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| 14. ABSTRACT This final report covers 6 years of progress of the 1997 MURI on RF Photonics for Antenna Arrays at the University of Colorado, Montana State University, George Mason University, and the University of California Davis. Novel techniques for optical control and processing of the wideband RF and microwave signals encountered in phased array antennas have been developed, guided by research in spatio-temporal adaptive processing algorithms and active quasi-optical RF antenna arrays. The primary goal of this research is to develop enabling optical techniques that provide dramatic improvements in antenna array performance over conventional RF, optical, and digital techniques, allowing the efficient processing of large broadband antenna arrays. Coherent modulation and detection is made robust and practical by the use of dynamic holography in photorefractive and optical coherent transient media. This report summarizes the teams management, educational, and outreach activities, as well as technical progress summarized in 3 attached PhD theses on broadband adaptive optical array processing spatio-temporal holographic-processing algorithms, coherent-transient true-time-delay, photorefractive signal extraction, optical antenna control, and polymer in-line fiber modulators. | | | | | |
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RF Photonics for Array Processing MURI Final Report

1997 Topic: *Photonics in RF Systems*
Funded by the Office of the Secretary of Defense, DDR&E

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1 Final Report Executive Summary

This report summarizes the five funded years and final no cost extension year of the MURI in RF Photonic Systems which assembled team from the University of Colorado, the University of California-Davis, Montana State University, and George Mason University into a systems oriented research team investigating the application of photonic techniques to the control and processing of RF phased arrays. Under this MURI funding, the prime contract was administered through the University of Colorado under the direction of Prof. Kelvin Wagner.

Photonic techniques have emerged as the preferred approach to RF communication and remoting tasks throughout the microwave/millimeter-wave bands, when size, weight, power, and dispersion free bandwidth are key factors. In addition, applications such as controlling time delay, spectral filtering, mixing, frequency generation, antenna array control, beam forming, wide-band signal processing, and target recognition are being implemented optically. Much of this development has been driven by the evolution of high frequency photonic devices such as 100 GHz detectors, 40 GHz modulators, 20 GHz lasers, and 3 THz fiber optic

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transmission and delay lines. Often these technologies have been used as direct replacement of individual RF components with their optical counterparts, relying on the smaller size and lighter weight of the optical components and waveguides to yield a resulting system advantage. More sophisticated applications utilize the incredibly large bandwidth of optical transmission to simultaneously wavelength-multiplex a large number of RF signals for efficient parallel transmission or to control the element time delays through dispersion. The approach of this MURI team takes RF photonics to an even higher level of sophistication, in which the massive parallelism possible using dynamic volume holography in photorefractive and photon-echo materials enables the implementation of optimal adaptive and nonlinear algorithms for array processing in the optical domain.

The system research groups comprising this MURI team have pursued several different avenues towards one common goal of inserting photonics into RF array systems. We have developed solutions that build on the strengths of each approach, and identified the optimal combination of devices, materials, algorithms, and systems. The BEAMTAP approach (Broadband and Efficient Adaptive Method for True-time-delay Array Processing) has been investigated theoretically and implemented experimentally to demonstrate efficient adaptive beam forming using acousto-optic deflectors, traveling-fringes detectors, and photorefractive adaptive weights. The novel physics of optical coherent transients (OCT) have been developed for applications as programmable RF time delays as well as array signal processors, since these nonlinear materials can directly produce the necessary delayed RF signals as photon echoes. Both of these approaches utilize coherent beam forming in the optical domain which can improve the noise figure of optically remoted arrays and optical novelty filtering developed at CU can enable robust RF signal combination even in the presence of phase errors and drifts. Optically controlled quasi-optical active antenna arrays provide a near term test vehicle for optically controlled arrays, allowing rapid switching between polarizations, transmit/receive (T/R) mode, and frequency response, and in addition, demonstrate the capability of producing multiple simultaneous true-time-delay (TTD) beams as a front end for beam-space adaptive optical processors. Optical nonlinearities have been explored as an approach to dynamically solving the problem of signal extraction from small RF antenna arrays. Practical polymeric in-line fiber (PILF) modulators with high-speed coplanar waveguide (CPW) electrode structures have been developed as the front end RF-to-optical transducers for the antenna arrays. All of these efforts have been tied together by investigations of spatio-temporal signal processing algorithms compatible with RF photonic technology, which allows us to evaluate and compare the various optical systems techniques being investigated. As an example system developed as a unique collaboration between MURI team members, an RF antenna array has been coupled into a photorefractive optical system for extracting the principle component in the RF signal environment, and the

resulting system has been packaged as a portable suitcase demonstrator.

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2 Education, Presentations, Outreach, and Management

2.1 MURI Team

This MURI effort has directly or indirectly funded the 7 principal investigators, 14 post-doctoral or visiting research scientists, 22 graduate students, 14 undergraduate students, 3 research assistants, and fractions of a financial manager and secretary.

2.1.1 Principal Investigators

The original MURI team of 6 PIs was joined by Andre Knoesen from UC Davis in year 2 year, replacing Ted Weverka. Prof. Andre Knoesen worked on PILF modulators on a separately funded subcontract which ends this year. Weverka's project on coherent optical beam combination for phased array processing is being continued at the University of Colorado as the required front end to the BEAMTAP processor.

Table 1: Principal investigators involved in the RF Photonic Systems program.

| Researcher | Department | Institution |
|-------------------------------|------------|--------------------------|
| Prof. Kelvin Wagner | ECE/OCS | CU-Boulder |
| Prof. Zoya Popović | ECE | CU-Boulder |
| Prof. Dana Anderson | JILA | CU-Boulder |
| Prof. William Randall Babbitt | Physics | Montana State University |
| Dean Lloyd Griffiths | ITE | George Mason University |
| Prof. Andre Knoesen | ECE | UC-Davis |
| Robert T. Weverka | years 1-2 | Photonics Data Systems |

2.1.2 Students, Post-Doctoral Researchers, and other Personnel

2.1.3 Students Graduated from the MURI program

1. Carrie S. Cornish (UW PhD granted August 2000)
2. Zachary Cole, January 2000, MSU, MS
3. Jun Zhao, January 2000, MSU, MS
4. Xiaofang Chen, May 2000, MSU MS

Table 2: Undergraduate students who have been involved in MURI related research during the entire project. Again, those who worked on closely related projects in collaboration with the MURI effort are indicated by *.

| Undergrad | Status | Position | Advisor | Dept. | Inst. |
|-----------------|-----------------------|---------------|----------|---------|-------|
| Eric Hoyt | graduated BS/MS 12/02 | Undergraduate | Wagner | OCS | CU |
| Kip Morgan | Temporary | Undergraduate | Wagner | OCS | CU |
| Robert Derstad | Temporary | Undergraduate | Wagner | OCS | CU |
| Jack Hong Loui | Senior project | Undergraduate | Popović | ECE | CU |
| Paul Smith | Senior project | Undergraduate | Popović | ECE | CU |
| Alex Morrow | Senior project | Undergraduate | Popović | ECE | CU |
| Tom Miller | Senior project | Undergraduate | Popović | ECE | CU |
| Heidi Becker | Summer REU | Undergraduate | Anderson | Phys | CU |
| Kevin Henderson | REU | Undergraduate | Anderson | Phys | CU |
| John Jost | Assistant | Undergraduate | Anderson | Phys | CU |
| Joe Fischer* | graduated 6/02 | Undergrad | Babbitt | Physics | MSU |
| Joe Galbraith* | graduated | Undergrad | Babbitt | Physics | MSU |
| Zeb Barber | graduated 6/03 | Undergrad | Babbitt | Physics | MSU |
| Jesse Law | continuing | Undergrad | Babbitt | Physics | MSU |

5. Pete Kirkpatrick, December 1999, CU BS/MS.
6. Scott A. Hamilton, Ph.D., Dissertation Title: Traveling Wave In-Line Directional Coupler Modulator, 1999, UC Davis.
7. Carl Arft, MS, Spring 2000, UC Davis.
8. Jim Vian, November 2000, CU, ECE, PhD, Popovic. Dr. Jim Vian, graduate student, graduated in January 2001, supported since beginning of project. Thesis title: "Optically Controlled Transmit/Receive Lens Arrays for Space-Time Adaptive Processing". Currently with the MIT Lincoln Laboratories.
9. Valeria Damiao, November 2000, CU, ECE, PhD, Anderson
10. Paulo Silveira, March 2001, CU, ECE, PhD, Wagner
11. Ken Anderson, May 2001, CU, ECE, PhD, Wagner
12. Jan Peeters Weem, June 2002, CU, ECE, PhD, Popović. Thesis title: "Broadband antenna arrays and noise coupling for radio astronomy."

Table 3: Senior MURI personnel indicating those funded by this program. Those who worked on closely related projects in collaboration with the MURI effort are indicated by *.

| Researcher | Status | Position | Advisor | Dept. | Inst. |
|-------------------|--------------------|----------------------|----------|---------|-------|
| Andrew Kiruluta | 6/02-11/02 | Post-doc | Wagner | OCS | CU |
| | 8/03-12/03 | Post-doc | Wagner | OCS | CU |
| G.S.Pati | 9/99 -1/01 | Post-doc | Wagner | OCS | CU |
| Paulo Silveira | 1/03-4/03 | Post-doc | Wagner | OCS | CU |
| Valeria Damiao | 3/01-4/01 | Post Doc | Wagner | OCS | CU |
| Bruce Tieman | 3/01-4/01 | Post Doc | Wagner | OCS | CU |
| Stefania Romisch | | Postdoc | Popović | ECE | CU |
| Kris Merkel | continuing 50% | Research Scientist | Babbitt | Physics | MSU |
| Kevin Repasky* | continuing | Research Scientist | Babbitt | Physics | MSU |
| Mingzhen Tian | continuing | Research Scientist | Babbitt | Physics | MSU |
| Diego Yankelevich | 3/99-present | Adjunct Prof. | Knoesen | EE | Davis |
| Joe Shamir | 9/02-10/02 | Visiting MURI fellow | Wagner | OCS | CU |
| Yoshio Hayasaki* | 9/97-3/98 | Visiting scientist | Wagner | OCS | CU |
| Vladimir Shkunov | finishing 2/00 | Res. Ass. | Anderson | JILA | CU |
| Alex Zozulya | Visiting scientist | Anderson | JILA | CU | |
| Sam Weaver | left Feb 2000 | Prof. Res. Asst. | Wagner | OCS | CU |
| Leslie Czaia | continuing | Prof. Res. Asst. | Anderson | JILA | CU |
| John Getty | | EE engineer | Babbitt | Physics | MSU |
| Norm Williams | | Machinist | Babbitt | Physics | MSU |
| Buz Smith | consultant | Financial Admin. | | OCS | CU |

13. Randy Reibel, August 2002, MSU, Physics, PhD, Babbitt.
14. Edeline Fotheringham, May 2003, CU, ECE, PhD, Anderson. Thesis title: "Microwave signal processing with photorefractive dynamic holography."
15. Greg Kriehn, May 2003, CU, ECE, PhD, Wagner. Thesis title: "Coherent optical signal processing for broadband adaptive phased-array antennas using the BEAMTAP algorithm."

Table 4: MURI Grad students indicating those funded by this program. Those who worked on closely related projects in collaboration with the MURI effort are indicated by *.

| Researcher | Status | Position | Advisor | Dept. | Inst. |
|----------------------|------------------------|---------------|----------|---------|-------|
| Edilene Fotheringham | graduated 2003 | Grad Student | Anderson | JILA | CU |
| Valeria Damiao | PhD finished Nov 00 | Grad Student | Anderson | JILA | CU |
| Amy Sullivan* | Spring00 OSEP | Grad Student | Anderson | JILA | CU |
| Greg Kriehn | DoD fellow: grad 05/03 | Grad Student | Wagner | OCS | CU |
| Paulo Silveira | PhD finished 3/01 | Grad Student | Wagner | OCS | CU |
| Friso Schlottau | continuing | Grad Student | Wagner | OCS | CU |
| Ken Anderson* | PhD finished 5/01 | Grad Student | Wagner | OCS | CU |
| Robert T Weverka | continuing 03-04 | Grad Student | Wagner | OCS | CU |
| Shawn Stone | finished MS | Grad Student | Popovic | ECE | CU |
| Jim Vian | PhD finished 1/01 | Grad Student | Popović | ECE | CU |
| Darko Popovic* | graduated | Grad Student | Popović | ECE | CU |
| Paul Smith* | continuing | Grad Student | Popović | ECE | CU |
| Jan Peeters Weem | PhD finished 6/02 | Grad Student | Popović | ECE | CU |
| Jacques Hong Loui | continuing | Grad Student | Popović | ECE | CU |
| Bob Peters* | MS finished 8/01 | Grad Student | Babbitt | Physics | MSU |
| Randy Reibel | Graduated 8/02 | Grad Student | Babbitt | Physics | MSU |
| Hongyan Li | continuing | Grad Student | Babbitt | Physics | MSU |
| Ijaz Zafarullah | transferred 5/01 | Grad Student | Babbitt | Physics | MSU |
| Jun Zhoa | finished (1/00) | Grad Student | Babbitt | Physics | MSU |
| Steve Jia | continuing | Grad student | Babbitt | Physics | MSU |
| John Campbell | continuing | Grad student | Knoesen | EE | Davis |
| Liu Ming Wu | continuing | Grad student | Knoesen | EE | Davis |
| Pete Kirkpatrick | finished 12/99 | BS/MS student | Popović | OCS | CU |

2.2 MURI in RF Photonics for Arrays team meetings

Much of the effort was physically concentrated in Colorado, which led to a great ease of coordination among the three research groups located there. All researchers in Boulder meet formally every two weeks to exchange information, make presentations, as well as to discuss technical and management details. The entire MURI team gathers once or twice a year for intellectual exchange, discussions, and review regarding scientific progress during

the year. One of these meetings is primarily an internal MURI meeting, and the other is a formal review for programmatic purposes. Future research directions are discussed at these meetings, along with key issues in technical coordination between the research efforts.

2.2.1 5th year MURI team Interactions

1. Prof. Popović's group has collaborated mainly with Prof. Anderson's group at CU, and somewhat with Prof. Griffiths at MSU.
2. Prof. Popović visited Prof. Knoessen's group at UC Davis and gave a graduate seminar, October 2002.
3. Prof. Babbitt visited UC-Boulder in November of 2002.

2.2.2 Third Annual review

Our 3rd annual review was held October 12, 2000 in Boulder in conjunction with the fourth annual UCLA MURI review held on the following day. It was attended by the 6 MURI PIs, all of the CU MURI students, and about 20 industrial advisors and government reviewers. The view graphs from this meeting are available on the web at our MURI home page http://optics.colorado.edu/MURI/3rdannmeet_0.html .

2.2.3 3rd Annual review schedule

RF Photonics Systems 3rd Annual MURI review, Oct 12, 2000

| Time | Name | Organization | Title |
|----------------|---------------------------------------|--------------|--|
| 8:00 - 8:30 | — Continental Breakfast — | | |
| 8:30 - 8:35 | Kelvin Wagner | CU | Welcome |
| 8:35 - 8:45 | Bill Miceli | ONR | DoD MURI Program Goals |
| 8:45 - 9:15 | Kelvin Wagner | CU | RF Photonic Systems Program Overview |
| 9:15 - 9:30* | Guest speaker 1 | | |
| 9:30 - 9:45 | Jim Vian | CU | Optically controlled T/R antenna |
| 9:45 - 10:00 | Zoya Popovic | CU | Quasi-optical arrays |
| 10:00 - 10:15 | Dana Anderson | CU | Dynamic Holography for RF photonics |
| 10:15 - 10:30 | E. Fotheringham | CU | miniature auto-tuning filter |
| 10:30 - 10:45* | Tom Mader | LightLogic | |
| 10:45 - 11:00 | Feedback on Morning Session | | |
| 11:00 - 11:15 | — Coffee Break — | | |
| 11:15 - 12:15 | Lab Tour 1 | | |
| | JILA Labs (Anderson) | | |
| | Quasi-optics lab (Popovic) | | |
| | BEAMTAP and photon echo labs (Wagner) | | |
| | CU Photon Echo lab (Babbitt/Wagner) | | |
| 12:15 - 1:00 | — Buffet Lunch Break — | | |
| 1:00 - 1:30 | Greg Kriehn | CU | BEAMTAP |
| 1:30 - 1:45* | Jaap Bregman | NFRA | SKA |
| 1:45 - 2:00 | Lloyd Griffiths | GMU | Issues in STAP |
| 2:00 - 2:15 | Paulo Silveira | CU | Optical LMS Array Processing |
| 2:15 - 2:30* | Azad Siahmakoun | RHIT | WOMBAT |
| 2:30 - 2:45 | R. Babbitt | MSU | Coherent Transients |
| 2:45 - 3:00 | K. Merkel | MSU | Coherent Transient True Time Delay |
| 3:00 - 3:15 | — Coffee Break — | | |
| 3:15 - 3:30* | Nicolas Breuil | Thomson | |
| 3:30 - 3:45 | Andre Knoesen | UC-Davis | High Speed Polymeric Modulators |
| 3:45 - 4:00 | John Campbell | UC-Davis | Modulators for Photonic Array Antennas |
| 4:00 - 4:30 | Feedback on Afternoon Session | | |
| 4:30 - 5:00 | Advisory Board meeting | | |
| 4:30 - 6:00 | Lab tours and posters in the labs | | |
| | JILA Labs (Anderson) | | |
| | Quasi-optics lab (Popovic) | | |
| | BEAMTAP and photon echo labs (Wagner) | | |
| | CU Photon Echo lab (Babbitt/Wagner) | | |

6:30 - Joint CU/UCLA MURI Banquet at Regal Harvest House

* indicates guest speakers

2.2.4 3rd Annual review attendees

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| Diego R. Yankelevich | University of California, Davis | yankelev@ece.ucdavis.edu |
| Weimin Zhou | Army Research Laboratory | wzhou@arl.army.mil |

2.2.5 4th year MURI team Interactions

1. Aug 11-14, 2000: Lloyd Griffiths visits Boulder for discussions with Wagner, Popović, Vian, Kriehn, and Silveira.
2. Aug 4-Oct 20, 2001: Joseph Shamir from Technion in Israel visits with the CU MURI team and collaborates with Wagner on analyzing the BEAMTAP processor using operator algebra.
3. Oct 12 2000, Entire MURI team visits Boulder for the Annual review.
4. Oct 26 2000, Kelvin Wagner visits Sanders for discussions of Signal Processing applications of high speed SLMS.
5. November 2-3 2000, W.R. Babbitt and Randy Reibel visit Boulder for discussions with Wagner group on photon echo based RF processing and Popovich group for technology transfer on broadband Vivaldi array elements.
6. Dec 4-5, 2000: Lloyd Griffiths visits Boulder for discussions with Wagner, Popović, Vian, Kriehn, and Silveira.
7. Dec 19-20, 2000, Kelvin Wagner visits Sanders for an all-day long colloquium/tutorial on advanced applications of optical techniques to signal processing and control of large RF antenna arrays.
8. Jan 8, 2001 Kelvin Wagner visits Prof. Knoesen and students at the University of California Davis.
9. Feb 9, 2001 Jim Harvey from ARL visits UC Boulder for discussions with Z. Popovic and K. Wagner.
10. Feb 19, 2001 Lloyd Griffiths visits Boulder for discussions with Wagner, Popović, Schlottau, Kriehn, and Silveira.
11. Feb 19, 2001 Jim Harvey from ARL visits UC Boulder for discussions with Z. Popovic and K. Wagner.
12. March 2, 2001: Kelvin Wagner visits Rockwell Science Center for discussion on collaboration about optical BEAMTAP.
13. March 8, 2001 Charles Garvin of CTI visits Prof. Wagner at UC Boulder.

