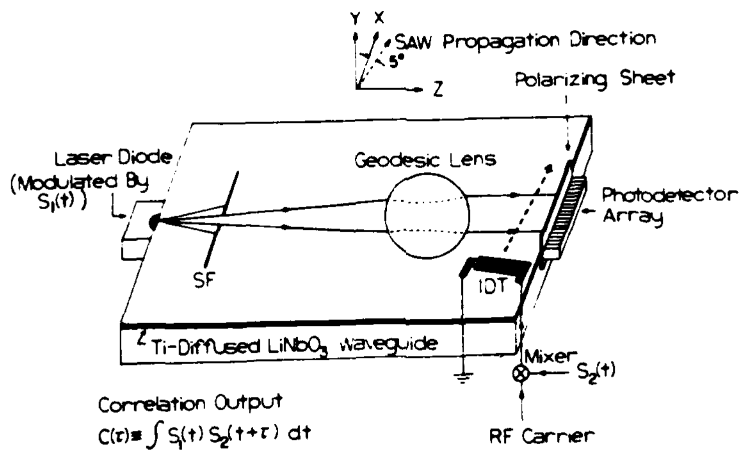


Fig. 10 Acoustooptic Time-Integrating Correlator Using Anisotropic Bragg Diffraction And Hybrid Optical Waveguide Structure.

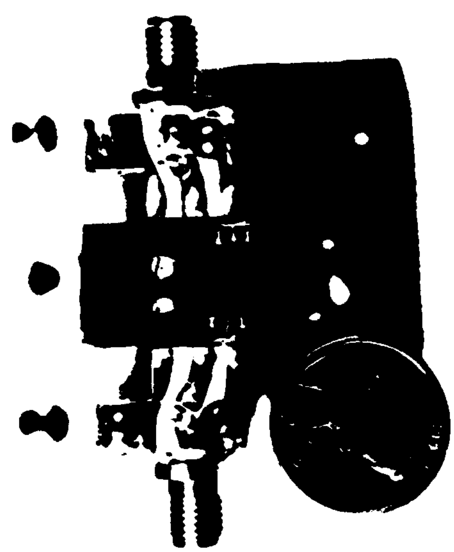


Fig. 11 Hybrid Integrated Acoustooptic Time-Integrating Correlator Module.

configuraton, working principle, and experimental results of the resulting AO correlator module now follows.

Time-integrating correlation of RF signals using bulk-wave isotropic AO Bragg diffraction[19] has become a subject of great interest because of its applications in radar signal processing and communications.[20-22] Some encouraging results with the experiments which utilize guided-wave isotropic Bragg diffraction were also reported earlier.[23-26] Subsequently, hybrid and monolithic structures for integrated optic implementations were suggested.[24] In a conventional configuration that utilizes either bulk-wave or guided-wave isotropic Bragg diffraction, a pair of imaging lenses and a spatial filter are used to separate the diffracted light beam from the undiffracted light beam. Under this ARO program a new and novel hybrid structure which utilizes guided-wave anisotropic Bragg diffraction and hybrid integration (see Fig. 10) [17,18] was explored. This new structure can conveniently incorporate a thin-film polarizer to separate the diffracted light from the undiffracted light prior to detection and, therefore, eliminates the need of imaging lenses and spatial filter. As a result, the AO time-integrating correlator is not only much smaller in dimension along the optical path and capable of providing a larger time window and a lower optical insertion loss, but also easier to be implemented in integrated optic format. A laser diode and a thin-film polarizer/photodetector array (CCPD) composite were butt-coupled to the input and the output end faces of a Y-cut $LiNbO_3$ plate (2mm x 12mm x 15.4mm), respectively. A single geodesic lens (with 8mm focal length) was used to collimate the input light beam prior to interaction with the SAW. The SAW propagates at 5 degrees from the X-axis of the $LiNbO_3$ plate to facilitate anisotropic Bragg diffraction between TE_0- and TM_0-modes. In operation, the correlation between the two signals $S_1(t)$ and

$S_2(t)$ was performed by separately modulating the laser diode and the RF carrier to the SAW transducer. Finally, the time-integrating correlation waveform was read out from the detector array by the charged-coupled device.

The preliminary experiment carried out with the correlator module using hybrid integration at 0.6328μm wavelength and the SAW at 391 MHz center frequency had demonstrted a bandwidth of 60 MHz and a time bandwidth product of 4.2×10^5, and a dynamic range of -27dB. A considerably larger bandwidth should be achievable as it is now possible to design and fabricate GHz bandwidth planar acoustooptic Bragg cells[27,28] and it is also possible to modulate the diode laser at GHz rates. Fig. 11 shows the $LiNbO_3$ substrate of the module with the geodesic lens located at the center and the SAW transducer at the right end. Finally, it is to be mentioned that the TIPE microlens referred to previously should constitute an ideal replacement for the geodesic lens, and thus greatly facilitate eventual manufacturing of such integrated optic correlator modules.

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D. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL AND DEGREES AWARDED

Chen S. Tsai, Principal Investigator and Professor of Electrical Engineering

Chin C. Lee, Research Associate

De Y. Zang, Research Associate and Ph.D. candidate

Chin L. Chang, Ph.D. candidate

Kuan Y. Liao, Ph.D. candidate

Ching T. Lee, Ph.D. candidate

Phat Le, M.S. candidate

H. C. Hong, Research Assistant

Ph.D. Awarded

1. Chin L. Chang, Thesis Title, "Optical Channel Waveguide TIR Devices And Applications," September, 1982.
2. Kuan Y. Liao, Thesis Title, "Wideband Real-Time Signal Processing Using Integrated Optics," September, 1982.
3. Ching T. Lee, Thesis Title, "Acoustooptic Channel Waveguide Devices And Applications," September, 1982.

M.S. Awarded

1. H. C. Hong, January, 1984.
2. Phat Le, Thesis Title, "High Speed Crossed-Channel Waveguide Electrooptic Modulator/Switch," November, 1985.

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