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14. ABSTRACT
The program's objective was to develop design and fabrication techniques for integrated optical/microwave RF systems and mid-IR optical components. Research in the area of specific integrated optical systems and has yielded the development of the crystal ion slicing (CIS) technique for single-crystal $LiNbO_3$ films for integrated photonics applications. We have also demonstrated second harmonic generation in these lithium niobate films, direct bonding of metal oxides films onto semiconductor substrates, and a new capability in the beam propagation method simulation of integrated photonic devices.

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New Techniques for Heterogeneous Integration for Sensing Systems

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FINAL REPORT

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Table of Contents

1. Objectives

The objective of this program is to develop design and fabrication techniques for integrated optical/ microwave RF systems and mid-IR optical components.

2. View of Effort

During the period from November 15, 1998 to November 14, 2001 we have made significant progress in two efforts directed toward specific integrated optical systems, one using RF/photonics for RF sensing and one for mid-IR systems for countermeasures. Both used our capabilities in computer-aided design of optical systems and in new methods of materials fabrication. In addition, we completed a third task which was a more general technology effort to develop practical methods for reducing the physical dimensions of optical circuits through manipulation of the device geometry and refractive-index profile.

Briefly, our research has yielded the development of the crystal ion slicing (CIS) technique for fabrication of single-crystal $LiNbO_3$ films for integrated photonics applications. We have also demonstrated second harmonic generation in these lithium niobate films, direct bonding of metal oxides films onto semiconductor substrates, and a new capability in the beam propagation method simulation of integrated photonic devices. Finally, we have also begun examining photonic band gap structures for compact optical isolators

3. Accomplishments/New Findings

a) Development of novel devices

i. Electro-optic modulator in single-crystal CIS $LiNbO_3$ films

Electro-optic modulation has been demonstrated in 10μm-thick single-crystal $LiNbO_3$ films obtained by crystal-ion-slicing (CIS). This technique uses ion implantation of single-crystal bulk samples followed by selective etching. The measured electro-optic response of these films is comparable, within experimental error, to that of single-crystal bulk $LiNbO_3$ and is superior to previously reported values for epitaxial polycrystalline thin films. The product of half-wave voltage and modulator length, $V_\pi L$, is 8 Vcm. Post-lift-off annealing (PLA) has been shown to be of key importance in improving the modulator extinction-ratio.

ii. Thin-layer design of X-Cut $LiNbO_3$ modulators

Microwave-optical velocity matching and 50 Ω impedance matching are difficult to achieve with $LiNbO_3$ traveling wave modulators. We have studied simulation of the microwave and optical performance characteristics for modulators using thin layer (few

micrometers), x-cut $LiNbO_3$ and find significant improvements in velocity and impedance matching together with a lower $V_\pi L$.

iii. Novel CIS-based pyroelectric detector

We have packaged a rectangular 3mm x 4mm, 10-μm–thick Z-cut lithium niobate ($LiNbO_3$) film produced by crystal ion slicing (CIS) and evaluated its performance as a pyroelectric optical detector. We show that the freestanding detector has much greater sensitivity than the same detector bonded to a substrate. The sensitivity of CIS-film detectors is greater than that of a detector based on a thick $LiNbO_3$ plate, as is its noise-equivalent power.

iv. Second harmonic generation in lift-off $LiNbO_3$ films

The nonlinear optical properties of the CIS lithium niobate films have been investigated by comparing the second-order nonlinear response via second harmonic generation at 1.55μm. Two crystal orientations have been studied: that of a conventional z-cut lithium niobate, and the other cut for phase-matched frequency doubling of 1.55μm signals. In the latter case, room-temperature, phase-matched doubling and conversion from TE (n=0, ω) to TM (m=2, 2ω) modes has been obtained; however, only after small, ion implantation-induced shifts in the refractive index profiles for ordinary and extraordinary indices have been removed by annealing the films at ~500°C for ~6 hours. The obtained results were compared with those of the bulk with the same orientation, and the second-order film nonlinearity was found to closely match that of the corresponding bulk (to within the experimental error).

The nonlinear response was analyzed in the z-cut films as well. The slight refractive indices shifts in the films region due to ion implantation reduced the large birefringence seen in a negative uniaxial crystal of lithium niobate (ω to 2ω values). This effect was used to effectively phase-match the interacting fields at ω and 2ω at temperatures greatly reduced from those required for bulk doubling at 1.55μm (500°C to 250°C). Again, the second-order nonlinearity of the z-cut CIS lithium niobate films closely approximated that of the z-cut bulk. It has, therefore, been shown that ion implantation could be used as a tool for tailoring CIS-film nonlinear optical devices for integrated optics applications.

v. Zero-order half-wave plates of $LiNbO_3$ for integrated optics applications at 1.55 μm