14. April 26-28, 2001, Kelvin Wagner visits MSU for discussions with W.R. Babbitt, K. Merkel, R. Cone, A. Rebane, K. Repasky, and students about OCT applications in RF signal processing.
15. May 12-19 Ivan Logere from CNRS lab Aime Cotton in Orsay, France visits CU for experiments and collaboration with Prof Wagner and Ken Anderson on optical scanners for RF signal processing.
16. May 29- June 1, 2001: Prof. Babbitt visits CU for Ken Anderson's PhD defense and discussion on collaborations for future proposals.
17. June 1-July 2, 2001 Kelvin Wagner and Ken Anderson visit CNRS lab Aime Cotton in Orsay, France to work with Jean-Louis Legouet on OCT spectrum analyzers for wideband RF applications.
18. June 11, 2001: Kelvin Wagner visits NFRA in Dwingeloo the Netherlands for discussions about the applications of RF photonics for radio astronomical applications of array processing.
19. July 10-11 Ian McMichael from Rockwell Scientific, and Sid Theis (consultant) visit CU for detailed briefing on the modifications to BEAMTAP necessary for radar applications in preparation for a joint proposal.
20. July 16-17, 2001: Jaap Bregman from the NFRA in the Netherlands visits CU for collaborations on coherent photonics applied to radio astronomy based large array processing.
21. September 4-30, 2001: Yasuhiro Awatsuji visits Prof Wagner for collaborations in coherent multiwavelength optical processing.
22. Aug 13-Oct 5, 2001: Prof Joseph Shamir of Technion visits to work on BEAMTAP rigorous operator analysis paper.
23. Oct 19, 2001: Bill reed from AT&T visits for discussion of the applications of OCT to fiber dispersion compensation.
24. Oct 23, 2001: GE photonics group visits CU for potential collaborations.
25. Oct 24, 2001: kelvin Wagner attends the Rose-Hulman WOMBAT center review as a member of the advisory board.
26. November 11-21, 2001: Prof. Voloshinov from Moscow State University visits Prof. Wagner at CU Boulder to develop specialized acousto-optic devices.

27. Nov 29-30, 2001: Prof. Wagner visits Prof. Babbitt and Spectrum Labs at MSU.
28. Mark Neifeld of the University of Arizona visited with W. R. Babbitt and Spectrum Lab on several occasions to discuss information capacity, signal fidelity, and delay resolution issues in optical coherent transient devices.
29. The Workshop on Applications of Spectral Hole Burning 2001 was held in Jackson WY, July, 2001, as part of the PQE (Physics of Quantum Electronics) meeting.
30. W. R. Babbitt and his group have worked closely on MURI related research with the researchers in the groups of Rufus Cone, Alex Rebane, and John Carlsten of MSU Physics and MSU Spectrum Lab, including Alan E. Craig, Pete Selin, Tiejun Chang, Zack Cole, Alex Dimitrov. Kris Merkel and Kevin Repasky have been jointly funded by Spectrum Lab and the MURI.
31. Frequent visits from Prof. Harris group members to UC Davis.

2.2.6 Second Annual review

Our second annual review was held December 14, 1999 in Los Angeles at UCLA in conjunction with the third annual UCLA MURI review held on the following day. It was attended by the 7 MURI PIs, 4 of the CU MURI students, and about 20 industrial advisors and government reviewers. The view graphs from this meeting are available on the web at our MURI home page <http://optics.colorado.edu/MURI/review99>.

2.2.7 2nd Annual review schedule

DECEMBER 14th UNIVERSITY OF COLORADO MURI REVIEW

| Time | Name | Organization | Title |
|---------------|--|--------------|--------------------------------------|
| 8:00 - 8:30 | — Continental Breakfast — | | |
| 8:30 - 8:35 | Kelvin Wagner | (CU) | Welcome |
| 8:35 - 8:45 | Bill Miceli | (ONR) | DoD MURI Program Goals |
| 8:45 - 9:15 | Kelvin Wagner | (CU) | RF Photonic Systems Program Overview |
| 9:15 - 9:45 | Greg Kriehn | (CU) | BEAMTAP |
| 9:45 - 10:00 | Paul Biernacki | (NRL) | Fiber based photonic array steering |
| 10:00 - 10:30 | Ted Weverka | (PDS) | Coherent Optical Array Processing |
| 10:30 - 10:45 | — Coffee Break — | | |
| 10:45 - 11:00 | Lloyd Griffiths | (GMU) | Issues in STAP |
| 11:00 - 11:30 | R. Babbitt | (MSU) | Coherent Transient True Time Delay |
| 11:30 - 12:00 | Andre Knoesen | (UC-Davis) | PILF modulators |
| 12:00 - 12:30 | Feedback on Morning Session | | |
| 12:30 - 1:30 | — Buffet Lunch Break — | | |
| 1:30 - 1:45 | Arnold Van Ardenne | (NFRA) | SKA and RF Photonics |
| 1:45 - 2:00 | Zoya Popovic | (CU) | Quasi-optical arrays |
| 2:00 - 2:15 | Jim Vian | (CU) | Optically controlled T/R antenna |
| 2:15 - 2:30 | Daniel Dolfi | (Thomson) | TTD & RF Photonics at Thomson |
| 2:30 - 3:00 | Dana Anderson | (CU) | Dynamic Holography for RF photonics |
| 3:00 - 3:10 | Zoya Popovic | (CU) | RF/Optical Techniques class |
| 3:10 - 3:30 | Feedback on Afternoon Session | | |
| 3:30 - 4:00 | — Coffee Break — | | |
| 4:00 - 4:30 | Planning for 2000 for RF Photonic Systems Research | | |
| 4:30 - 5:00 | Additional steering committee feedback | | |

2.2.8 2nd Annual review attendees

University of California at Los Angeles, December 14, 1999

| Name | Organization | Contact Info |
|-------------------------------|--------------------------|---------------------------------|
| Dr. Bill Miceli, Sponsor | ONR | wmiceli@onreur.navy.mil |
| Prof. Kelvin Wagner, PI | CU - OCS | kelvin@colorado.edu |
| Prof. Dana Anderson, PI | CU - Physics | dana@colorado.edu |
| Prof. Randy Babbitt, PI | MSU | babbitt@physics.montana.edu |
| Prof. Lloyd Griffiths, PI | GMU | griffiths@gmu.edu |
| Prof. Andre Knoesen, PI | UC - Davis - ECE | knoesen@ece.ucdavis.edu |
| Prof. Zoya Popovic, PI | CU - ECE | zoya@colorado.edu |
| Mr. Ted Weverka, PI | Photonic Data Systems | weverka@pacbell.net |
| Ms. Edilene Fotheringham, GRA | CU - Physics (Anderson) | fotherin@jilau1.colorado.edu |
| Mr. Greg Kriehn, GRA | CU - OCS (Wagner) | kriehn@colorado.edu |
| Ms. Ming Zhen Tian, GRA | MSU - Physics | tian@physics.montana.edu |
| Mr. Jim Vian, GRA | CU - ECE (Popovic) | vian@colorado.edu |
| Dr. Arnold van Ardenne | NFRA | ardenne@nfra.nl |
| Dr. Paul Biernacki | NRL | biernack@ccf.nrl.navy.mil |
| Dr. Jaap Bregman | NFRA | bregman@nfra.nl |
| Dr. Daniel Dolfi | Thomson-CSF/LCR | daniel.d.d.dolfi@lcr.thomson.fr |
| Dr. John Gallo | BAE Systems | |
| Dr. Anthony Jacomb-Hood | Lockheed Martin M&S | anthony.w.jacombhood@lmco.com |
| Dr. Kyung Kim | Lockheed Martin TAS | |
| Dr. Stuart Kingsley | SRICO, Inc. | |
| Dr. Jian Ma | Rockwell Science Center | ma@rsc.rockwell.com |
| Dr. Michael Nesnidal | Focused Research | |
| Dr. Irwin Newberg | Raytheon | |
| Dr. James Nichter | AFRL | |
| Dr. Steve Pappert | SPAWAR | spappert@nosc.mil |
| Dr. Azad Siahmakoun | Rose-Hulman Inst of Tech | |
| Dr. Richard Sparks | MTT-S | |
| Mr. Michael St. John | St. John Scientific, LLC | |
| Dr. Gregory Tangonan | HRL Laboratories | tangonan@hrl.hac.com |
| Dr. Larry Thomas | Toyon Research Corp | |
| Dr. Timothy Van Eck | Lockheed Martin M&S | |
| Dr. Michael VanBlaricum | Toyon Research Corp | mikevanb@toyon.com |
| Dr. George Webb | Innova Labs Inc/UCSD | |
| Prof. Ming Wu | UCLA | wu@ee.ucla.edu |
| Dr. Daniel Yap | HRL Laboratories | |

2.2.9 3rd year MURI team Interactions

1. Nov 17 1999: Visit by Charles Garvin of CTI to discuss collaboration on RF photonics, LIDAR, and optical processing.
2. Nov. 19, 1999: Presentation by G. Kriehn on BEAMTAP at OCS retreat.
3. Nov 19, 1999: Presentation by K. Anderson on photon echo array processing at OCS retreat.
4. Dec 14, 1999: CU MURI Review at UCLA attended by Wagner, Popović, Anderson, Griffiths, Babbitt, Weverka, Knoesen, Fotheringham, Kriehn, Tian, Vian, and 20 industry and government advisors.
5. Dec 15, 1999: Researchers including Wagner, Babbitt, Knoesen, Fotheringham, Kriehn, Tian, and Vian attended UCLA MURI review.
6. Dec 20-21, 1999: Jaap Bregman from NFRA visits CU to discuss RF photonics collaborations with Wagner, Popović, Vian, Kriehn, and Schlottau.
7. Jan 7, 2000: Greg Kriehn presents BEAMTAP talk at URSI annual meeting in Boulder.
8. Jan 31, 2000 Dave Carrott from Task visits to discuss with Wagner past and future collaborations with Litton on Optical RF Processing.
9. Feb 11, 2000: Jim Harvey from ARO visits to discuss upcoming programs in RF and Photonics with Wagner and Popović.
10. Feb 13, 2000: Dave Brady from University of Illinois visits to discuss possible collaborations in integrated sensor processing.
11. Feb 16-18, 2000: Wagner and Kriehn attend PSAA meeting in Monterey.
12. March 13, 2000: Dave Pepper from Hughes visits CU Boulder to discuss collaborations with Anderson, Wagner, and Popović.
13. March 21, 2000: Ted Weverka of Network Photonics meets with Wagner to discuss future collaborations extending ideas developed in the MURI to fiber optics communication. Joint development of multimode fiber dispersion compensation system planned.
14. March 29-30, 2000: Wagner attends OIDA roadmap planning meeting for RF Photonics in LA.

15. April 7, 2000: Wagner and Babbitt visit Boeing to present MURI research to Geoff White and Michael Hamilton. Agreement to collaborate and to provide access to Boeing array technology is discussed.
16. May 14-17, 2000: Jean-Louis Legouet from CNRS in Orsay visits for collaborations and experiments on spectral hole burning processing of RF signals.
17. May 14-July 20, 2000 Loic Menagere from CNRS in Orsay visits for extended collaborations and experiments on spectral hole burning processing of RF signals.
18. May 17, 2000: Kelvin visits Sanders for discussions on optical processing.
19. May 25-26, 2000: Wagner attends Acoustooptic-2000 meeting in Brugge, Belgium
20. May 29-30,2000: Wagner visits Jaap Bregman at NFRA in Netherlands for discussion on array processing for the Square Kilometer Array (SKA) and the applications of RF photonic techniques.
21. May 31, 2000: Wagner visits Daniel Dolfi at Thomson for collaborations on traveling fringes detectors developed at Thomson in BEAMTAP processor.
22. June 18-23, 2000: Silveira attends Optics in Computing 2000 in Quebec City and presents sonar array processing results.
23. June 29, 2000: Wagner visits Honeywell for discussions on radar imaging.
24. June 30, 2000: Wagner attends WOMBAT kickoff meeting at Rose-Hulman Institute of Technology as a member of the advisory board to this Navy center in RF photonics.
25. July 9-12, 2000: Visit by Kelvin Wagner and Ken Anderson to Bozeman, to attend Persistent Spectral Hole Burning Meeting in Big sky.
26. July 12-22, 2000: Ken Anderson works with Kris Merkel at MSU Bozeman on photon echo processing for phased arrays, demonstrates TTD array steering using novel acoustooptic technique (patent pending).
27. Aug 6-8, 2000: Wagner attends the DARPA Integrated Signal Processing workshop organized by Dave Brady and held in Boulder. Presented BEAMTAP as an ISP system.
28. Aug 11-14, 2000: Lloyd Griffiths visits Boulder for discussions with Wagner, Popović, Vian, Kriehn, and Silveira.

29. Aug 4-Oct 20, 2000: Joseph Shamir from Technion in Israel visits with the CU MURI team and collaborates with Wagner on analyzing the BEAMTAP processor using operator algebra.
30. Krishna Mohan of Lund Institute in Sweden has visited with Kris Merkel on several occasions to develop an fiber optic amplifier at 793 nm for optical coherent transient applications. This technology is being transferred to Colorado and a joint JOP grant is to be submitted.
31. Mark Neifeld of the University of Arizona visited with W. R. Babbitt and Spectrum Lab on several occasions to discuss information capacity, signal fidelity, and delay resolution issues in optical coherent transient devices.
32. The Workshop on Applications of Spectral Hole Burning 2000 was held in Big Sky, Montana, July 9-12, 2000, organized by Alan Craig of MSU. Researchers from all over the world came to discuss the physics and applications of optical coherent transient devices.
33. W. R. Babbitt and his group have worked closely on MURI related research with the researchers in the groups of Rufus Cone, Alex Rebane, and John Carlsten of MSU Physics and MSU Spectrum Lab, including Alan E. Craig, Pete Selin, Tiejun Chang, Zack Cole, Alex Dimitrov. Kris Merkel and Kevin Repasky have been jointly funded by Spectrum Lab and the MURI.
34. W. R. Babbitt has started a company, LightSmyth Technologies, with Thomas W. Mossberg of the University of Oregon. The company is exploiting a new device technology processes RF-photonic (multi-GHz) signals in the optical domain, with applications in the optical networking marketplace.
35. Dana Anderson visited Daniel Dolfi and Collaborators at Thomson CSF in Orsay, France, Summer 2000.
36. Diego Yankelvich visited Larry Dalton and collaborators at University of Southern California, June 2000.
37. Frequent visits from Prof. Harris group members to UC Davis.
38. Prof. Shiao Min Tseng visited UC Davis to discuss fabrication of inline fiber coupler, Fall 1999.

2.2.10 First Annual review

Our first annual review was held in Boulder on January 19 1999. It was attended by the MURI PIs, about 14 students and postdocs, and nearly 20 industrial advisors and government reviewers. The vugraphs from this meeting are available on the web at our MURI homepage <http://optics.colorado.edu/MURI>.

