# FINAL PROGRESS REPORT

for Office of Naval Research
for the period August 1988 through January 1991

1. **Contract Title:**
An Investigation of Optically Controlled, Integrated Millimeter Wave Receiving Phased Arrays

**Principal Investigators:**
Professor Alan R. Mickelson
Professor David C. Chang
Department of Electrical and Computer Engineering
Campus Box 425
University of Colorado
Boulder, CO 80309-0425



**Program Manager:**
Dr. Arthur Jordan

2. **Technical Objectives:**
The principal objective of this project is to determine the most efficient means of encoding a microwave/millimeter wave signal from a patch antenna onto an optical carrier in an electro-optical substrate for subsequent optical processing of the microwave/millimeter wave signal.

3. **Approach:**
Our approach was to develop design models that would relate the performance of integrated electro-optic devices to the fabrication parameters used in making them and then experimentally verify their performance. Where lack of agreement was observed, the models were rethought and modified to improve their predictive behavior. Such performance characteristics included modal field distributions, propagation constants, coupling coefficients of channel waveguides and coupling lengths of proton exchanged directional couplers. This information was then used to design patch antennas and integrated optical modulators using various fabrication techniques and substrates. Similar design methods were used to determine the depth of modulation of electro-optic modulators.

4. **Accomplishments:**
In order to achieve optically-controlled integrated millimeter-wave receiving phase arrays, single sideband modulation of an optical carrier by an incoming millimeter wave must be performed. Our research in this area began with the investigation of traveling wave structures used to obtain 90 degree phase shifts in millimeter wave signals. These structures consisted of slots in microstrip lines and were analyzed using a numerical (moment method) program. A theoretical model describing the interaction of a millimeter or microwave signal with an optical carrier was developed and used to determine the optical depth of modulation. A strip dipole was fabricated onto one arm of an integrated optical Mach Zender interferometer.

Modeling and fabrication of electrooptic devices in $LiNbO_3$ was then initiated. This led to the fabrication and packaging of microwave patch antennas in $LiNbO_3$ with 50 ohm microstrip feedlines. Eventually coplanar dipole antenna electrodes for electrooptic modulators were designed, modeled, fabricated and tested. It was determined that the most efficient way to couple the microwave signals to optical signals was by use of a patch antenna, amplifier and resonant electrode

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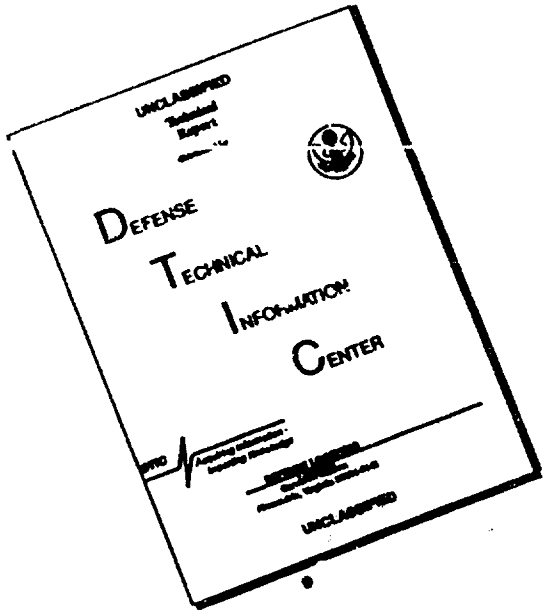


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integrated optical modulator. Finally a patch antenna fed resonant electrode single side band integrated optical modulator was modeled, fabricated and tested.

A considerable amount of work has been done on the use of proton exchanged $LiNbO_3$ and $LiTaO_3$ for electro-optic devices. It has been determined that fabrication of optical waveguides using proton exchange produces a larger effective index change than standard Ti indiffusion and that $LiTaO_3$ devices have higher refractive index damage thresholds, allowing larger optical signals to be transmitted.

The modal field distributions, propagation constants and coupling coefficients of channel waveguides were calculated for various fabrication parameters and compared to experimental results. Calculations were done by starting with the refractive index profile and then using the matrix effective refractive index method with coupled mode analysis. Such straight forward modeling techniques were used for such purposes in that they could be run at significantly faster rates of speed with significantly less memory than more accurate techniques. Our purpose was to relate actual experimental fabrication parameters to actual measured performance. The experimental uncertainty greatly exceeded any round-off or truncation error due to our simple analysis techniques. Similar calculations were done to verify the coupling length of proton exchanged and annealed directional couplers as a function of thermal anneal time and device geometry.