We have demonstrated that first zeroth-order half-wave plates of $LiNbO_3$ can be fabricated by crystal ion slicing (CIS). Polarization rotation was demonstrated in 10-μm-thick freestanding $LiNbO_3$ films with 30-dB conversion rations and negligible material loss. Polarization-independent performance was demonstrated in a hybrid-optic device comprising a CIS wave plate integrated with single-mode silica-based channel waveguides.

vi. Demonstration of miniaturized MMI-routers

We have demonstrated a new ultracompact 2 x 2 coupler in InGaAsP/InP. The design uses the recently proposed tapered MMI devices, which have been shown to lead to substantial reductions in device geometries. The fabrication and testing of a series of parabolically tapered 3-dB 2 x 2 MMI devices have been accomplished in the InP-InGaAsP double heterostructure system. The measured splitting ratios of these devices are compared to the results of beam propagation method simulations, based on the finite-difference method, and good correlation is obtained. The results validate previous predictions and yield device geometries about 40% smaller than the shortest previous 3-dB 2 x 2 MMI device.

vii. High-index-contrast 90° waveguide bend structures

We have evaluated the parameters involved in designing low-loss right-angle waveguide bonds based on a high index contrast materials system. To do this we applied the finite difference time domain method (FDTD) to several two-dimensional bend structures and study the effects of varying the bend geometry. This study is relevant for the understanding of bend mechanisms and for the optimization and fabrication of high-density, high-contrast integrated optical components. The study indicated that high bend transmission can be achieved with the addition of a low-Q resonant cavity; however, similar or even better performance can be achieved with a structure that combines a corner mirror with a phase retarder. The use of a double corner mirror structure further increases the bend transmission, with little increase in bend area.

viii. Advanced Isolator Designed

We performed a theoretical study of enhancement of magnetooptical rotation on light reflection of light from a periodic system with a defect. Using calculations based on a coupled mode approach and the transfer matrix method we demonstrated that an asymmetric placing of a single defect allows arbitrary Kerr rotations with better than 99% reflectivity from very short devices. In general, however, these photonic crystals containing defects produce enhanced Faraday rotation but existing designs have low intensity output. We show that designs with two-defects possess sufficient freedom to attain high transmission over a large range of rotation angles in very short lengths. We optimized such systems for 45° rotation in optical isolators.

b) Advances in Photonic Simulation Tools

The design of complex integrated systems requires the use of advanced computer-aided design. A particularly important capability, in this regard, is the development of algorithms to deal with strongly-reflective structures, commonly used in optical filters. Typically, computer-aided designs use finite difference techniques, which are accurate but very expensive in computational time and memory. We have now developed an iterative bi-directional BPM to overcome the limitations of methods like Finite-Difference Time-Domain (FD-TD) method. Our results show that the bi-directional

BPM technique results in significant time reduction and memory savings compared to FD-TD method for simulating many reflective photonic structures. This technique has recently (2001) been made into commercial product. Intellectual property generated by this commercial now funds some research aspects of the Osgood group.

c) Thin Oxide Films for Heterogeneous Integration

i. Improved CIS of $LiNbO_3$ Films

Crystal ion slicing (CIS) is a useful technique for producing thin films of lithium niobate based on the selective etching of a sacrificial layer. CIS makes it possible to integrate single-crystal $LiNbO_3$ LN with otherwise incompatible heterogeneous substrates into hybrid optical systems. However, by applying a step of rapid thermal annealing, whereby the samples are exposed to short-term (~60s) high temperature treatment (300-400C), the internal pressure existing within the microvoids of the ion implanted layer is further increased and the etch selectivity is enhanced yielding the overall time for full epitaxial film liftoff reduced by factors as large as 10-100. Furthermore, no etch rate saturation was observed upon rapid thermal annealing, thus indicating no limitation of how large a film one could obtain. Films of arbitrary crystal orientation and as large as 10 mm x 10 mm were fabricated in just a matter of a few hours, and consequently bonded onto hybrid substrates.

ii. Wafer Bonding of CIS Films onto Semiconductors

We have also realized the direct bonding of ferroelectric oxides onto various semiconductors (Si, GaAs, InP) by low temperature techniques. The bonding has measurable strength and holds at elevated temperatures (<500°C). Helium-implanted samples have also bonded. The latter are important for the epitaxial liftoff of single-crystal thin films.

d) Design and Fabrication of mid-IR components

Low-damage etching of GaSb and GaInAsSb/AlGaAsSb multiple quantum well structures with electron cyclotron resonance plasma etching was investigated. Patterns were defined with electron beam lithography followed by a metal lift-off process, producing a series of metallic dots of various sizes that served as masks for subsequent dry etching. Smooth and anisotropic features at low substrate bias were obtained under appropriate conditions and the etch quality of the multiple quantum well was investigated with photoluminescence spectroscopy. The photoluminescence data from the etched features agreed well with a model that assumes a low-damage etching process.