CU/MSU/GMU/ONI 1st Annual MURI review schedule

January 19, 1999 - room 380, Benson Earth Sciences building, University of Colorado, Boulder

| | | | |
|---------------|--|----------|---|
| 8:00 - 8:30 | — Continental Breakfast — | | |
| 8:30 - 8:40 | Bill Miceli | ONR | DoD Goals |
| 8:40 - 9:10 | Kelvin Wagner | CU | Introduction to program |
| 9:10 - 9:30 | Lloyd Griffiths | GMU | Future issues in STAP |
| 9:30 - 9:45 | David Martinez | MITLL | Real time digital STAP at Lincoln Labs |
| 9:45 - 10:05 | Greg Kriehn | CU | BEAMTAP |
| 10:05 - 10:20 | Paul Matthews | NRL | Dispersive fiber true time delay |
| 10:20 - 10:50 | — Coffee Break — | | |
| 10:50 - 11:10 | John Hong | Rockwell | Microwaves & Photonics at Rockwell |
| 11:10 - 11:30 | Ted Weverka | ONI* | Coherent Optical Array Processing |
| 11:30 - 11:45 | Tom Mader | Hughes | RF and Photonics at Hughes |
| 11:45 - 12:00 | Feedback | | |
| 12:00 - 1:00 | — Buffet Lunch Break — | | |
| 12:30 - 1:00 | Dana Anderson | CU | Tutorial on Dynamic Holography |
| 1:00 - 1:15 | Bahram Jalili | UCLA | UCLA RF Photonics MURI |
| 1:15 - 1:30 | Frank Kustas | LMC | SEPCPAA Photonical Antennas |
| 1:30 - 1:50 | Zoya Popovic, Jim Vian | CU | Optically controlled T/R active antenna |
| 1:50 - 2:10 | Edeline Fotheringham | CU | Autotuning Filters for RF Arrays |
| 2:10 - 2:25 | Daniel Dolfi | Thomson | TTD, AODs, RF Photonics at Thomson |
| 2:25 - 2:45 | Kris Merkel | MSU | Coherent Transient True Time Delay |
| 2:45 - 3:00 | Kelvin Wagner | CU | Wrapup and Feedback |
| 3:00 - 3:30 | — Coffee Break — | | |
| 3:30 - 4:30 | Rountable Discussion of RF Photonic Signal Processing Issues | | |
| | Zoya Popovic | CU | Broad-bandwidth arrays and circuitry |
| | Kelvin Wagner | CU | Choice of Wavelength |
| | Ted Weverka | ONI | Dynamic range |
| 4:30 - 5:00 | Additional steering committee feedback | | |
| 4:00 - 6:00 | Posters and Lab Tours | | |
| 6:30 - | — Banquet — | | |

2.2.11 Attendee list for first annual review of OSD MURI on RF Photonics

| Name | Organization | Contact Info |
|---------------------------------|-------------------------|-----------------------------|
| Dr. Bill Miceli, Sponsor | ONR | wmiceli@nosc.mil |
| Prof. Kelvin Wagner, PI | CU - OCS | kelvin@colorado.edu |
| Prof. Dana Anderson, PI | CU - Physics | dana@colorado.edu |
| Prof. Randy Babbitt, PI | MSU | babbitt@physics.montana.edu |
| Prof. Lloyd Griffiths, PI | GMU | griffiths@gmu.edu |
| Prof. Zoya Popovic, PI | CU - ECE | zoya@colorado.edu |
| Ted Weverka, PI | Optical Networks, Inc. | okuma@a.crl.com |
| Prof. Ren Su, ECE Chair | CU - ECE | sur@colorado.edu |
| Dr. Vladimir Shkunov, vis. sci. | CU - Physics | shkunov@jila02.colorado.edu |
| Dr. Andrew Kiruluta, postdoc | CU - ECE | kirulut@colorado.edu |
| Dr. Kris Merkel, postdoc | MSU | merkel@physics.montana.edu |
| Sam Weaver, PRA | CU - OCS | samw@colorado.edu |
| Ken Anderson, GRA | CU - OCS (Wagner) | kanderso@colorado.edu |
| Valeria Damiao, GRA | CU - Physics (Anderson) | damiao@spot.colorado.edu |
| Edilene Fotheringham, GRA | CU - Physics (Anderson) | fotherin@jila1.colorado.edu |
| Shawn Kraut, GRA | CU - ECE (Scharf) | kraut@dsp.colorado.edu |
| Greg Kriehn, GRA | CU - OCS (Wagner) | kriehn@colorado.edu |
| Paulo Silveira, GRA | CU - OCS (Wagner) | paulo@colorado.edu |
| Shawn Stone, GRA | CU - ECE (Popovic) | stones@colorado.edu |
| Jim Vian, GRA | CU - ECE (Popovic) | vian@colorado.edu |
| Dr. Abdul Awwal, vis. sci. | Wright st | aawwal@colorado.edu |
| Dr. David Begley | Ball | dbegley@ball.com |
| Dr. Norman Bernstein | RADC | bernsteinn@rl.af.mil |
| Dr. Jaap Bregman | NFRA | jbregman@nfra.nl |
| Dr. Johnathon Dixon | MIT-LL | dixonj@ll.mit.edu |
| Dr. Daniel Dolfi | Thomson | dolfi@lcr.thomson.fr |
| Dr. Colin Edge | GMMT | colin.edge@gecm.com |
| Dr. Peter Guilfoyle | OptiComp | perterg@opticomp.com |
| Dr. Charles Garvin | Martin Marietta | charles.g.garvin@lmco.com |
| Dr. John Hong | Rockwell | jhhong@rsc.rockwell.com |
| Dr. Bahram Jalali | UCLA | jalali@ucla.edu |
| Dr. Frank M. Kustas | Martin Marietta | frank.m.kustas@lmco.com |
| Dr. Thomas Mader | Hughes | tbmader@mail.hac.com |
| Dr. Vladimir Manasson | WaveBand | vmanasson@earthlink.net |
| Dr. David Martinez | MIT-LL | dmartinez@ll.mit.edu |
| Dr. Paul Matthews | NRL | pjm@ccf.nrl.navy.mil |
| Prof. Ruth Ann Mullen | UW | rmullen@u.washington.edu |
| Dr. George Simonis | ARL | gsimonis@arl.mil |
| Dr. Terry Turpin | Essex | turpin@essexcorp/com |

2.2.12 Working session 07/19/99, Boulder, CO – Eaton conf.rm.

A working meeting to discuss progress and raise issues acting as roadblocks was held in Boulder during the week of the SPIE annual meeting which was held in Denver this year. This review was attended by nearly all of the MURI PIs as well as all of the CU students and postdocs, and was highlighted by productive discussions.

| | | |
|------|----------------------|---|
| 1:00 | | Lunch |
| 2:00 | Kelvin Wagner | Welcome, RFLICs, and IAB at UCLA |
| 2:15 | Dana Anderson | Discussion of Photorefractive Processing |
| 2:30 | Edeline Fotheringham | Update on PRC array processing circuits |
| 2:45 | Valeria Damiao | update on antenna front end processing |
| 3:00 | Zoya Popovic | Discussion of Quasi optical arrays |
| 3:15 | Pete Kirkpatrick | EO devices |
| 3:30 | Jim Vian | Update on optically controlled arrays |
| 3:45 | | Break |
| 4:00 | Ted Weverka | Coherent Array Gain |
| 4:15 | Paulo Silveira | All-optical BEAMTAP |
| 4:30 | Greg Kriehn | Traveling Fringes Detectors and BEAMTAP |
| 4:45 | Paulo Silveira | E/O Nonlinearities in array processing |
| 5:00 | Andrew Kiruluta | Sonar BEAMTAP |
| 5:15 | Randy Babbitt | Discussion of OCTs and Array Processing |
| 5:30 | Kris Merkel | OCT Time Delay and Correlation Processing |
| 5:45 | Ken Anderson | OCT Adaptive Arrays |
| | | Wrapup |

2.2.13 Visits by MURI researchers

1. January 16-17 visit by Babbitt and Merkel to Boulder for discussions and experiments.
2. January 19 MURI review in Boulder attended by Griffiths, Weverka, Babbitt, Merkel.
3. Visit by Peter Guilfoyle of Opticomp Jan 20 to discuss possible collaborations involving array processing and Opticomp device and system technology.

4. Visit and discussions Jan 20,21,22 by Jaap Bregman from NFRA with K. Wagner, Z. Popovic, and students regarding quasi-optics and optical adaptive array processing for SKA.
5. January 26 DARPA presentation for RF photonics and low V_{π} modulators.
6. Wagner, Kriehn, Vian, Merkel, Weverka, Griffiths attend and meet at PSAA in Monterey Feb 17-19.
7. K. Wagner gives ECE department seminar on MURI in RF Photonics and BEAMTAP Optical processing.
8. K. Wagner attends B. Miceli's Circular Array workshop at GMU Feb 22, visits L. Griffiths.
9. K. Wagner and K. Andersen visit Coherent Technology, give seminar on photon echoes and phased array processing.
10. Visit to CU March 3-6 by Dr. Ivan Logere from CNRS for joint experiments on laser stabilization for photon echoes.
11. Wagner, Anderson, Babbitt, Merkel meet at Persistent Spectral Hole Burning Meeting, Bozeman MT March 7-10. Anderson stays for an additional week of joint experiments. Results in 1 paper and 1 patent.
12. Wagner, Kriehn, Silveira, Anderson, Kiruluta, and Merkel meet at Optics in Computing Topical Meeting, Snowmass, CO, April 12-16.
13. Delores Etter from OSD DDR&E visits CU April 30 and is briefed on RF Photonics Systems MURI by K. Wagner, Z. Popovic, and D. Anderson.
14. Lloyd Griffiths visits Boulder for discussions with Wagner, Popovic, Kriehn, Kiruluta, Silveira on May 13-15.
15. Jaap Bregman visits CU, May 17-18, for collaborations with Wagner, Popovic, Kriehn, Kiruluta on BEAMTAP for radio astronomy.

16. MURI workshop in Boulder July 19 attended by Weverka, Babbitt, Merkel.
17. Joint experiments in Boulder July 22-23 attended by Babbitt and Merkel.
18. Visit by Wagner to University of Washington to discuss circular arrays with Jim Ritcey.
19. Joint proposal written by Wagner with Hong and Higgins of Rockwell sciences for single chip BEAMTAP implementation.
20. Visit by Peter Kirkpatrick to Bozeman on August 16, 1999.
21. Visit by Kelvin Wagner to Bozeman, August 15, 1999.
22. Wagner, Babbitt, Merkel meet at Hole Burning/Nano-opticis workshop in Lyon France, September 16, 1999.
23. Wagner, Babbitt, Merkel, Tian meet at Hole Burning workshop in Hourtin France, September 19-23, 1999.
24. Presentation by Wagner on RF Photonics MURI center and BEAMTAP to IDA visitors at CU-Boulder, Oct. 7, 1999.
25. Presentation by G. Kriehn on BEAMTAP at OCS retreat, Nov. 19, 1999.
26. Presentation by K. Anderson on photon echo array processing at OCS retreat Nov 19 1999.
27. Lloyd Griffiths visits Boulder for discussions with Wagner, Popovic, Kriehn, Kiruluta, Silveira on May 29-30.
28. Visit by Tom Mader from Hughes for discussions with Zoya Popovic on RF photonics.
29. Visit by Dr. Scott Bundy from US West research for discussions with Zoya Popovic on adaptive arrays.
30. Visit by Dr. Bart Smolders from NFRA.
31. Visit by Dr. Mike McDonald from Lincoln Labs for discussions with Zoya Popovic on adaptive arrays.

32. Visit by Dr. Stein Hollung from Chalmers Univ for discussions with Zoya Popovic on quasi optics.
33. Visit by Prof. Gabriel Rebeiz from Michigan for discussions with Zoya Popovic on phase shifters and adaptive arrays.

2.2.14 Kickoff Meetings

Our MURI kickoff meeting was held on September 23, 1997 in Boulder. The first annual technical meeting was held in Boulder on July 13-14, 1998.

Some of the MURI PIs have also been involved in other MURI reviews. Prof. Wagner presented on overview of the CU MURI at the first annual review of the UCLA MURI in RF photonics on Oct 22, 1998. Prof. Popovic is a co-PI in two other MURIs in the related area of Quasi-optics, and she has been involved in these MURI reviews for the last 2 years.

2.2.15 CU RF Photonics MURI Kickoff Meeting Schedule, Sept 23, 1997

8:00 - 8:30 AM — Continental Breakfast —

| | | |
|-----------------|--------------------------|-------------------------|
| 8:30 - 8:40 AM | Dean Branch - CU | Welcome |
| 8:40 - 9:05 AM | Kelvin Wagner - CU | Introduction to program |
| 9:05 - 9:30 AM | Lloyd Griffiths - GMU | STAP |
| 9:30 - 9:55 AM | Kelvin Wagner - CU | BEAMTAP |
| 9:55 - 10:20 AM | Ted Weverka - Optivision | Optical beamforming |

10:20-10:40 AM — Coffee Break —

| | | |
|----------------|---------------------|--|
| 10:45-11:10 AM | Randy Babbitt - MSU | Coherent transients for array processing |
| 11:10-11:35 AM | Dana Anderson - CU | Nonlinear optics for array processing |
| 11:35-12:00 AM | Zoya Popovic -CU | Optical control of quasi-optical arrays |

12:00- 1:30 PM — Lunch —

| | | |
|----------------|------------------------|--|
| 1:30 - 2:30 PM | William Miceli - ONR | DoD overview of array processing needs |
| 2:30 - 2:45 PM | John Brock - TRW | TRW and RF Photonics |
| 2:45 - 3:00 PM | Mike Hamilton - Boeing | Boeing and RF Photonics |
| 3:00 - 3:15 PM | Daniel Dolfi - Thomson | Thomson and RF photonics |
| 3:15 - 3:30 PM | John Hong - Rockwell | Rockwell and RF Photonics |

3:15 - 3:30 PM — Coffee Break —

| | |
|----------------|-------------------------|
| 3:30 - 4:30 PM | Discussion and Feedback |
| 4:30 - 6:00 PM | Lab Tours |

6:00 PM — Reception and Dinner —

2.2.16 Attendees of Kickoff meeting Sept 23, 1997

| Name | Organization | Contact Info |
|---------------------------|---------------------------|----------------------------------|
| Dr. Bill Miceli, Sponsor | ONR | wmiceli@nosc.mil |
| Prof. Kelvin Wagner, PI | CU - OCS | kelvin@colorado.edu |
| Prof. Dana Anderson, PI | CU - Physics | dana@colorado.edu |
| Prof. Randy Babbitt, PI | MSU | babbitt@physics.montana.edu |
| Prof. Lloyd Griffiths, PI | GMU | griffiths@gmu.edu |
| Prof. Zoya Popovic, PI | CU - ECE | zoya@colorado.edu |
| Ted Weverka, PI | Optivision | weverka@optivision.com |
| Prof. Mel Branch, Dean | CU - Engineering | melvyn.branch@colorado.edu |
| Prof. Ren Su, ECE Chair | CU - ECE | sur@colorado.edu |
| Sam Weaver, PRA | CU - OCS | samw@colorado.edu |
| Paulo Silveira, GRA | CU - OCS (Wagner) | paulo@colorado.edu |
| Greg Kriehn, GRA | CU - OCS (Wagner) | kriehn@colorado.edu |
| Ken Anderson, GRA | CU - OCS (Wagner) | kanderso@colorado.edu |
| Shawn Stone, GRA | CU - ECE (Popovic) | stones@colorado.edu |
| Stein Hollung, GRA | CU - ECE (Popovic) | hollung@colorado.edu |
| Dr. Gregory Zagar | RADC | zagarg@rl.af.mil |
| Dr. Norman Bernstein | RADC | bernstein@rl.af.mil |
| Dr. Howard Schlossberg | AFOSR | schlossb@afosr.af.mil |
| Dr. Joon Y. Choe | NSWC | jchoe@relay.nswc.navy.mil |
| Dr. John Pellegrino | ARL | pell@arl.mil |
| Dr. Weimin Zhou | ARL | zhou@arl.mil |
| Dr. Steve Pappert | NCCOSC | spappert@nosc.mil |
| Dr. John Brock | TRW | john.brock@trw.com |
| Dr. Michael Hamilton | Boeing | michael.c.hamilton@boeing.com |
| Dr. John Hong | Rockwell | jhhong@scimail.risc.rockwell.com |
| Dr. Frank M. Kustas | Martin Marietta | frank.m.kustas@lmco.com |
| Dr. Sammy Henderson | Coherent Tech. | sammy@ctilidar.com |
| Dr. Daniel Dolfi | Thomson | daniel.d.d.dolfi@lcr.thomson.fr |
| Dr. A. van Ardenne | NFRA | ardenne@nfra.nl |
| Robert Munson | Munson Antenna Consulting | |

2.2.17 First internal review and workshop, July 13-14, 1998

July 13 – Tutorials and research reviews

| | | |
|-------------|---------------------|--|
| 8:30- 9:00 | Kelvin Wagner | Tutorial on Array Processing and True Time Delay |
| 9:00- 9:45 | Andrew Kiruluta | BEAMTAP system overview and analysis |
| 9:45-10:30 | Ted Weverka | Tutorial on coherent array feed and progress |
| 10:30-10:45 | COFFEE BREAK | |
| 10:45-11:30 | Randy Babbitt | Tutorial on photon echo |
| 11:30-12:00 | Ken Anderson | Multidimensional photon echo processing |
| 12:00-12:30 | Randy Babbitt | Phased array processing with photon echoes |
| 12:30- 1:30 | LUNCH catered AE142 | |
| 1:30- 2:30 | Zoya Popovic | Tutorial on quasi optics |
| 2:30- 3:10 | Jim Vian | Optically controlled arrays |
| 3:10- 3:30 | Shawn Stone | Optically tuneable arrays |
| 3:30- 4:00 | COFFEE BREAK | |
| 4:00- 4:45 | Dana Anderson | Tutorial on nonlinear optical signal processing |
| 4:45- 5:15 | Dana Anderson | Nonlinear array processing |
| 5:15- 5:30 | Kelvin Wagner | wrapup |
| 7:00 | Dinner | |

July 14 – Discussion sessions

| Time | Discussion leader | Topic |
|--------------------------------------|-------------------|--|
| 8:00- 8:30 | Ted Weverka | Dynamic range |
| 8:30- 9:00 | Andrew Kiruluta | Detectors |
| 9:00- 9:30 | Kelvin Wagner | Choice of Wavelength |
| 9:30-10:00 | Zoya Popovic | Broadbandwidth arrays and circuitry |
| 10:00-10:30 | Randy Babbitt | 10 GHz demos |
| 10:30-11:00 | COFFEE BREAK | |
| 11:00-11:30 | Ted Weverka | RF Electro optic modulators |
| 11:30-12:00 | Vladimir Shkunov | RF Laser diode: amplification and modulation |
| 12:00-12:30 | Dana Anderson | PR Xtals for RF |
| LUNCH | | |
| Clark conference room - Deans office | | |
| 2:00-3:00 | PIs | Executive Committee |

2.2.18 Attendees of First internal review workshop, July 23 1998

| Name | Organization | Contact Info |
|--------------------------------------|--------------------|-----------------------------|
| Prof. Kelvin Wagner, PI | CU - OCS | kelvin@colorado.edu |
| Prof. Dana Anderson, PI | CU - Physics | dana@colorado.edu |
| Prof. Randy Babbitt, PI | MSU | babbitt@physics.montana.edu |
| Prof. Zoya Popovic, PI | CU - ECE | zoya@colorado.edu |
| Ted Weverka, PI | Optivision | weverka@optivision.com |
| Sam Weaver, PRA | CU - OCS | samw@colorado.edu |
| Andrew Kiruluta, postdoc | CU - OCS (Wagner) | kirulut@colorado.edu |
| Ken Anderson, GRA | CU - OCS (Wagner) | kanderso@colorado.edu |
| Shawn Stone, GRA | CU - ECE (Popovic) | stones@colorado.edu |
| Jim Vian, GRA | CU - ECE (Popovic) | vian@colorado.edu |
| Vladimir Shkunov, visiting scientist | CU - Physics | shkunov@jila02.colorado.edu |

2.3 Additional Collaborations and Related Research**2.3.1 2003 Collaborations**

1. Prof. Joseph Shamir of the Technion in Israel was the MURI fellow and visited Prof. Wagner's group between Sept. and Oct. of 2002.
2. Prof. Wagner and Friso Schlottau from CU visited Prof. Babbitts labs at MSU during July 2003.
3. Prof. Wagner spent the fall semester 2003 visiting Prof. Babbitts labs at MSU Bozeman as the MURI was ending in order to pursue further collaborations.