Optical depth of modulation measurements of proton exchanged integrated optical modulators with patch antennas and resonant coplanar waveguide electrode structures were made using the swept frequency technique. Narrowband Mach-Zender electrode structures were fabricated with proton exchange techniques and 100 percent depth of modulation was demonstrated at x-band frequencies.

Alternative methods of generating microwave signals are also been investigated, including laser locking and grid oscillators. By locking a slave laser to a master laser, an intermediate microwave signal can be generated. Measurements on locking bandwidth and locking transients are being carried out.

## 5. Significance:

From our theoretical and experimental work, it has been shown that it is feasible to build a single side band modulator for millimeter/microwave signals. Such devices will consist of patch antennas used as resonant electrodes for electro-optic modulators. Optical processing using such devices as Butler matrices, can be used to perform signal processing and beam forming of signals. Such techniques require gain at each antenna element and provide both transmit and receive processing. Techniques employing locked lasers can also be used for the transduction of antenna signals onto optical carriers.

## 6. Future Efforts:

A new electrode design consisting of a coplanar 3dB coupler for use in a single side band modulator is currently being tested. Our efforts will continue to pursue alternative substrates for fabrication of electro-optic devices, including $LiTaO_3$ and $LiNbO_3$. For antennas being used in the receive mode, active elements that will provide isolation from extraneous signals will be investigated.

## 7. Publications and Presentations Partially Supported Under This Grant Since Last Report Period

Please see the attached complete list of publications.

(a) D.R. Hjelme, A.R. Mickelson, "Voltage Calibration of the Direct Electrooptic Sampling Technique," Submitted to IEEE-MTT (February 1991), see also Guided Wave Optics Laboratory Report No. 31 (April 1991).

(b) S. Bundy, T. Mader, Z. Popovic, R. Ellingsen, D. Hjelme, M. Surette, M. Yadlowsky, A.R. Mickelson, "Quasi-Optical Mesfet VCO's," SPIE, Orlando, FL (March 1991). See also Guided Wave Optics Laboratory Report No. 30, (April 1991).

(c) D.R. Hjelme, A.R. Mickelson, "Characterization and Modeling of MIMICs by Optical Sampling," Guided Wave Optics Laboratory Report No. 28, (April 1991).

## Theses During Project

(a) W. Charczenko, "Coupled Mode Analysis, Fabrication, and Characterization Of Microwave Integrated Optical Devices", PhD Thesis, University of Colorado (September 1990).

(b) P. Weitzman, "Evaluation Of Electric Field Distributions. and Capacitance Of Electrode Structures Used In Integrated Optic Modulators", MS Thesis, University of Colorado (May 1990).

(c) H. Klotz, "An Experimental Study to Determine Fabrication Parameters for Proton Exchanged Waveguides in $LiNbO_3$", MS Thesis, University of Colorado (December 1989).

## 8. Participants

Professor Alan R. Mickelson
Professor David C. Chang
Walter Charczenko
Peter Weitzman
Holger Klotz
Paul Matthews
Marc Surette
Doris I. Wu