Modelling and fabrication of photonic crystal structures for mid-infrared filter applications is being pursued. These materials are important because of the presence of wide bandgaps and narrow transmission resonance peaks, making it possible to have filters with high quality factors. In addition to the conventional finite difference time domain (FDTD) technique, a bidirectional beam propagation method is also investigated

to simulate photonic crystals. Fabrication of a variety of structures including silicon-on-insulator and a novel semiconductor-polymer heterostructure are being pursued. Highly selective wet chemical etching has been combined with electron beam lithography and reactive ion etching to successfully fabricate a silicon air-bridge structure. A bridge structure in the III-V material was achieved by using an epitaxial lift-off technique to bond an ultrathin InGaAsP layer onto a polymer of low refractive index.

4. Personnel Supported:

a) Research Personnel

Robert Scarmozzino
Miguel Levy

b) Graduate Students or Postdocs

Johnny Huang (graduated 1999, Ph.D., Boston Consulting)
David Levy (graduated 1998, Ph.D., Lucent Technologies)
Rokan Ahmad (graduated 2001, PhD., Omniguide)
Juni Fujita (graduated 2000, PhD., Telephotonics (Dupont)
Tomoyuki Izuhara
Hongling Rao (graduated 2002, PhD., R Soft)
Tony Radojevic (graduated 2002, PhD., Telephotonics (Dupont)
Dr. Michael Steel (RSoft)
Dr. Gabor Nagy (Intel)

5. Publications

1. M.J. Steel and R.M. Osgood, Jr., "Polarization and dispersive properties of elliptical-hole Photonic crystal fibers," Journal of Lightwave Technology 19, 495 (April 2001)

2 Richard L. Espinola, R.U. Ahmad, M.J. Steel, and R.M. Osgood, Jr., "A Study of High-Index-Contrast 90° Waveguide Bend Structures," Optics Express 8, 518 (April 2001)

3. H. Rao, M.J. Steel, R. Scarmozzino, and R.M. Osgood, Jr., "VCSEL Design Using Bidirectional Beam Propagation Method." J. Quantum Electronics 37, 1435 (November 2001)

4. A.M. Radojevic, M. Levy and R. M. Osgood, Jr., "Second-order Optical Nonlinearity of 10-μm-thick Periodically Poled $LiNbO_3$ films," Optics Letters, 25, 1034 (July 2000)

5. R.U. Ahmad, G. Nagy, and R.M. Osgood, Jr., "Electron Cyclotron Resonance Plasma Etching of GaSb and GaSb-based Alloys." Applied. Physics Letters 77, 1008 (August 2000)

6. M.J. Steel and R. M. Osgood Jr., "Elliptical-hole Photonic crystal fibers," Optics Letters 26, 288 (August 2000)

7. M.J. Steel, M. Levy, and R.M. Osgood Jr., "Large Magneto-optical Kerr Rotation with High Reflectivity from Photonic Band Gap Structures," Journal of Lightwave Technology, 18, 1289 (September 2000)

8. M.J. Steel, M. Levy, and R. M. Osgood, Jr., "Photonic Band Gaps with Defects and the Enhancement of Faraday Rotation," Journal of Lightwave Technology, 18, 1297 (September 2000)

9. M.J. Steel, M. Levy and R.M. Osgood, Jr., "High Transmission Enhance Faraday Rotation in One-dimensional Photonic Crystals with Defects" IEEE Photonics Technology Letters, 12, 1171 (September 2000)

10. A.M. Radojevic, M.Levy, and R.M. Osgood, Jr., "Strong nonlinear optical response in epitaxial liftoff single-crystal $LiNbO_3$ films" Applied Physics Letters, 75, 2888 (November 2000)

11. A. Radojevic, M. Levy, and R. M. Osgood, Jr., J. H. Lehman, C. N. Pannell, "Fabrication and evaluation of a freestanding Pyroelectric Detector made from Single-crystal $LiNbO_3$ film" Optics. Letters 25, 1657 (November 2000)

12. A.M. Radojevic, Student Member IEEE, R.M. Osgood, Jr., Fellow IEEE, M.Levy, A.Kumar, and H. Bakhru, "Zero-order Half-wave Plates of $LiNbO_3$ for Integrated Optics Applications at 1:55 μm" IEEE Photonics Technology Letters 12, 1653 (December 2000)

13. Gheorma, P. Savi and R.M. Osgood, Jr., "Thin Layer Design of X-cut $LiNbO_3$ Modulators" IEEE Photonic Technology Letters 12, 1618 (December 2000)