2.3.2 2003 Other related grants

1. "Applications of Optical Coherent Transient Technology: Pulse Shaping, Spectral Filtering, Arbitrary Waveform Generation, and RF Beamforming," AFOSR/DEPSCOR,

- PI: W. R. Babbitt, co-PI: Mingzhen Tian, \$310,067 plus \$155,034 match, 7/02-7/05, \$80K subcontract to Prof Wagner at CU.
2. "Wide-Bandwidth and Multidimensional Analog Signal Processing," DARPA, Lead: W. R. Babbitt, Co-PIs Kelvin Wagner, Univ. of Colorado and Randy Equall, Scientific Materials Corp., and Kris Merkel, Krishna Rupavatharam, and Rufus Cone at MSU, \$1.9M, 10/02-9/04.
 3. "Spatial Spectral Coherent Holographic Integrating Processor-S2-CHIP: Device characterization, performance evaluation, and optimization," Montana Board for Research and Commercialization of Technology, PI: W. R. Babbitt, co-PIs: Kris Merkel and Mark Ivey, \$149,420, 11/02-7/03, matched by NASA grant.
 4. "S2-chip award to Scientific Materials Sept 2003-2007, approximately \$15 million, with subcontracts to Prof. Babbitt at CU and Prof. Wagner at MSU.
 5. \$350K Prof. Wagner PI, Real-time Multibeam Imaging and High-Resolution Spectral Analysis for Large, Wideband Antenna Arrays – awarded by NRO DII (National Reconnaissance Office Directors Innovation Initiative). \$350,000 for 9 months. Status: Awarded on Sep 10, 2003.
 6. Prof. Wagner, co-PI, \$80K DEPSCOR subcontract from MSU, Optical coherent-transient time-delay control using acousto-optic distributed local oscillators, \$80K, plus \$40K CU matching 7/2002-12/2004.
 7. Prof. Wagner PI, Coherent Optical Array Processing, DARPA Analog Optical Signal Processing (AOSP) program, awarded in 2002. In effect 2002-2006.
 8. \$600K 4/03-4/06, PI: RF array imaging and spectral analysis using spatial-spectral holography, with Co-PIs Jaap Bregman at NFRA and J.L. Legouet at CNRS. Submitted to ONR NICOP program for international collaborations, CU portion \$80K/3 years. AWARDED
 9. \$350K DoD NRO DII, 10/23/03-7/23/04. K. Wagner PI. LIDAR Sensing and Signal

Processing Using Spatial-Spectral Holography in Inhomogeneously Broadened Gain Media, \$114,579 CU portion, with subcontracts to MSU and CTI.

10. NSF IGERT, Graduate Research Traineeships, PI Dana Anderson, \$2500K for 5 years, 1998-2003.

2.3.3 2002 Collaborations

The MURI has enabled a wide variety of collaborations among the PIs as well as with other groups. In this section some notable collaborations are discussed and outgrowths from the MURI into new areas are mentioned.

1. Prof. Joseph Shamir of the Technion in Israel was the MURI fellow and visited Prof. Wagner's group between Aug. and Sept. of 2001 and between Sept. and Oct. of 2002.
2. Prof. Vitaly Voloshinov of Moscow State University in Russia was the MURI fellowship visitor to Prof. Wagner's group to work on acousto-optic devices, Nov 11-21, 2001.
3. Prof. Babbit explored Raman amplification at 793nm for OCTs with Directed Energy Systems of Colorado Springs in the Fall of 2002.
4. Two graduate students under the supervision of Prof. Popović have been for 3 months at the NFRA facility at Dwingeloo (Jan Peeters Weem and Eric Bryerton). Several papers have resulted from this collaboration.
5. Technische Universität München (Germany) and Univ. of Karlsruhe (Germany): Two German students, Holger Matern and Johannes Russer were sent (and supported by their home country) to work in Prof. Popović's group on their MS theses in the area of RF photonics. Holger developed a 5-channel electrooptic modulator and Johannes is finishing a fast optically-controlled microwave phase shifter.

2.3.4 2002 Other related grants

1. Profs. Popović and Wagner submitted new proposals on optical processing of RF signals from broadband RF antenna arrays. Any subsequent grant will be a direct result of the Co-PI's joint work under this MURI.

2. Prof. Popovic and Anderson have received a follow-on grant from NSF to expand the optical processing to wireless communications. This grant is now ending, and they submitted a follow-on proposal to the NSF ITP program, Dec. 2002. The proposal is currently under review.
3. "High Performance Correlators based on Spectral Hole Burning Technology," NASA, PI: Alan Craig, \$5,096,000, 4/99-4/03. PI changed to W. R. Babbitt in 12/2001.
4. Prof. Babbitt received an award from Montana Board for Research and Commercialization of Technology: matching grant for the MURI grant \$7,810, 5/01-5/02.
5. "Consortium for Stable Laser Applications," NSF Partners for Innovation (PFI), PI: Alan Craig, co-PI Jim McMillan, \$598,553, 10/01-9/03, changed PI to W. R. Babbitt in 12/01.
6. "Applications of Optical Coherent Transient Technology: Pulse Shaping, Spectral Filtering, Arbitrary Waveform Generation, and RF Beamforming," AFOSR/ DEPCOR, PI: W. R. Babbitt, co-PI: Mingzhen Tian, \$310,067 plus \$155,034 match, 7/02-7/05.
7. "Wide-Bandwidth and Multidimensional Analog Signal Processing," DARPA, Lead: W. R. Babbitt, Co-PIs Kelvin Wagner, Univ. of Colorado and Randy Equall, Scientific Materials Corp., and Kris Merkel, Krishna Rupavatharam, and Rufus Cone at MSU, \$1.9M, 10/02-9/04.
8. "Spatial Spectral Coherent Holographic Integrating Processor-S2-CHIP: Device characterization, performance evaluation, and optimization," Montana Board for Research and Commercialization of Technology, PI: W. R. Babbitt, co-PIs: Kris Merkel and Mark Ivey, \$149,420, 11/02-7/03, matched by NASA grant.
9. Prof. Wagner, \$60K subcontract to University Nebraska Lincoln for ONR proposal on Random Noise Radar. Title: Acoustooptic Delay Line/Correlator for random noise radar, 8/00 - 8/02.
10. \$350K Prof. Wagner PI, Real-time Multibeam Imaging and High-Resolution Spectral Analysis for Large, Wideband Antenna Arrays – submitted to NRO DII (National

Reconnaissance Office Directors Innovation Initiative). \$350,000 for 9 months. Status: Awarded on Dec 21, 2001, rescinded award due to NRO budget cut.

11. \$20K Prof. Wagner PI, Joint Optoelectronic Project Proposal – Double-clad Thulium doped fiber for use in a fiber amplifier for optical coherent transient experiments. An equipment proposal to the Joint Optoelectronics Project (JOP). Status AWARDED: \$20,000 in custom optical fiber
12. \$14.5K Prof. Wagner PI, NSF/CNRS collaboration, multidimensional photon echo optical processing, notice of award Jan 3 2000, in effect 2000-2004.
13. Prof. Wagner, co-PI, \$80K DEPSCOR subcontract from MSU, Optical coherent-transient time-delay control using acousto-optic distributed local oscillators, \$80K, plus \$40K CU matching 7/2002-12/2004.
14. Prof. Wagner PI, Coherent Optical Array Processing, DARPA Analog Optical Signal Processing (AOSP) program, awarded in 2002. In effect 2002-2006.

2.3.5 2002 Collaborations

1. Prof. Babbitt assumed the role of the director of Spectrum Labs at Montana State University, which involves dozens of researchers at MSU and elsewhere investigating the applications of Optical Coherent Transient and spectral hole burning technology for memory and signal processing applications.
2. Prof. Babbitt led a team with Prof. Wagner to apply for a DARPA Analog Optical Signal Processing (AOSP) program utilizing Optical Coherent Transients for wideband signal processing, waveform generation, and array processing. The team also included Prof. Rufus Cone, Dr. Alan Craig, and Dr. Kris Merkel, all of MSU, Dr. Randy Equal of Scientific Materials, and Terry Turpin of Essex. Although the proposal was not selected, numerous extremely novel and powerful applications of OCT technology were invented and refined.
3. Prof. Wagner worked with Prof. Popovic and Dr. Mark Rosker and Dr. Ian McMichael of Rockwell Sciences on a DARPA AOSP proposal for the further development of

BEAMTAP. Specifically, a fieldable prototype was to be designed and developed for application in jam resistant GPS arrays, time-delay detectors using III-V CCD technology appropriate for BEAMTAP time delays were to be fabricated, and the BEAMTAP architecture was modified with a front end beamsteering system allowing squint-free broadband operation in radar and surveillance scenarios. Although this proposal was not successful with DARPA, extremely useful collaborations with industry were developed.

4. Prof. Wagner also led a team with Drs. Al Samuel, Silvio Cardero, and Harry Schmidt from Raytheon in Tucson, to propose the use of 3-dimensional signal processing in the volume of photorefractive crystals for array processing, in order to calculate range-doppler-angle surfaces. This system was to be designed and built at the University of Colorado and tested by Raytheon with real array data in scenarios appropriate for their missile applications.
5. Prof. Wagner also collaborated with Lockheed Martin Corporation on the application of photorefractive phased array processing for large array applications.
6. Prof. Popović collaborated with Prof. Anderson on the demonstration of a 2-channel optical processor for a quasi-optical (QO) receiving array. A complete system was engineered and characterized, starting from the microwave 10-GHz active antenna front end, to the photodetector and RF demodulator circuits. The system is able to adaptively separate a strong jammer from a signal over shared bandwidth. This could not have been accomplished without multidisciplinary experience in microwave engineering, optics, and electronics. The graduate students involved in the project are now competent in both optics and RF engineering, and the first demonstration of a complete system is now practically completed.
7. Prof. Popović collaborated with Prof. Griffiths on adaptive algorithms for lens array antennas. They have applied an LMS adaptive algorithm to a lens antenna array and compared it to a standard 2-D antenna array in terms of noise and adaptation (learning) speed. They are currently working on a paper that summarizes the results

and points to the advantages of quasi-optical arrays for adaptive front ends.

8. Profs. Babbitt and Wagner worked together on a DEPCOR project that investigated applications of photon echo processing to radar systems. This additional interaction greatly benefited the MURI program since it allowed Prof. Wagner to undertake photon echo experiments not supported by the MURI, as well as direct Prof. Babbitt's work beyond true-time-delay towards fully adaptive processing. Recent results include a preliminary demonstration of true-time-delay array beam steering using novel acoustooptic steering techniques in combination with chirped photon echoes (patent pending). [DEPCOR]
9. Prof. Knoesen collaborated with Prof. Larry Dalton of the University of Southern California to incorporate the new nonlinear polymeric materials developed by Prof. Larry Dalton into modulator devices.
10. Prof. Knoesen collaborated with Prof. Shiao-Min Tseng of the National Tsing Hua University of Taiwan to obtain long interaction length half-couplers used in in-line modulators.
11. Prof. Knoesen collaborated with Intelligent Fiber Optic Systems Inc., Sunnyvale CA. to extend inline fiber devices to tunable in-line filters.
12. Prof. Knoesen collaborated with Prof. James S. Harris of Stanford University to extend inline fiber concepts to in-line GaAs/AlGaAs modulators, filters, detectors, and emitters.

2.3.6 2001 Other related grants

1. "NSF ITR investigating ultrafast non linear optics switching," \$499,000, 2000-2003, PI Kelvin Wagner with Co-PI Frank Wise at Cornell.
2. "Real-time Multibeam Imaging and High-Resolution Spectral Analysis for Large, Wide-band Antenna Arrays", Prof. Wagner, \$350K from the NRO DII, 2/1/2001-10/31/2001.

3. "Quasi-optics," ARO MURI in Quasi-Optical Power Combining, Co-PI: Zoya Popović, with Caltech, UCSB and U of Hawaii.
4. "Low-power electronics for wireless," NSF, \$1.5 million, Co-PI: Zoya Popović, with Varanasi, Maksimovic, Brown.
5. "Adaptive optical processing for arrays in wireless base stations," NSF, \$250K, PIs: Zoya Popović with Dana Anderson. Profs. Popović and Anderson received a NSF grant under the wireless communications initiative to demonstrate how the optical processor developed under this MURI can be applied to wireless channels with interference.
6. "Diversity in wireless systems," NSF wireless program, \$800K, Co-PI: Zoya Popović, Scharf, Varanasi, with U of Wisconsin.
7. "Low-power electronics," ARO MURI, Co-PI: Zoya Popović with U of Michigan.
8. "High performance correlators based on spectral hole burning technology", NASA, PI: Alan Craig, Co-investigators: W. R. Babbitt, J. L. Carlsten, and R. L. Cone, \$2M/year, 4/99-4/04.
9. "Advanced Coherent Transient Systems and Devices," Air Force Office of Scientific Research, PI: W. R. Babbitt, \$457,844 (plus \$9,749 cost-share), 3/98- 2/01.
10. "Wide-Band Optical True-Time-Delay and Adaptive Beamforming," Army Research Office PI: W. R. Babbitt, \$299,199 (plus \$149,899 cost-share) 5/98- 4/01
11. "Optically-controlled RF switch for polarization-diversity wireless communication receiver," NSF wireless program, PIs Zoya Popović, Mahesh Varanasi, Louis Scharf.
12. "MURI in atom optics," PI Dana Anderson.
13. "Low-index polymer structures integrated in in-line fiber devices", UC Micro in collaboration with intelligent fiber optic systems, \$38,080, 1999-2000, PI Andre Knoesen.
14. "Tunable add-drop in-line fiber multiplexer devices for fiber optic systems", UC Core in collaboration with Intelligent Fiber Optic Systems, \$183,083, 1999-2001, PIs Andre Knoesen and Diego Yankelovich.

2.3.7 2000 Collaborations

The MURI has enabled a wide variety of collaborations among the PIs as well as with other groups. In this section some notable collaborations are discussed and outgrowths from the MURI into new areas are mentioned.

1. Prof. Popović collaborated with Prof. Anderson on the demonstration of a 2-channel optical processor for a quasi-optical (QO) receiving array. A complete system was engineered and characterized, starting from the microwave 10-GHz active antenna front end, to the photodetector and RF demodulator circuits. The system is able to adaptively separate a strong jammer from a signal over shared bandwidth. This could not have been accomplished without multidisciplinary experience in microwave engineering, optics, and electronics. The graduate students involved in the project are now competent in both optics and RF engineering, and the first demonstration of a complete system is now practically completed.
2. Prof. Popović collaborated with Prof. Griffiths on adaptive algorithms for lens array antennas. They have applied an LMS adaptive algorithm to a lens antenna array and compared it to a standard 2-D antenna array in terms of noise and adaptation (learning) speed. They are currently working on a paper that summarizes the results and points to the advantages of quasi-optical arrays for adaptive front ends.
3. Profs. Babbitt and Wagner are working together on a DEPSCOR project that is investigating applications of photon echo processing to radar systems. This additional interaction will greatly benefit the MURI program since it will allow Prof. Wagner to undertake photon echo experiments not supported by the MURI as well as direct Prof. Babbitt's work beyond true-time-delay towards fully adaptive processing. Recent results include a preliminary demonstration of true-time-delay array beam steering using novel acousto-optic steering techniques in combination with chirped photon echoes (patent pending). [DEPSCOR]
4. Prof. Babbitt, PI, Co-founded a new company, LightSmyth Technologies, that uses new device technologies to perform processing of optical signals in telecommunication

networks. While these devices are not OCT based, there are many parallels to OCTs and the insights learned will benefit the MURI project. Mingzhen Tian, who has been with the project for two years and is becoming a permanent member of the MSU team as a research scientist, runs the day to day operation of Prof. Babbitt's Coherent Transients Lab. Dr. Kris Merkel and Dr. Kevin Repasky, research scientist in MSU Spectrum Lab, will continue to be part of the MURI team, both directly and in collaborations between MURI and MSU Spectrum Lab.