# Publications and Presentations Partially Supported Under This Grant

1. P. Weitzman, J.M. Dunn and A.R. Mickelson, "Approximate Calculation of Transmission Line Parameters of Field Distributions of Coplanar Electrodes in the Presence of A Buffer Layer" Guided Wave Optics Laboratory Report No. 22.
2. P. Weitzman, J.M. Dunn and A.R. Mickelson, "An Efficient Numerical Method For the Calculation of the Electrical Properties of Coplanar Electrodes in the Presence of a Buffer Layer", see Guided Wave Optics Laboratory Report No. 21.
3. W. Charczenko, P.S. Weitzman, H. Klotz, M. Surette, J.M. Dunn and A.R. Mickelson, "Characterization and Simulation of Proton Exchanged Integrated Optical Modulators With Various Dielectric Buffer Layers", Journal of Lightwave Technology, Volume 9, Number 1, (January 1991). See also Guided Wave Optics Laboratory Report No. 18 (May 1990).
4. M. Surette and A.R. Mickelson, "Coherent Guided Wave Implementations for Photonic Control of Phased Array Radar Systems, OSA Annual Meeting, Boston, MA, (November 1990).
5. W. Charczenko, P.S. Weitzman, J.M. Dunn and A.R. Mickelson, "Characterization and Simulation of Proton Exchanged Integrated Optical Modulators with Various Dielectric Buffer Layers," OSA Annual Meeting, Boston, MA, (November 1990).
6. P. Matthews, M. Surette and A.R. Mickelson, "Characteristics of Proton-Exchanged Lithium Tantalate Waveguides," OSA Annual Meeting, Boston, MA (November 1990).
7. W. Charczenko, D.R. Hjelme, and A.R. Mickelson, "Comparison of Time and Frequency Domain Measurement Methods For High Speed Optical Modulators", presented at the Optical Fiber Symposium, National Institute of Standards and Technology, Boulder, CO (September 1990).
8. W. Charczenko, M. Surette, R. Fox, S.T. Vohra, S. Asher, and A.R. Mickelson, "Comparison of Numerical Simulations to Experimental Measurements of Proton-Exchanged and Annealed Channel Waveguides and Direction Couplers in $LiNbO_3$, submitted to Applied Optics. See also Guided Wave Optics Laboratory Report No. 26 (September 1990).
9. W. Charczenko, "Coupled Mode Analysis, Fabrication and Characterization of Microwave Integrated Optical Devices", PhD Thesis and Guided Wave Optics Laboratory Report No. 27 (September 1990).
10. W. Charczenko, M. Surette, P. Matthews, H. Klotz and A.R. Mickelson, "Integrated Optical Butler Matrix For Beam Forming In Phased Array Antennas," Proceedings of SPIE, Los Angeles, CA (January 1990).
11. P. Weitzman, J.M. Dunn and A.R. Mickelson, "Calculation of Transmission Line Parameters and Electric Field Distribution of Coplanar Electrodes on Layered Dielectric Substrates," National Radio Science Meeting, Boulder, CO (January 1990).
12. P.J. Matthews, M.R. Surette and A.R. Mickelson, "Optically Implemented Butler Matrices for Microwave Processing," National Radio Science Meeting, Boulder, CO (January 1990).
13. W. Charczenko, H.R. Klotz and A.R. Mickelson, "Microwave Integrated Optical Transducer for Optical Readout of Patch Antennas," National Radio Science Meeting, Boulder, CO (January 1990).
14. S.T. Vohra, "Diffusion Characteristics and Waveguiding Properties of Li1-xHxNbo3 Optical Waveguides and Devices", Guided Wave Optics Laboratory Report No. 8 (June 1989).
15. W. Charczenko, H. Klotz, P. Matthews, and A.R. Mickelson, "Integrated Optics For Microwave and Millimeter-Wave Detection and Signal Processing", Paper 1177-15, Proc. of the SPIE, Boston (September 1989).
16. D.I. Wu and D.C. Change, "Numerical Experimentation of Slotted Microstrip Antennas," Paper BA1-3, National Radio Science Meeting, Boulder, CO (January 1990).

17. B.L. Brim, D.C. Chang and D.I. Wu, "Input Impedance of a Microstrip Fed Rectangular Patch Antenna," presented at the Joint IEEE-AP/URSI Meeting, San Jose, CA, (June 1989).

18. W. Charczenko and A.R. Mickelson, "Symmetric and Asymmetric Perturbations of the Index of Refraction in Three-Waveguide Optical Planar Couplers," J. Opt. Society Am. A., Vol. 6, No. 2, pp. 202-212, (February 1989).

19. W. Charczenko, S.T. Vohra, and A.R. Mickelson, "Computer Analysis of Surface Mode Interactions in Integrated Optical Devices," URSI National Radio Science Meeting Abstracts, Session D-2, p. 219 (Jan. 4-6, 1989).

20. R. Fox, W. Charczenko, and A.R. Mickelson, "A Numerical Method for Determining Index Profiles for Near Field Intensities of Optical Guide Wave Devices," URSI National Radio Science Meeting Abstracts, Session D-2, p.220, (Jan. 4-6, 1989).