14. A.M. Radojevic, M.Levy, R.M. Osgood Jr., K.Atul, H.Bakhru, C.Tian, and C. Evans, "Large Etch-Selectivity Enhancement in the Epitaxial Liftoff of Single-Crystal $LiNbO_3$ films" Applied Physics Letters, 74, 3197 (May 1999)

15. H. Rao, R. Scarmozzino, and R.M. Osgood, Jr., "A Bi-directional Beam Propagation Method for Multiple Dielectric Interfaces," IEEE Photonic Technology Letters, 11, 830 (July 1999)

16. D.S. Levy, K.H. Park, R. Scarmozzino, R.M. Osgood, Jr., C. Dries, P. Studenkov, and S. Forrest, "Fabrication of Ultracompact 3dB 2x2 MMI Power Splitters," IEEE Photonic Technology Letters 11, 1009 (August 1999)

6. Interactions/Transitions

a. Meetings, Conferences, Seminars

1. 224th ACS National Meeting, Boston, MA, August 18-22, 2000.
"Photoreaction dynamics of CH3I multilayers on GaAs(110): REMPI probing of the CH3 umbrella mode." A. Srivastava, R. M. Osgood Jr."

2. 16th International Conference on the Application of Accelerators in Reasearch and Industry, CAARI 2000, Denton, Texas, Nov. 1-5, 2000 "Slicing Dielectric Crystals with Ions: A New Material Processing Technique for Electronic and Optoelectronic Materials integration." R. M. Osgood, Jr., Antonije M. Radojevic, Miguel Levy, and Hassaram Bakhru.

3. AACG/West. Seventeenth Conference on Crystal Growth and Epitaxy. The Stanford Sierra Camp, Fallen Leaf Lake, California. June 4-7, 2000. "Slicing Dielectric Crystals with Ions: A New Material Processing Technique for Electronic and Optoelectronic Materials integration." R.M. Osgood, Jr.

4. CNSR/OSA, Meeting, Washington, D.C., July 27, 2000. "GaAs doping by rapid thermal diffusion of a laser-deposited elemental Zn source film: Shallow and laterally graded diffusions." R.M. Osgood, Jr.

5. European Materials Research Society. EMRS Spring 2000 Meeting. Strasbourg, France, May 3 - June 2, 2000. "Fundamental Surface Processes in Advanced Photon Processing." R.M. Osgood, Jr.

6. IEEE/LEOS, OSA. Conference on Lasers and Electro-Optics (CLEO) 2000. San Francisco, California. May 7-12, 2000. "Complex Propagators for Evanescent Waves in Bidirectional Beam Propagation Method," Hongling Rao.

7. Materials Research Society, Symposium, Boston, Mass., Nov.29-Dec.3, 1999. "Narrow-Linewidth Yttrium Iron Garnet Films for Heterogeneous Integration." M. Levy, R. M. Osgood, Jr., F.J. Rachford, A. Kumar, and H. Bakhru.

8. Materials Research Society, Symposium, Boston, Mass., Nov. 29 -Dec. 3, 1999. "Helium-Implantation Induced Layer Detachment and Electrical Properties of Single-Crystal Potassium Tantalate Films." M. Levy, R.M. Osgood, Jr., A. Bhalla, L.E. Cross, A. Kumar, and H. Bakhru.

9. Michigan State University invited talk, Michigan State Univ. Center for Fundamental Materials Research, Jan. 28, 2000. "Optical Manipulation of Simple Electron Transfer Reactions on Ideal Surfaces." R. M. Osgood, Jr.

10. OSA, CLEO 2000, San Francisco, CA, May 2000, "Complex Propagators for Evanescent Waves in Bidirectional Beam Propagation Method." H. Rao, M.J. Steel and R. M. Osgood.

11. OSA, OSA IPR 2000, Quebec City, Canada, July 12-14, 2000. "Progress in Integrated Optical Isolators." J. Fujita, M. Levy, and R.M. Osgood, Jr.

12. OSA ILS-XV 1999, Symposium on Lasers at Surfaces, Santa Clara, CA, Sept. 26-30, 1999. Optical Manipulation of Surface Electrons: Chemical Reactions and Quantum Structures." R.M. Osgood, Jr.

b. Consultative and Advisory Functions

Prof. Osgood has continued to work with M.I.T. Lincoln Laboratory on developing improved processing techniques for integrated optics.

c. Transitions

Continued join development of simulation techniques with RSoft, Inc. (NY-based commercial software firm). Discussion of lift-off techniques with Telephotonics.

7. New Discoveries, Inventions or Patent Disclosures

U.S. patent Application No. 09/025, 114
Crystal Ion Slicing of Single-Crystal Films
Miguel Levy and Richard M. Osgood, Jr.

Continuation in part of U.S. Application No. 09/025, 114
Crystal Ion Slicing of Single-Crystal Films
Miguel Levy, Richard M. Osgood, Jr. and Antonije Radojevic