5. Prof. Knoesen collaborated with Prof. Larry Dalton of the University of Southern California to incorporate the new nonlinear polymeric materials developed by Prof. Larry Dalton into modulator devices.
6. Prof. Knoesen collaborated with Prof. Shiao-Min Tseng of the National Tsing Hua University of Taiwan to obtain long interaction length half-couplers used in in-line modulators.
7. Prof. Knoesen collaborated with Intelligent Fiber Optic Systems Inc., Sunnyvale CA. to extend inline fiber devices to tunable in-line filters.
8. Prof. Knoesen collaborated with Prof. James S. Harris of Stanford University to extend inline fiber concepts to in-line GaAs/AlGaAs modulators, filters, detectors, and emitters.

2.3.8 2000 Other related grants

1. "Quasi-optics," ARO MURI in Quasi-Optical Power Combining, Co-PI: Zoya Popović, with Caltech, UCSB and U of Hawaii.
2. "Low-power electronics for wireless," NSF, \$1.5 million, Co-PI: Zoya Popović, with Varanasi, Maksimovic, Brown.
3. "Adaptive optical processing for arrays in wireless base stations," NSF, \$250K, PIs: Zoya Popović with Dana Anderson. Profs. Popović and Anderson received a NSF grant under the wireless communications initiative to demonstrate how the optical processor developed under this MURI can be applied to wireless channels with interference.

4. "Diversity in wireless systems," NSF wireless program, \$800K, Co-PI: Zoya Popović, Scharf, Varanasi, with U of Wisconsin.
5. "Low-power electronics," ARO MURI, Co-PI: Zoya Popović with U of Michigan.
6. "High performance correlators based on spectral hole burning technology", NASA, PI: Alan Craig, Co-investigators: W. R. Babbitt, J. L. Carlsten, and R. L. Cone, \$2M/year, 4/99-4/04.
7. "Advanced Coherent Transient Systems and Devices," Air Force Office of Scientific Research, PI: W. R. Babbitt, \$457,844 (plus \$9,749 cost-share), 3/98- 2/01.
8. "Wide-Band Optical True-Time-Delay and Adaptive Beamforming," Army Research Office PI: W. R. Babbitt, \$299,199 (plus \$149,899 cost-share) 5/98- 4/01
9. "Optically-controlled RF switch for polarization-diversity wireless communication receiver," NSF wireless program, PIs Zoya Popović, Mahesh Varanasi, Louis Scharf.
10. "MURI in atom optics," PI Dana Anderson.
11. "NSF ITR investigating ultrafast non linear optics switching," \$499,000, 2000-2003, PI Kelvin Wagner with Co-PI Frank Wise at Cornell.
12. "Low-index polymer structures integrated in in-line fiber devices", UC Micro in collaboration with intelligent fiber optic systems, \$38,080, 1999-2000, PI Andre Knoesen.
13. "Tunable add-drop in-line fiber multiplexer devices for fiber optic systems", UC Core in collaboration with Intelligent Fiber Optic Systems, \$183,083, 1999-2001, PIs Andre Knoesen and Diego Yankelvich.

2.3.9 1999 Collaborations

Prof. Babbitt and Wagner are working together on a DEPCOR project that intends to investigate applications of photon echo processing to radar systems. This additional interaction will greatly benefit the MURI program since it will allow Prof. Wagner to

undertake photon echo experiments not supported by the MURI and it will direct Prof. Babbitt's work beyond true-time-delay towards fully adaptive processing.

2.3.10 1999 related grants

1. "Quasi-optics," ARO MURI, Co-PI: Zoya Popovic, with Caltech, UCSB and U of Hawaii.
2. "Low-power electronics for wireless," NSF, \$1.5 million, Co-PI: Zoya Popovic, with Varanasi, Maksimovic, Brown.
3. "Adaptive optical processing for arrays in wireless base stations," NSF, \$250K, PIs: Zoya Popovic with Dana Anderson.
4. "Diversity in wireless systems," NSF wireless program, \$800K, Co-PI: Zoya Popovic, Scharf, Varanasi, with U of Wisconsin.
5. "Low-power electronics," ARO MURI, Co-PI: Zoya Popovic with U of Michigan.
6. "Advanced Coherent Transient Systems and Devices," Air Force Office of Scientific Research, PI: W. R. Babbitt, \$457,844 (plus \$9,749 cost-share), 3/98- 2/01.
7. "Wide-Band Optical True-Time-Delay and Adaptive Beamforming," Army Research Office PI: W. R. Babbitt, \$299,199 (plus \$149,899 cost-share) 5/98- 4/01
8. "Optical Coherent Transient Processors and True-Time-Delays," Air Force Office of Scientific Research/DURIP, PI: W. R. Babbitt, \$149,800, 3/98-2/99.
9. Optically-controlled RF switch for polarization-diversity wireless communication receiver, NSF wireless program, PIs Zoya Popovic, Mahesh Varanasi, Louis Scharf.

2.3.11 1998 Additional Collaborations

The MURI involves collaborative projects between the PIs, but in addition these interactions have spun off additional collaborations between the PIs that may not have occurred without the MURI. Some of these are briefly listed here.

Prof Babbitt has been awarded a DEPCOR to investigate other applications of photon echo processing to radar systems, and a sub-award to Prof. Wagner will allow him to initiate simple photon echo experiments. It is expected that this additional interaction will benefit the MURI by increasing the expertise of the MURI researchers in the complimentary areas not funded under the MURI.

An NSF SBIR collaboration between Weverka at Optical Networks and Babbitt at MSU led to a phase 1 award on Spatial-Spectral Holographic Buffers for Optical Networks. This spin off effort would use the time delay functions being developed under the MURI program as buffer memories in optical network wavelength selective cross-connects.

NRL has provided support to Prof. Wagner in collaboration with Prof. Griffiths and Prof. Anderson to investigate sonar applications of similar technological approaches investigated in the MURI for radar applications, and specifically an optical implementation of the P-vector algorithm developed by Prof. Griffiths has been pursued.

Prof. Anderson in combination with Profs. Popovic and Wagner and other CU optics professors has been awarded an NSF IGERT award for the 5 year advanced PhD traineeships in optics related fields. This \$3 million program will undoubtedly attract some of the worlds best optics students to CU and help leverage the MURI investment in graduate student education.

And finally on a happier and lighter note our MURI can boast a unique collaboration through the marriage of two of our PIs, Profs. Anderson and Popovic this spring.

2.4 Awards and Honors for the PIs and students

1. Best Poster Award granted to Friso Schlottau, Randy Babbit, Jean-Louis Le Gouet and Kelvin Wagner for the CPIA poster entitled "Spatial spectral holography for wideband spectral analysis," Nov. 2002.
2. MWP 2001 on Jan. 2002. Best student presentation runner-up: Friso Schlottau and Kelvin Wagner, "RF Photonics for Simultaneous Multiple TTD Beamforming for 2-D Antenna Arrays," IEEE Microwave Photonics Meeting, Long Beach, Oct 2001 (delayed to Jan. 2002).

3. Prof. Kelvin Wagner was elevated to the status of fellow of the OSA (Optical Society of America) for "Contributions to adaptive spatio-temporal optical processing systems."
4. Zoya Popović and Dana Anderson both received the prestigious Humboldt Award for Senior US Scientists from the German Alexander von Humboldt Stiftung (2001).
5. Zoya Popović received the HP/ASEE Terman Award for combined teaching and research excellence, October 2001.
6. Zoya Popović became a Fellow of the IEEE.
7. Zoya Popović received the Outstanding Speaker Award at the ONR Workshop on Challenges for Multifunctional Digital Transmit Arrays, Marco Island, Nov. 2001.
8. Zoya Popović received the CU-Subaru Educator Spotlight Award, 2003.
9. Prof. Babbitt was awarded the Charles and Nora L. Wiley Faculty Award for Meritorious Research and Creativity, 2002.
10. Ph.D. student Randy Reibel received MSU's Graduate Achievement Award, 2003.
11. Undergraduate student Zeb Barber was nominated a Goldwater Scholar (2002) and graduated with Highest Honors (6/2003).
12. Randy Babbitt, became Director of Spectrum Lab, February 2002-present.
13. Committee chairs for Randy Babbitt: Chair of program subcommittee, Holography, Wavemixing, Photorefractives, and Storage, Conference on Lasers and Electro-Optics, Long Beach, CA, May 2002. Chair of program subcommittee, Holography, Wavemixing, Photorefractives, and Storage, Conference on Lasers and Electro-Optics, Baltimore, MD, June 2003. Co-Chair, Spectral Holeburning, Single Molecules, and Related Spectroscopies 2003, Bozeman, MT, July 2003.
14. Zoya Popović and Dana Anderson both received the prestigious Humboldt Award for Senior US Scientists from the German Alexander von Humboldt Stiftung. Zoya was the only engineer to get this award this year, and the youngest. The award supported

a 6-month stay in Germany, and the ceremonial part included a visit with the German President Herr Johannes Rau in his palace in Berlin.

15. Zoya Popovic received the ASEE Terman Award, given by Hewlett Packard for simultaneously maintaining a strong research group and developing undergraduate teaching and a textbook before age 40. Specifically, she has authored *Introductory Electromagnetics*, a textbook and student workbook for ECE juniors, published in 2000 by Prentice Hall.
16. Zoya Popovic became a Fellow of the IEEE.
17. Zoya Popovic received the Outstanding Speaker Award at the ONR Workshop on Challenges for Multifunctional Digital Transmit Arrays, Marco Island, Nov. 2001.
18. Prof. Popović gave an invited talk at MWP 2000 on optically controlled Quasi-optical antennas.

J. Vian, Z. Popović, "Optical Control of Microwave Circuits and Antennas," *Invited Talk, IEEE MWP Topical Meeting*, Oxford, UK, September 2000.
19. Friso Schlottau was awarded the best poster award at the MWP 2001 conference. Kelvin H. Wagner, Greg Kriehn, and Friso Schlottau, Wideband All-optical BEAM-TAP, IEEE Microwave Photonics meeting, Long Beach, Oct 2001 (moved to Jan 2002).
20. Randy Babbitt, Program subcommittee member, Dynamic Holography, Wavemixing, Photorefractives, and Storage, Conference on Lasers and Electro-Optics, Baltimore, Maryland, May 6-11, 2001.
21. Randy Babbitt, Chair of program subcommittee, Holography, Wavemixing, Photorefractives, and Storage, Conference on Lasers and Electro-Optics 2002.
22. Randy Babbitt, Co-organizer, Spectral Holeburning, Single Molecules, and Related Spectroscopies 2003, Bozeman, MT, July 2003.
23. "A Transmit/Receive Active Antenna with Fast Low-Power Optical Switching," J. Vian, Z. Popović, *2000 IEEE IMS Symposium Digest*, pp.847–850, Boston, MA, June

2000. Awarded the 2nd Prize in Best Student Paper Competition. The conference had over 11,000 attendees and about 160 papers competed for Best Student Paper Awards. 3d Prize was shared by Caltech and the University of Michigan.

24. Prof. Wagner is giving an invited talk at MWP 2000 on BEAMTAP in a special session on Photonic Systems for Arrays.

Gregory Kriehn, G. S. Pati, Paulo E. X. Silveira, Friso Schlottau, Kelvin H. Wagner, Daniel Dolfi and J. P. Huignard, Demonstration of optical beam forming using BEAM-TAP *Invited Talk, IEE Microwave Photonics MWP-2000*, Oxford UK, September 2000.

25. Prof. Popović is also giving an invited talk at MWP 2000 on optically controlled Quasi-optical antennas.

J. Vian, Z. Popović, "Optical Control of Microwave Circuits and Antennas," *Invited Talk, IEEE MWP Topical Meeting*, Oxford, UK, September 2000.

26. Kelvin H. Wagner, Greg R. Kriehn, Andrew J. M. Kiruluta, and Paulo E. X. Silveira, RF-Photonic adaptive-array processing, *Invited Paper at SFO Horizons d'optique*, Bordeaux, France, Sept 8 1999.

27. K. H. Wagner, K. E. Anderson, K. D. Merkel, and W. R. Babbitt "Photon Echo Adaptive Array Processor" *Invited Paper* presented at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRS'99), September 18-23, 1999, Hourtin, France.

28. RF Photonic Systems for Array Control and Processing – An overview of the RF Photonic Systems for Antenna Arrays MURI, Kelvin H. Wagner, Zoya Popović, Dana Anderson, W. R. Babbitt, L. Griffiths, A. Knoesen, R. T. Weverka, *Invited Paper, DARPA Photonic Systems for Antenna Applications Symposium, PSAA-10*, February 2000.

29. J. Vian, Z. Popović, "Optically-controlled T/R active lens array," *Invited presentation, 1999 URSI General Assembly Digest*, pp.674, Toronto, Canada, August 1999.

30. Zoya Popović was elected Senior Member of the IEEE.

31. Zoya Popović received a Humboldt Research Award from the Alexander von Humboldt Foundation, Germany.
32. OTHER: Two of the Co-PIs have a new daughter, Fiona Popović Anderson, 7 months.

2.5 MURI Publications

2.5.1 Papers published in 2003 (since 8/15/02)

1. Andrew Kiruluta, G. S. Pati, Gregory Kriehn, Paulo E. X. Silveira, Anthony W. Sarto and Kelvin Wagner, "Spatio-temporal operator formalism for holographic recording and diffraction in a photorefractive based true-time-delay phased array processor," APPLIED OPTICS 42 (26): 5334-5350 SEP 10 2003
2. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, Optoelectronic implementation of a 256-channel sonar adaptive array processor, Accepted for publication in Applied Optics, 2004.
3. D.Z. Anderson, Holographic scheme for independent component analysis, J APPLIED PHYSICS, 95 (7): 3272-3278 APR 1 2004
4. V. Damiao, D.Z. Anderson, The geometry underlying photorefractive two-beam coupling, J OPT A-PURE APPLIED OPTICS, 5 (6): S536-S549 NOV 2003.
5. E. Fotheringham, D.Z. Anderson, A miniature photorefractive circuit for principal component extraction, APPLIED OPTICS, 42 (23): 4736-4746 AUG 10 2003
6. H. Loui, J. Peeters Weem, Z. Popovic, "Dual-band dual-polarized nested Vivaldi slot array with multi-level ground plane," IEEE T ANTENNAS and PROPAGATION, 51 (9): 2168-2175 SEP 2003
7. Merkel KD, Mohan RK, Cole Z, et al. Multi-gigahertz radar range processing of baseband and RF carrier modulated signals in Tm : YAG J LUMIN 107 (1-4): 62-74 MAY 2004
8. Reibel RR, Barber ZW, Fischer JA, et al. Broadband demonstrations of true-time delay using linear sideband chirped programming and optical coherent transients J LUMIN 107 (1-4): 103-113 MAY 2004

9. Neifeld MA, Babbitt WR, Mohan RK, et al. Power budget analysis of image-plane storage in spectral hole-burning materials J LUMIN 107 (1-4): 114-121 MAY 2004
10. Chang TJ, Tian MZ, Babbitt WR Numerical modeling of optical coherent transient processes with complex configurations - I. Angled beam geometry J LUMIN 107 (1-4): 129-137 MAY 2004
11. Chang TJ, Tian MZ, Barber ZW, et al. Numerical modeling of optical coherent transient processes with complex configurations - II. Angled beams with arbitrary phase modulations J LUMIN 107 (1-4): 138-145 MAY 2004
12. Tian MZ, Barber ZW, Fischer JA, et al. The geometric phase in two-level atomic systems J LUMIN 107 (1-4): 155-159 MAY 2004
13. Burr GW, Harris TL, Babbitt WR, et al. Incorporating excitation-induced dephasing into the Maxwell-Bloch numerical modeling of photon echoes J LUMIN 107 (1-4): 314-331 MAY 2004
14. Harris TL, Tian MZ, Babbitt WR, et al. Chirped excitation of optically dense inhomogeneously broadened media using Eu³⁺: Y₂SiO₅ J OPT SOC AM B 21 (4): 811-819 APR 2004
15. Tian MZ, Reibel RR, Barber ZW, et al. Observation of the geometric phase using photon echoes PHYS REV A 67 (1): Art. No. 011403 JAN 2003
16. Cole Z, Bottger T, Mohan RK, et al. Coherent integration of 0.5 GHz spectral holograms at 1536 nm using dynamic biphasic codes APPL PHYS LETT 81 (19): 3525-3527 NOV 4 2002
17. J. Campbell, A. Knoesen and D. R. Yankelevich, "Measurement of the modulation efficiency of an optical phase-modulator using a self-homodyne receiver," IEEE Phot. Tech. Letters, vol. 14, no. 9, pp. 1330-1332, 2002.

2.5.2 Papers published in 2002 (since 8/15/01)

1. Andrew Kiruluta, G. S. Pati, Gregory Kriehn, Paulo E. X. Silveira, Anthony W. Sarto and Kelvin Wagner, "Spatio-temporal operator formalism for holographic recording and diffraction in a photorefractive based true-time-delay phased array processor," accepted for publication in Applied Optics, Sept. 2003.

2. J. Shamir and K. Wagner, "Generalized Bragg selectivity in volume holography," *Applied Optics* 41(32), pp. 6773-6785, Nov. 2002.
3. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, "Optical Finite Impulse Response Neural Networks," *Applied Optics*, vol. 41, no. 20, pp. 4162-4180, 2002.
4. Steve Blair and Kelvin Wagner, Gated Logic with Optical Solitons, in "Collision-Based Computing", ed by Andrew Adamatzky, Springer-Verlag, UK, to be published in 2002.
5. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner "Optoelectronic implementation of a 256-channel sonar adaptive array processor," to be submitted to *Applied Optics*, 2003.
6. D. Z. Anderson, V. Damiao, D. Popovic, Z. Popovic, S. Romisch, A. Sullivan, "-70dB optical carrier suppression by two-beam coupling in photorefractive media," *Applied Physics B*, 72, pp. 743-748, 2001
7. E. Fotheringham, S. Romisch, P. Smith, D. Popovic, D. Anderson and Z. Popovic, "A lens antenna array with adaptive optical processing," *IEEE Trans. Antennas and Propagation*, Special Issue on Wireless Communications, vol. 50, no. 5, pp. 607-617, May 2002.
8. H. Loui, J. Peeters Weem, Z. Popovic, "Dual-band dual-polarized nested Vivaldi slot array with multi-level ground plane," to appear in *IEEE Trans. on Antennas and Propagation*, 2003.
9. J. Peeters Weem, Z. Popovic, "Noise coupling in active phased array antennas," to be submitted to the *IEEE Trans. on Microwave Theory and Techniques*.
10. P. Smith, E. Fotheringham, Z. Popovic, D. Anderson, "An optoelectronic implementation of independent component analysis," to be submitted to *IEEE Trans. on Circuits and Systems*, August 2003.
11. R. Reibel, Z. Barber, M. Tian, and W. R. Babbitt, "High bandwidth spectral grating programmed with linear frequency chirps," *J. Lumin.* 98, 355-365 (2002).
12. Z. Barber, M. Tian, R. Reibel, and W. R. Babbitt, "Optical pulse shaping using optical coherent transients," *Opt. Exp.* 10, 1145-1150 (2002)

13. R. Reibel, Z. Barber, M. Tian, W.R. Babbitt, Z. Cole, and K.D. Merkel, "Amplification of high bandwidth phase modulated signals at 793nm," *J. Opt. Soc. Am. B.* 19, pp. 2315 (2002).
14. R. Reibel, Z. Barber, J. Fischer, M. Tian, and W. R. Babbitt, "High Bandwidth Linear Sideband Chirped Programming for Optical Coherent Transients," to be published in 2003.
15. J. Campbell, A. Knoesen and D. R. Yankelevich, "Measurement of the modulation efficiency of an optical phase-modulator using a self-homodyne receiver," *IEEE Phot. Tech. Letters*, vol. 14, no. 9, pp. 1130–1132, 2002.

2.5.3 Papers published in 2001 (since 8/15/00)

1. M.Z. Tian, R. Reibel, and W. R. Babbitt, Demonstration of optical coherent transient true-time delay at 4 Gbits/s *Optics Letters*, 26 (15): 1143-1145, Aug 1 2001 .
2. M. Tian, J. Zhao, Z. Cole, R. Reibel, and W. R. Babbitt, Dynamics of Broadband Accumulated Spectral Gratings in Tm³⁺: YAG, *JOSA B* 18, 673-8 (2001).
3. C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang, Demonstration of highly efficient photon echoes," *Optics Letters* 25, 1276-8 (2000). (Related work funded by AFOSR)
4. K. D. Merkel, R. D. Peters, P. B. Sellin, K. S. Repasky and W. R. Babbitt, Accumulated programming of a complex spectral grating, *Optics Letters*, 25 (22): 1627-1629 Nov 15 2000.
5. R. Reibel, Z. Barber, M. Tian and W. R. Babbitt, Temporally overlapped linear frequency chirped programming for true-time delay amplification," submitted to *Opt. Lett.*
6. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, Optical FIR Neural Networks, accepted for publication *Applied Optics*, 20002
7. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, Experimental demonstration of an optoelectronic sonar adaptive array, to be submitted to *Applied Optics*, December 2001.
8. D.Z. Anderson, V. Damaio, D. Popović, Z. Popović, S. Romanish, and A. Sullivan, Optical Carrier Suppression by two-beam coupling in a photorefractive medium,

9. D.Z. Anderson, V. Damaio, E. Fotheringham, D. Popović, Z. Popović, S. Romanish, and A. Sullivan, Optically Smart Active Antenna Array,
10. D.Z. Anderson, V. Damaio, E. Fotheringham, “Photorefractive two-beam coupling modules”, Applied Optics.
11. Damiao VB, Manuzak DL, Bickel WS, et al. Two-beam coupling modules for photorefractive optical circuits Applied Optics, 40 (20): 3365-3370 JUL 10 2001
12. Damiao VB, Fotheringham E, Shkunov V, et al. Photorefractive BaTiO₃ spheres and spherical disks Optics Letters, 26 (9): 611-613 MAY 1 2001
13. Anderson D, Damiao V, Popovic D, et al. -70 dB optical carrier suppression by two-beam coupling in photorefractive media, Applied Physics B, 72, pp. 743-748, 2001.
14. E. Fotheringham, S. Romisch, P. Smith, D. Popovic, D. Anderson, Z. Popovic, A lens antenna array with adaptive optical processing, Submitted to the special issue of IEEE Trans. on Antennas and Propagation on Wireless Communications: (July 2001)
15. T J. Vian, Z. Popović, A transmit/receive active antenna with fast low-power optical switching, *IEEE Trans. on Microwave Theory and Techniques Vol 48, No. 12*, pp 2686-2691, Dec. 2000
16. LM Wu , A Knoesen Absolute absorption measurements of polymer films for optical waveguide applications by photothermal deflection spectroscopy J Polymer science pol phys, 39 (22): 2717-2726 NOV 15 2001
17. E Mao, D.R. Yankelevich, C.-C Lin, et al. Narrow-band light emission in semiconductor-fibre asymmetric waveguide coupler Electronics Letters, 36 (16): 1378-1379 AUG 3 2000
18. C_l Arft, D.R. Yankelevich, A. Knoesen, E. Mao, J. S. Harris, “In-Line Fiber Evanescent Field Electro-optic Modulators,” Journal of Nonlinear Optical Physics and Materials, Vol. 9, No. 1, 2000, p. 79-94.
19. E. Mao, D.R. Yankelevich, C.-C. Lin, O. Solgaard, A. Knoesen, J.S. Harris Jr., “Narrow-band light emission in semiconductor-fibre asymmetric waveguide coupler”, Electronics Letters, vol.36, No.16, IEE, 2000, p. 1378-9.

2.5.4 Papers published in 2000 (since 8/15/99)

1. K.D. Merkel and W. R. Babbitt, "Optical coherent transient continuously programmed continuous processor," *Optics Letters*, 24, 172-174 (1999).
2. K. D. Merkel, Z. Cole, and W. R. Babbitt, "Signal correlator with programmable variable time delay based on optical coherent transients," *J. of Luminescence*, 86 375-382 (2000).
3. K. D. Merkel, R. D. Peters, P. B. Sellin, K. S. Repasky and W. R. Babbitt, "Accumulated programming of a complex spectral grating," accepted for publication in *Optics Letters*.
4. M. Tian, J. Zhao, Z. Cole, R. Reibel, and W. R. Babbitt, "Dynamics of Broadband Accumulated Spectral Gratings in Tm³⁺: YAG," submitted to *JOSA B*.
5. K.D. Merkel, W.R. Babbitt, K.E. Anderson, and K.H. Wagner, "Variable-time delay optical coherent transient signal processing," *Optics Letters*, 24, 1386-8 (1999). (related paper funded by DEPCOR or AFOSR)
6. T.L. Harris, Y. Sun, W.R. Babbitt, R.L. Cone, J.A. Ritcey, and R.W. Equall, "Spatial spectral holographic correlator at 1536nm using 30-symbol quadriphase and binary-phase-shift keyed codes," *Optics Letters*, 25, 85-7 (2000). (related paper funded by DEPCOR or AFOSR)
7. K. D. Merkel and W. R. Babbitt, "Continuous waveform variable true-time delay by optical coherent transients," *Optics Comm.* 180, 103-110 (2000). (related paper funded by DEPCOR or AFOSR)
8. C. Sjaarda Cornish, L. Tsang, and W. R. Babbitt, "Demonstration of highly efficient photon echoes in an absorbing medium," accepted for publication in *Optics Letters*. (related paper funded by DEPCOR or AFOSR)
9. Gregory Kriehn, Andrew Kiruluta, Paulo E. X. Silveira, Sam Weaver, Shawn Kraut, Kelvin Wagner, R. Ted Weverka, and Lloyd Griffiths, "Optical BEAMTAP beam-forming and jammer nulling system for phased-array antennas", *Applied Optics*, vol 39(2), pp 212-230, Jan 10, 2000.
10. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, *Optical FIR Neural Networks*, to be submitted to *Applied Optics*, October 2000.

11. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, Experimental demonstration of an optoelectronic sonar adaptive array, to be submitted to Applied Optics, November 2000.
12. D. Z. Anderson and R.W. Brockett and N. Nuttall, Information dynamics of photorefractive two-beam coupling, Phys. Rev. Lett., 82 no. 7, 1418-21, 1999.
13. V. Damaio, E. Fotheringham, L. Czaia, V. Shkunov and D.Z. Anderson, Photorefractive Crystal Spheres and Disks, in preparation.
14. D.Z. Anderson, V. Damaio, D. Popović, Z. Popović, S. Romanish, and A. Sullivan, Optical Carrier Suppression by two-beam coupling in a photorefractive medium, in preparation.
15. D.Z. Anderson, V. Damaio, E. Fotheringham, D. Popović, Z. Popović, S. Romanish, and A. Sullivan, Optically Smart Active Antenna Array, in preparation.
16. D.Z. Anderson, V. Damaio, E. Fotheringham, "Photorefractive two-beam coupling modules", submitted to Applied Optics.
17. Arft, C.; Yankelevich; D. R., Knoesen, A.; Mao, E.; Harris, J. S.; "In-Line Fiber Evanescent Field Electro-optic Modulators," Journal of Nonlinear Optical Physics and Materials, Vol. 9, No. 1, 2000, p. 79-94.
18. Mao, E.; Yankelevich, D. R.; Lin, C.-C.; Solgaard, O.; Knoesen A.; Harris, J.S. Jr.; "Wavelength-selective semiconductor in-line fiber photodetectors," Electronics Letters, vol.36, No.6, IEE, 2000. p. 515-16.
19. Mao, E.; Yankelevich, D. R.; Lin, C.-C.; Solgaard, O.; Knoesen A.; Harris, J.S. Jr.; "Narrow-band light emission in semiconductor-fibre asymmetric waveguide coupler", Electronics Letters, vol.36, No.16, IEE, 2000, p. 1378-9.

2.5.5 Papers published in 1999

1. K.D. Merkel and W. R. Babbitt, "Optical coherent transient continuously programmed continuous processor," Optics Letters, 24, 172-174 (1999). [MURI/AFOSR]
2. W.R. Babbitt and T. W. Mossberg, "Optical waveform processing and routing with structured surface gratings," Optics Comm. 148, 23-26 (1998). [AFOSR]

3. M. Azadeh, C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang , "Efficient photon echoes in optically thick media," *Physical Review A* 57, 4662-8 (1998). [AFOSR]
4. Gregory Kriehn, Andrew Kiruluta, Paulo E. X. Silveira, Sam Weaver, Shawn Kraut, Kelvin Wagner, R. Ted Weverka, and Lloyd Griffiths, "Optical BEAMTAP Beamforming and Jammer Nulling System for Phased Array Antennas", to be published *Applied Optics*, Jan 10, 2000.
5. Z.Popovic, "T/R lens amplifier antenna arrays for X-band and Ka-band," Invited Cover Article, *Applied Microwave and Wireless*, February 1999, pp. 30-46.
6. P. M. Techau, J. R. Guerci, T. H. Slocumb, and L. J. Griffiths, "Performance Bounds for Interference Mitigation in Radar Systems," *IEEE Trans. on Aerospace Electronic Systems*, 1999.
7. Hamilton, S. A.; Yankelevich, D. R.; Knoesen, A.; Weverka, R. T.; Hill, R.A. and Bjorklund, G.C.; "Polymer in-line fiber modulators for broadband radio-frequency optical links," *Journal of the Optical Society of America B (Optical Physics)*, vol.15, no.2, Opt. Soc. America, 1998. p.740-50
8. Hamilton, S. A.; Yankelevich, D. R.; Knoesen, A.; Weverka, R. T. and Hill, R. A.; "Comparison Of An In-Line Asymmetric Directional Coupler Modulator With Distributed Optical Loss To Other Linearized Electro-Optic Modulators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, 1999, p. 1184-1193.
9. Arft, C.; Yankelevich; D. R., Knoesen, A.; Mao, E.; Harris, J. S.; "In-Line Fiber Evanescent Field Electro-optic Modulators," submitted to: *J. Nonlinear Optical Physics and Materials*, October 1999.

2.5.6 Conference Presentations during 2003 (since 8/15/02)

1. Max Colice and Kelvin Wagner, Phase-cohering holography for coherent analog optical signal processing, GOMAC 03, Tampa Fl, Apr 1 2003. K. H. Wagner, M. Colice, G. Kriehn F. Schlottau and R. T. Weverka, Photonic Multiple Beam Forming for Broadband RF Antenna Arrays, GOMAC 03, Tampa Fl, Apr 2 2003.

2. W. R. Babbitt, K. D. Merkel, M. Tian, R. Krishna Mohan, Z. Cole, Y. Sun, Rufus R. L. Cone, K. H. Wagner, and R. W. Equall, Optical-Coherent-Transient technologies for wide-bandwidth and multidimensional analog signal processing, GOMAC 03, Tampa FL, Apr 3 2003.
3. K. H. Wagner, F. Schlottau, M. Colice, G. Kriehn, and R. T. Weverka, Photonic Multiple Beam Forming Systems for Broadband RF Antenna Arrays, IEEE MWP 2003 (Microwave Photonics), Budapest, Sept 2003.
4. F. Schlottau, K.H. Wagner, J. Bregman, and J.L. Le Gouet, Sparse Antenna Array Multiple Beamforming and Spectral Analysis using Spatial-Spectral Holography, IEEE MWP 2003 (Microwave Photonics), Budapest, Hungary, September 2003.
5. K. Wagner, F. Schlottau, Jaap Bregman, Jean-Louis Le Gouet, Spatial-Spectral Holography for RF Antenna Array Multi-Beam Imaging, Invited talk at Hole Burning and Single Molecule Spectroscopies, Bozeman, MT, July 2003.
6. G. Kriehn, K. Wagner, and M. Colice, Photorefractive Phased-Array Signal Processor, PR03 (Photorefractive topical meeting), Nice France, June 2003.
7. P. Smith, E. Fotheringham, D. Anderson, Z. Popović, "Adaptive signal processing for microwave carrier broadband signals," 2003 GOMAC conference digest, Tampa, FL, April 2003.
8. D. Z. Anderson, M. Baylor, E. Fotheringham, Z. Popovic, P. C. Smith, Cocktail party dynamics and independent component analysis, PR03 (Photorefractive topical meeting), Nice France, June 2003.
9. H. Ye, O. Nilsen, V. Bright, D.Z. Anderson, A real time handheld olfactory sensor, PR03 (Photorefractive topical meeting), Nice France, June 2003.

2.5.7 Conference Presentations during 2002 (since 8/15/01)

1. G. Kriehn and K. Wagner, "Experimental Demonstration of Adaptive Phased-Array Signal Processing," (poster) *Colorado Photonics Industry Association*, November 2002.
2. G. Kriehn, F. Schlottau, and K. Wagner, "Optically-Implemented 2-D Beam Steering and Jammer Nulling using BEAMTAP," *Optical Computing*, April 2002.

3. G. Kriehn, F. Schlottau, G. S. Pati, and K. Wagner, "Demonstration of RF Photonic Beam Forming using the BEAMTAP Algorithm," *General Electric Meeting*, November 2001.
4. G. Kriehn and K. Wagner, "Experimental Adaptive Beam Forming with Polarization Read-Write Multiplexing using BEAMTAP," (poster) In *The International Topical Meeting on Microwave Photonics*, IEEE, Jan. 2002.
5. G. Kriehn, "Optical Phased Array Signal Processing," (poster) *Colorado Photonics Industry Association*, November 2001.
6. G. Kriehn and K. Wagner, "Experimental Adaptive Beam Forming with Polarization Read-Write Multiplexing using BEAMTAP," *The International Topical Meeting on Microwave Photonics MWP 2001*, January, 2002.
7. Balakishore Yellampalle, Kelvin Wagner, and Steve Blair, "Anti-guide assisted spatial soliton logic gate," *OSA topical meeting on Non-linear Optical Guided Waves*, Como, Italy, Sept. 2002.
8. Kelvin Wagner, Friso Schlottau, and Jaap Bregman, "Array imaging using spatial-spectral holography," *IOG Information Optics meeting*, Mannheim, Germany, Sept. 2002.
9. Alexandre R. S. Romariz and Kelvin Wagner, "Optoelectronic implementation of a FitzHugh-Nagumo neural model," *Neural Information Processing System (NIPS)*, Vancouver, CA, Dec. 2002.
10. Max Colice and Kelvin Wagner, "Phase-cohering holography for coherent analog optical signal processing," *GOMAC 03*, Tampa FL, Apr. 2003.
11. K. H. Wagner, M. Colice, G. Kriehn, F. Schlottau, and R. T. Weverka, "Photonics Multiple Beam Forming for Broadband RF Antenna Arrays," *GOMAC 03*, Tampa, FL, Apr. 2003.
12. W. R. Babbit, K. D. Merkel, M. Tian, R. Krishna Mohan, Z. Cole, Y. Sun, Rufus R. L. Cone, K. H. Wagner, and R. W. Equall, "Optical-Coherent-Transient technologies for wide-bandwidth and multidimensional analog signal processing," *GOMAC 03*, Tampa, FL, Apr. 2003.

13. Kelvin H. Wagner, Zoya Popovic, Dana Z. Anderson, Randall W. Babbitt, Lloyd Griffiths, Andre Knoesen, "RF Photonic Systems for Array Control and Processing," Invited MURI overview at GOMAC, Monterey CA, March 2002
14. F. Schlottau and K. Wagner, "RF Photonics for Simultaneous Multiple TTD Beamforming for 2-D Antenna Arrays," The International Topical Meeting on Microwave Photonics MWP 2001, January 2002.
15. K. Wagner, Greg Kriehn, Friso Schlottau, Wideband All-optical BEAMTAP, The International Topical Meeting on Microwave Photonics MWP 2001, January 2002.
16. G. Kriehn, F. Schlottau, and K. Wagner, "Optically-Implemented 2-D Beam Steering and Jammer Nulling using BEAMTAP," submitted to ICO Topical Meeting on *Optics in Computing*, SPIE, April 2002.
17. Kelvin H. Wagner, Friso Schlottau, and Jaap Bregman, Array Imaging Using Spatial-Spectral Holography, submitted to ICO Topical Meeting on *Optics in Computing*, SPIE, April 2002.
18. J.A. Hagerty, Z. Popović, Passive Millimeter-Wave Ranging using Discrete Lenses with Wave-Front Coding, *2001 European Microwave Conference Digest*, pp.421-424, London, Sept. 2001.
19. J. Vian, Z. Popović, "Smart lens antenna arrays," 2001 IEEE International Microwave Symposium Digest, pp.129-132, Phoenix, Arizona, 2001.
20. D. Anderson, E. Fotheringham, S. Romisch, P. Smith, Z. Popović, "Smart antenna arrays with adaptive optical processing," *IEEE Trans. Antennas and Propagation*, Special Issue on Wireless Communications, pp. 607-617, May 2002.
21. P. Smith, E. Fotheringham, D. Anderson, Z. Popović, "Adaptive signal processing for microwave carrier broadband signals," 2003 GOMAC conference digest, Tampa, FL, April 2003.
22. R. Reibel, Z. Barber, M. Tian, W. R. Babbitt, "Temporally Overlapped Linear Frequency Chirp Programming for True Time Delay Applications," poster, Holeburning, Single Molecules, and Related Spectroscopies, November 18-23, 2001, Taipei, Taiwan.
23. M. Tian, R. Reibel, Z. Barber, W. R. Babbitt, "Broadband true-time delay in Tm:YAG," poster, Holeburning, Single Molecules, and Related Spectroscopies, November 18-23,

2001, Taipei, Taiwan.

24. M. Tian, R. Reibel, Wm. R. Babbitt, "Demonstration of broadband true-time delay with optical coherent transient," MWP'2001, January 2002, Long beach, CA.
25. M. Tian, Z. Barber, T. Chang, R. R. Reibel, and W. R. Babbitt* (* Invited Speaker), "The Effects of Optical Nutation on Stimulated Photon Echoes," Holeburning, Single Molecules, and Related Spectroscopies, November 18-23, 2001, Taipei, Taiwan. (Related work funded by AFOSR)
26. M. Tian*, R. R. Reibel, Z. Barber, J. Fischer, W. R. Babbitt (* Invited speaker), "Optical Coherent Transient True-time delay: Broadband programming methods," 2002 Physics of Quantum Electronics Conference, Snowbird, UT, January 2002.
27. Joe Fischer, Zeb Barber, Randy Reibel, Mingzhen Tian, and Randy Babbitt, "Linear Phase Chirp Programming for OCT's," Optec2001, (Bozeman, MT, August, 2001)
28. M. Tian, R. R. Reibel, Z. Barber, J. Fischer, and W. R. Babbitt, "Optical Coherent Transient True-Time Delay Generator Programmed with Linear Phase Chirp," in Conference on Lasers and Electro-Optics, Technical Digest (Optical Society of America, Washington DC, 2002), May 2002, Long Beach, CA.

2.5.8 Conference Presentations during 2001 (since 8/15/00)

1. Gregory Kriehn, Paulo E. X. Silveira, G. S. Pati, Friso Schlottau and Kelvin H. Wagner, "BEAMTAP RF-photonic adaptive-array processing", Interactions between Microwaves and Optics summer school, Autrans France, August 2000. [MURI]
2. Gregory Kriehn, G. S. Pati, Paulo E. X. Silveira, Friso Schlottau, Kelvin H. Wagner, Daniel Dolfi and J. P. Huignard, "Demonstration of optical beam forming using BEAMTAP", *Invited Talk, IEE Microwave Photonics MWP-2000*, Oxford UK, September 2000. [MURI]
3. G. Kriehn, F. Schlottau, G. S. Pati, and K. Wagner, "Demonstration of RF Photonic Beam Forming using the BEAMTAP Algorithm," OSA Topical Meeting on *Optical Computing*, January 2001.
4. G. Kriehn and K. Wagner, "Experimental Adaptive Beam Forming with Polarization Read-Write Multiplexing using BEAMTAP," The International Topical Meeting on

Microwave Photonics MWP 2001, January, 2002.

5. F. Schlottau and K. Wagner, "RF Photonics for Simultaneous Multiple TTD Beamforming for 2-D Antenna Arrays," The International Topical Meeting on Microwave Photonics MWP 2001, January 2002.
6. K. Wagner, Greg Kriehn, Friso Schlottau, Wideband All-optical BEAMTAP, The International Topical Meeting on Microwave Photonics MWP 2001, January 2002.
7. Ken E. Anderson and Kelvin H. Wagner, Demonstration of Chromatic Dispersion Compensation Using Spectral Holography, Persistent Spectral Hole Burning 2001, Taiwan, 2001.
8. G. Kriehn, F. Schlottau, and K. Wagner, "Optically-Implemented 2-D Beam Steering and Jammer Nulling using BEAMTAP," submitted to ICO Topical Meeting on *Optics in Computing*, SPIE, April 2002.
9. Kelvin H. Wagner, Friso Schlottau, and Jaap Bregman, Array Imaging Using Spatial-Spectral Holography, submitted to ICO Topical Meeting on *Optics in Computing*, SPIE, April 2002.
10. J. Vian, Z. Popović, "Optical Control of Microwave Circuits and Antennas," *Invited Talk, IEEE MWP Topical Meeting*, Oxford, UK, September 2000.
11. T J. Vian, Z. Popović, Smart lens antenna arrays, *2001 IEEE International Microwave Symposium Digest*, pp.129-132, Phoenix, Arizona, May 2001.
12. J.A. Hagerty, Z. Popović, Passive Millimeter-Wave Ranging using Discrete Lenses with Wave-Front Coding, *2001 European Microwave Conference Digest*, pp.421-424, London, Sept. 2001.
13. T J. Peeters Weem, Z. Popovic, A method for determining noise coupling in a phased array antenna, *2001 IEEE International Microwave Symposium Digest*, pp.271-274, Phoenix, Arizona, May 2001.
14. Z. Barber, R. Reibel, and W. R. Babbitt, "Applications of Binary Phase Shift Keying for Inhomogeneously Broadened Materials" *Optical Science and Laser Technology Conference*, Bozeman, Montana, August 14-16, 2000, poster.

15. K. Merkel, P. B Sellin, R. D. Peters, K. S. Repasky and W. R. Babbitt, "Accumulated Complex Spectral Gratings Using a Frequency Stabilized Laser," Optical Science and Laser Technology Conference, Bozeman, Montana, August 14-16, 2000.
16. M. Tian, R. Reibel, and W. R. Babbitt, "GHz Band True Time Delay and Auto-Correlation Via Accumulated Picosecond Photon Echo Process" Optical Science and Laser Technology Conference, Bozeman, Montana, August 14-16, 2000.
17. M. Tian, R. Reibel, and W.R. Babbitt, "Broadband true-time-delay with optical coherent transients," in Conference on Lasers and Electro-Optics, Technical Digest (Optical Society of America, Washington DC, 2001), May 2001, Baltimore, MD.
18. N. L. Seldomridge, R. Krishna Mohan, W. R. Babbitt and K. D. Merkel, "Steady-state accumulated complex spectral gratings for correlation signal processing" in Conference on Lasers and Electro-Optics, Technical Digest (Optical Society of America, Washington DC, 2001), May 2001, Baltimore, MD. (Related work funded by NASA and MURI)
19. R. Reibel, Z. Barber, M. Tian, W. R. Babbitt, "Temporally Overlapped Linear Frequency Chirp Programming for True Time Delay Applications," poster, Holeburning, Single Molecules, and Related Spectroscopies, November 18-23, 2001, Taipei, Taiwan.
20. M. Tian, R. Reibel, Z. Barber, W. R. Babbitt, "Broadband true-time delay in Tm:YAG," poster, Holeburning, Single Molecules, and Related Spectroscopies, November 18-23, 2001, Taipei, Taiwan.
21. M. Tian, R. Reibel, Wm. R. Babbitt," Demonstration of broadband true-time delay with optical coherent transient," MWP'2001, January 2002, Long beach, CA.
22. W. R. Babbitt, "Optical Coherent Transient Signal Correlators: Science and Applications", 2001 Physics of Quantum Electronics Conference, Snowbird, UT , January 2001.
23. M. Tian, Z. Barber, T. Chang, R. R. Reibel, and W. R. Babbitt F (F Invited Speaker), "The Effects of Optical Nutation on Stimulated Photon Echoes," Holeburning, Single Molecules, and Related Spectroscopies, November 18-23, 2001, Taipei, Taiwan. (Related work funded by AFOSR)

24. Z. Barber, R. Reibel, M. Tian, W. R. Babbitt, "Application of Phase Modulated Optical Signals to Inhomogeneously Broadened Materials," poster, American Physical Society Annual Meeting, March 11, 2001, Seattle, WA.
25. R. Reibel, Z. Barber and W. R. Babbitt, "Amplification of High Bandwidth Phase Modulated Signals at 793 nm," American Physical Society Annual Meeting, March 2001, Seattle, WA.
26. M. Tian, R. Reibel, and Wm. R. Babbitt, "Multi-gigahertz true-time-delay with optical coherent transient," American Physical Society Annual Meeting, March 2001, Seattle, WA.
27. Joe Fischer, Zeb Barber, Randy Reibel, Mingzhen Tian, and Randy Babbitt, "Linear Phase Chirp Programming for OCT's," Optec2001, (Bozeman, MT, August, 2001)

2.5.9 Conference Presentations during 2000 (since 8/15/99)

1. Kelvin H. Wagner, Greg R. Kriehn, Andrew J. M. Kiruluta, and Paulo E. X. Silveira, "RF-Photonic adaptive-array processing", *Invited Paper* at SFO Horizons d'optique, Bordeaux, France, Sept 8 1999. [MURI]
2. K. H. Wagner, K. E. Anderson, K. D. Merkel, and W. R. Babbitt "Photon Echo Adaptive Array Processor" *Invited Paper* presented at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRS'99), September 18-23, 1999, Hourtin, France. [MURI]
3. K. Anderson and K. Wagner, "High bandwidth multiple channel communications using multimode fiber spatial spectral holographic dispersion compensation", paper TuH2, OSA annual meeting, Santa Clara Sept 28 1999. [DEPSCOR]
4. K. Wagner, A. Kiruluta, G. Kriehn, P. E.X. Silveira, S. Weaver, D. Dolfi, "Photorefractive-based true-time-delay beamforming using a traveling fringes detector", paper TuT3, OSA annual meeting, Santa Clara Sept 28 1999. [MURI]
5. Kelvin H. Wagner, Gregory Kriehn and Paulo E. X. Silveira, "RF-Photonic Adaptive array processing", Proc. of the National Radio Science Meeting (URSI), p 238, Boulder CO, January 2000. [MURI]

6. RF Photonic Systems for Array Control and Processing – An overview of the RF Photonic Systems for Antenna Arrays MURI, Kelvin H. Wagner, Zoya Popović, Dana Anderson, R.W. Babbitt, L. Griffiths, A. Knoesen, R. T. Weverka, *Invited Paper*, DARPA Photonic Systems for Antenna Applications Symposium, PSAA-10, February 2000.
7. Kelvin H. Wagner, Gregory Kriehn and Paulo E. X. Silveira, “Experimental demonstration of broadband adaptive beam forming using the BEAMTAP algorithm”, DARPA Photonic Systems for Antenna Applications Symposium, PSAA-10, February 2000. [MURI]
8. Paulo E. X. Silveira, G. S. Pati and Kelvin H. Wagner, “Optical implementation of a single-layer finite impulse response neural network”, Proc. Int. Conf. on Optics in Computing, SPIE vol. 4089, pp 656-667 Quebec City, June 2000. [MURI]
9. Gregory Kriehn, Paulo E. X. Silveira, G. S. Pati, Friso Schlottau and Kelvin H. Wagner, “BEAMTAP RF-photonic adaptive-array processing”, Interactions between Microwaves and Optics summer school, Autrans France, August 2000. [MURI]
10. Gregory Kriehn, G. S. Pati, Paulo E. X. Silveira, Friso Schlottau, Kelvin H. Wagner, Daniel Dolfi and J. P. Huignard, “Demonstration of optical beam forming using BEAMTAP”, *Invited Talk*, IEE Microwave Photonics MWP-2000, Oxford UK, September 2000. [MURI]
11. J. Vian, Z. Popović, “Optically-controlled T/R active lens array,” *Invited presentation*, 1999 URSI General Assembly Digest, pp.674, Toronto, Canada, August 1999. [MURI]
12. P. Kirkpatrick, Z. Popović, “An X-band dielectric resonator electro-optic modulator,” presented at the 2000 National URSI Meeting, Boulder, Colorado, January 2000. [MURI]
13. J. Vian, Z. Popović, “A Transmit/Receive Active Antenna with Fast Low-Power Optical Switching,” 2000 IEEE MTT-S International Microwave Symposium, pp.847–850, Boston, June 2000. (Awarded the 2nd prize in Best Student Paper Competition.) [MURI]
14. D. Anderson, V. Damiao, E. Fotheringham, D. Popović, S. Romisch, Z. Popović, “Optically Smart Active Antennas,” 2000 IEEE MTT-S International Microwave Sympo-

- sium, pp.843–846, Boston, June 2000.
15. J. Vian, Z. Popović, “Optical Control of Microwave Circuits and Antennas,” *Invited Talk, IEEE MWP Topical Meeting, Oxford, UK, September 2000.*
 16. M. Tian, Z. Cole, K. D. Merkel, J. Zhao, and W. R. Babbitt “Accumulated Photon Echoes in a Tm³⁺:YAG Crystal by picosecond pulses,” poster presentation at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRIS’99), September 18-23, 1999, Hourtin, France. [MURI]
 17. K. D. Merkel, K. Repasky, and W. R. Babbitt “Demonstration of a continuously programmed optical coherent transient processor,” presented at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRIS’99), September 18-23, 1999, Hourtin, France. [MURI/AFOSR/DEPSCOR]
 18. K. D. Merkel, P. B. Sellin, R. D. Peters, K. S. Repasky and W. R. Babbitt, “Accumulated Complex Spectral Gratings using a Frequency Stabilized Laser,” Workshop on Applications of Spectral Hole Burning 2000, Big Sky, Montana, July 9-12, 2000.
 19. R. D. Peters, P. B. Sellin, K. S. Repasky, and W. R. Babbitt, “Frequency Stabilization of a Ti:Sapphire Laser to a Non-Persistent Spectral Hole in Tm:YAG,” Workshop on Applications of Spectral Hole Burning 2000, Big Sky, Montana, July 9-12, 2000, poster.
 20. R. Reibel, M. Tian, and W. R. Babbitt, “Optical Nutations on Three Pulse Accumulated Photon Echoes,” Workshop on Applications of Spectral Hole Burning 2000, Big Sky, Montana, July 9-12, 2000, poster.
 21. Z. Barber, R. Reibel, and W. R. Babbitt, “Applications of Binary Phase Shift Keying for Inhomogeneously Broadened Materials” Optical Science and Laser Technology Conference, Bozeman, Montana, August 14-16, 2000, poster.
 22. K. Merkel, P. B. Sellin, R. D. Peters, K. S. Repasky and W. R. Babbitt, “Accumulated Complex Spectral Gratings Using a Frequency Stabilized Laser,” Optical Science and Laser Technology Conference, Bozeman, Montana, August 14-16, 2000.
 23. M. Tian, R. Reibel, and W. R. Babbitt, “GHz Band True Time Delay and Auto-Correlation Via Accumulated Picosecond Photon Echo Process” Optical Science and Laser Technology Conference, Bozeman, Montana, August 14-16, 2000.

24. K. D. Merkel, Z. Cole, and W. R. Babbitt “Programmable variable time delay signal correlator based on six-wave mixing optical coherent transients,” poster presentation at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRS’99), Sept. 18-23, 1999, Hourtin, France. [DEPSCOR]
25. K. D. Merkel, Z. Cole, and W. R. Babbitt, “Signal correlator with programmable variable time delay based on optical coherent transients,” IEEE Lasers and Electro-Optics Society 1999 Annual Meeting, Nov. 8-11, 1999, San Francisco, CA. [DEPSCOR]
26. R. L. Cone, Y. Sun, F. Knz, N. M. Strickland, T. L. Harris, C.W. Thiel, T. Bttger, G. Reinemer, W. R. Babbitt, R. W. Equall and R. L. Hutcheson, R. M. Macfarlane, and J. A. Ritcey, “New Rare Earth Materials, Material Concepts, and Demonstrations of Spectral Hole Burning Applications,” presented at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRS’99), September 18-23, 1999, Hourtin, France. [AFOSR]
27. A. Rebane, A. Tchouassi-Djiki, and W. R. Babbitt, “Ultrafast frequency-conversion holograms by photo-induced gratings in glass,” IEEE Lasers and Electro-Optics Society 1999 Annual Meeting, Nov. 8-11, 1999, San Francisco, CA. [NSF MONTS]
28. C. Sajaarda Cornish, L. Tsang, W.R. Babbitt. “Demonstration of highly efficient photon echoes in absorbing media,” in Conference on Lasers and Electro-Optics, Technical Digest (Optical Society of America, Washington DC, 2000), pp. 216-217, May 2000, San Francisco, CA.
29. C. Sajaarda Cornish, L Tsang, and W.R. Babbitt, “A study of the energy source for photon echoes” in Conference on Lasers and Electro-Optics, Technical Digest (Optical Society of America, Washington DC, 2000), p. 491, May 2000, San Francisco, CA.
30. Z. Cole, K. Merkel, and W.R. Babbitt, “Atomic coherence state phase conjugation in optical coherent transients,” in Conference on Lasers and Electro-Optics, Technical Digest (Optical Society of America, Washington DC, 2000), pp.68-69, May 2000, San Francisco, CA.
31. C. Sjaarda Cornish, W. R. Babbitt, and L. Tsang, “Experimental Demonstration of Highly Efficient Photon Echoes in an Absorbing Medium.” Workshop on Applications of Spectral Hole Burning 2000, Big Sky, Montana, July 9-12, 2000.

32. D.Z. Anderson, V. Damaio, E. Fotheringham, D. Popović, Z. Popović, S. Romanish, and A. Sullivan, "Optically Smart Active Antenna Array", MTT, Boston MA, June, 2000.

2.5.10 Conference Presentations during 1999

1. G. Kriehn, P. Silveira, K. Wagner, A. Kiruluta, S. Weaver and T. Weverka, All optical multi GHz BEAMTAP system, DARPA Photonic Systems for Antenna Applications Symposium, PSAA, February 1999. [MURI]
2. Andrew Kiruluta, Greg Kriehn, Paulo E. X. Silveira, Sam Weaver, and Kelvin H. Wagner, Operator Notation Analysis of a Photorefractive Phased Array Processor, OSA Topical meeting on Optics in Computing, Snowmass CO, April 12-16 1999. [MURI]
3. Ken E. Anderson, Kelvin H. Wagner, W.R. Babbitt, K.D. Merkel, Optical Coherent Transient True-Time-Delay Beamforming Processor, OSA Topical meeting on Optics in Computing, Snowmass CO, April 12-16 1999. [DEPSCOR]
4. Paulo E. X. Silveira and Kelvin H. Wagner, Optical Architecture for Finite Impulse Response Neural Networks, OSA Topical meeting on Optics in Computing, Snowmass CO, April 12-16 1999. [MURI]
5. J. Gamo, P. R. Horche, R. Mcleod, and K. Wagner, Dynamic Switching of an Acousto-Optic Crossbar, EOS Topical meeting on Advances in Acousto-optics 99, June 10-11, Florence, Italy.
6. K. Wagner, Applications of Photorefractives for Adaptive Optical Processing of Phased Arrays, invited presentation at the Trend in Applied Optics symposium, Osnabrueck Germany, June 25-26 1999. [MURI]
7. K. H. Wagner, G. Kriehn, P. E. X. Silveira, A. Kiruluta, and S. Weaver Photorefractive BEAMTAP RF beamforming system, presented at the Photorefractive topical meeting, held in Helsingor Denmark, June 27-30 1999. [MURI]

8. Andrew Kiruluta, Gregory Kriehn, Paulo E. X. Silveira, Sam Weaver, and Kelvin Wagner, Adaptive Beamforming with TDI CCD Based True-Time-Delay Processing Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation, Denver, CO, July 18-23, 1999, Algorithms, Devices, and Systems for Optical Information Processing II, Vol. 3804, paper 3804-06 (1999). [MURI]
9. P. E. X. Silveira, Greg Kriehn, Kelvin H. Wagner, Andrew Kiruluta, Sam Weaver, All-optical adaptive antenna array beamforming system, Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation, Denver, CO, July 18-23, 1999, Radar Processing, Technology, and Applications IV, Vol. 3810, paper 3810-03 (1999). [MURI]
10. Paulo E. X. Silveira and Kelvin H. Wagner, Optical Finite Impulse Response Neural Networks using the Time-Integrating and Space-Integrating Architectures, Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation, Denver, CO, July 18-23, 1999, Algorithms, Devices, and Systems for Optical Information Processing II, Vol. 3804, paper 3804-07 (1999). [MURI]
11. K. H. Wagner, K. Anderson, W.R. Babbitt, and K. D. Merkel, Multidimensional photon echo processing, (Invited Paper) Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation, Denver, CO, July 18-23, 1999, Algorithms, devices, and systems for optical information processing II, Vol. 3804, paper 3804-03 (1999). [DEPSCOR]
12. J. Gamo, R.R. Mcleod, K. Wagner, P. R. Horche, Rapid Reconfiguration in an acousto-optic crossbar interconnection, Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation, Denver, CO, July 18-23, 1999, Photonic Devices and Algorithms for Computing, Vol. 3805, paper 3805-02 (1999)
13. Gregory Kriehn, Andrew Kiruluta, Kelvin Wagner, Daniel Dolfi and Jean-Pierre Huignard, Detection and Time Delay of a Broadband RF Signal using a Traveling Fringes Detector, Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation,

Denver, CO, July 18-23, 1999, Terrahertz and Gigahertz Photonics Vol 3795, paper 3795-12 (1999) [MURI]

14. Kelvin H. Wagner, Greg R. Kriehn, Andrew J. M. Kiruluta, and Paulo E. X. Silveira, RF-Photonic adaptive-array processing, Invited Paper at SFO Horizons d'optique, Bordeaux, France, Sept 8 1999. [MURI]
15. K. H. Wagner, K. E. Anderson, K. D. Merkel, and W. R. Babbitt "Photon Echo Adaptive Array Processor" presented at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBR99), September 18-23, 1999, Hourtin, France. [MURI]
16. K. Anderson and K. Wagner, High bandwidth multiple channel communications using multimode fiber spatial spectral holographic dispersion compensation, paper TuH2, OSA annual meeting, Santa Clara Sept 28 1999.
17. K. Wagner, A. Kiruluta, G. Kriehn, P. E.X. Silveira, S. Weaver, D. Dolfi, Photorefractive-based true-time-delay beamforming using a travelling fringes detector, paper TuT3, OSA annual meeting, Santa Clara Sept 28 1999.
18. J. Vian, P. Kirkpatrick, Z. Popović, "An optically-controlled transmit/receive active antenna," *9-th Annual DARPA Symposium on Photonic Systems for Antenna Applications Proceedings, Session 10, PSAA-9*, Monterey, CA, February 1999. [MURI]
19. S. Stone, J. Vian, Z. Popović, "Photonicly tuned slot antennas," *9-th Annual DARPA Symposium on Photonic Systems for Antenna Applications Proceedings, Session 10, PSAA-9*, Monterey, CA, February 1999. [MURI]
20. J. Vian, Z. Popovic, "Optically-controlled T/R active lens array," *Invited presentation, 1999 URSI General Assembly Digest*, pp.674, Toronto, Canada, August 1999. [MURI]
21. P. Kirkpatrick, Z. Popovic, "An X-band dielectric resonator electro-optic modulator," *to be presented at the 2000 National URSI Meeting*, Boulder, Colorado, January 2000. [MURI]

22. J. Vian, Z. Popovic, "A Transmit/Receive Active Antenna with Fast Low-Power Optical Switching," submitted to the 2000 IEEE MTT-S International Microwave Symposium, Boston, December 1999. [MURI]
23. D. Anderson, V. Damiao, E. Fotheringham, D. Popovic, S. Romisch, Z. Popovic, "Optically Smart Active Antennas," submitted to the 2000 IEEE MTT-S International Microwave Symposium, Boston, December 1999.
24. P. M. Techau, J. R. Guerci, T. H. Slocumb, and L. J. Griffiths, "Site-specific Performance Bounds for Interference Mitigation in Airborne Radar Systems," Proc. ASAP '99, Lincoln Laboratory, March, 1999.
25. D.Z. Anderson, L.G. Czaia, V.B. Damiao, E.B Fotheringham, V.V. Shkunov, "Low-order whispering-gallery modes of a BaTiO₃ disk," Proceedings CLEO'99, , Baltimore, 1999.
26. D.Z. Anderson, L.G. Czaia, V.B. Damiao, E.B Fotheringham, V.V. Shkunov, "Photorefractive Optical Circuits" International Symposium in Trends in Applied Optics, Osnabrueck, Germany, June, 1999 (Invited Talk).
27. K. D. Merkel and W. R. Babbitt, "Optical coherent transient continuously programmed continuous true-time-delay processor", PSAA 99, Monterey CA, Feb 1999.
28. M. Tian, Z. Cole, K. D. Merkel, J. Zhao, and W. R. Babbitt "Accumulated Photon Echoes in a Tm³⁺:YAG Crystal by picosecond pulses," poster presentation at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRS'99), September 18-23, 1999, Hourtin, France. [MURI]
29. K. D. Merkel and W.R. Babbitt, " Optical coherent transient continuously programmed continuous true-time delay processor," in The Ninth Annual DARPA Symposium on Photonic Systems for Antenna Applications (PSAA) session 3. Monterey, CA, February 17-19, 1999. [MURI/AFOSR]
30. K. D. Merkel, K. Repasky, and W. R. Babbitt "Demonstration of a continuously programmed optical coherent transient processor," presented at 6th Int. Meeting of Hole

- Burning and Related Spectroscopies: Science and Applications (HBRS'99), September 18-23, 1999, Hourtin, France. [MURI/AFOSR/DEPSCOR]
31. K. D. Merkel and W. R. Babbitt, "Continuously programmed optical coherent transient continuous signal processor", 1999 Optics in Computing OSA Topical Meeting, Snowmass, CO, April 12-16, 1999. [MURI/AFOSR]
 32. K. D. Merkel, Z. Cole, and W. R. Babbitt "Programmable variable time delay signal correlator based on six-wave mixing optical coherent transients," poster presentation at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBRS'99), Sept. 18-23, 1999, Hourtin, France. [DEPSCOR]
 33. K. D. Merkel, Z. Cole, and W. R. Babbitt, "Signal correlator with programmable variable time delay based on optical coherent transients," IEEE Lasers and Electro-Optics Society 1999 Annual Meeting, Nov. 8-11, 1999, San Francisco, CA. [DEPSCOR]
 34. K. D. Merkel and W. R. Babbitt, "Frequency-tuned continuous true-time delay by optical coherent transient technology," in Conference on Lasers and Electro-Optics, 1999 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1999) pp 171. Baltimore, MD, May 24-28, 1999. [DEPSCOR]
 35. T. L. Harris, Y. Sun, R.L. Cone, W.R. Babbitt, J. A. Ritcey, and R. W. Equall, "A spatial-spectral holographic correlator at 1536 nm using 30-symbol BPSK and QPSK codes optimized for secure communications," in Conference on Lasers and Electro-Optics, 1999 OSA Technical Digest Series (OSA, Washington, DC, 1999) pp 282. Baltimore, MD, May 24-28, 1999. [AFOSR]
 36. T. L. Harris, Y. Sun, R.L. Cone, W.R. Babbitt, J. A. Ritcey, and R. W. Equall, "A spatial-spectral holographic correlator at 1536 nm using 30-symbol BPSK and QPSK codes optimized for secure communications," 1999 Optics in Computing OSA Topical Meeting, Snowmass, CO, April 12-16, 1999. [AFOSR]
 37. R. L. Cone, Y. Sun, F. Knz, N. M. Strickland, T. L. Harris, C.W. Thiel, T. Bttger, G. Reinemer, W. R. Babbitt, R. W. Equall and R. L. Hutcheson, R. M. Macfarlane, and

- J. A. Ritcey, "New Rare Earth Materials, Material Concepts, and Demonstrations of Spectral Hole Burning Applications," presented at 6th Int. Meeting of Hole Burning and Related Spectroscopies: Science and Applications (HBR'S'99), September 18-23, 1999, Hourtin, France. [AFOSR]
38. M. Azadeh, R. B. Darling and W.R. Babbitt, "Smart pixel sensor arrays based on optoelectric feedback," in Conference on Lasers and Electro-Optics, 1999 OSA Technical Digest Series (Optical Society of America, Washington, DC, 1999) pp 199. Baltimore, MD, May 24-28, 1999. [NSF]
39. Rebane, A. Tchouassi-Djiki, and W. R. Babbitt, "Ultrafast frequency-conversion holograms by photo-induced gratings in glass," IEEE Lasers and Electro-Optics Society 1999 Annual Meeting, Nov. 8-11, 1999, San Francisco, CA. [NSF MONTS]
40. W.R. Babbitt, "Multidimensional signal processing with spatio-spectral holography," Proceedings of the SPIE, Optical Science, Engineering and Instrumentation, Denver, CO, July 18-23, 1999 Vol. 3802, paper 3802-32 (1999). (Invited Presentation) [DEP-SCOR]
41. K. Merkel, K. S. Repasky, and W.R. Babbitt, "Design issues in continuously programmed coherent transient processors," Proceedings of the SPIE, Optical Science, Engineering, and Instrumentation, Denver, CO, July 18-23, 1999, Vol. 3802, paper 3802-43 (1999). [MURI/DEPSCOR/AFOSR]
42. Knoesen, A.; Yankelevich, D. R.; Mao, E; Coldren, C. W.; Harris, J. S.; "In-line Fiber Evanescent Field Electro-optic Modulators," 4th Mediterranean Workshop on "Novel Optical Materials and Applications" , Cetraro, Italy 1999.

2.5.11 Conference Presentations during 1998

Some presentations and colloquia given by the MURI team on their MURI research are shown in Table 2.5.11.

| Presenter | Inst. | Location | Date | Title |
|---------------|-------|------------------------|------------------|------------------------------|
| Kelvin Wagner | CU | Georgiatech | Sept 18 1997 | BEAMTAP |
| Kelvin Wagner | CU | ETH Zurich | Nov 17 1997 | BEAMTAP |
| Kelvin Wagner | CU | Georgia Tech Lorraine | Nov 18 1997 | BEAMTAP |
| Kelvin Wagner | CU | Univ Eindhoven | Nov 20 1997 | BEAMTAP |
| Kelvin Wagner | CU | Thomson | Dec 10 1997 | BEAMTAP |
| Zoya Popovic | CU | National Radio Science | Jan. 1999 | Active Antennas |
| Kelvin Wagner | CU | PSAA | Jan 16, 1998 | BEAMTAP |
| Kris Merkel | MSU | PSAA | Jan 13, 1998 | Chirped Pulse Programming |
| Kelvin Wagner | CU | NATO radar | March 2, 1998 | Radar target recognition |
| Ken Anderson | CU | PSHB meeting | March 9-11, 1998 | Adaptive phased array radar |
| Kelvin Wagner | CU | IEEE Aerospace conf | March 27, 1998 | BEAMTAP |
| Kelvin Wagner | CU | Imaging Workshop | Aug 4, 1998 | Radar Imaging |
| R. Babbitt | MSU | MSU Physics Colloquium | Sept 18, 1998 | Spectral-Spatial Holography |
| Dana Anderson | CU | CLEO Europe | Sept 98 | Photorefractive Applications |
| Kelvin Wagner | CU | UCLA MURI review | Oct 22, 1998 | CU MURI overview |

Table 5: Some presentations and talks given by MURI participants

1. Kelvin H. Wagner, Sam Weaver, Shawn Kraut, Lloyd Griffiths, R. Ted Weverka, Broadband Efficient Adaptive Method for True-Time-Delay Array Processing, 8th annual DARPA Photonic Systems for Antenna Applications conference, Monterey Jan 1998.
2. Kelvin H. Wagner, Sam Weaver, Shawn Kraut, Lloyd Griffiths, R. Ted Weverka, "Broadband Efficient Adaptive Method for True-Time-Delay Array Processing," IEEE Aerospace conference, Aspen, April 1998.
3. Paulo E. X. Silveira and Kelvin H. Wagner, "Time Delay Optical Neural Network," Optical Computing Topical Meeting, Brugge, June 1998.
4. Gregory Kriehn, Andrew Kiruluta, Paulo E. X. Siveira, Sam Weaver, and Kelvin Wagner, "Imaging Analysis of Photorefractive Phased Array Beamforming," Proc. SPIE International Symposium on Optical Science, Engineering, and Instrumentation, July

1998.

5. Andrew Kiruluta and Greg Kriehn and Paulo E. X. Silveira and Sam Weaver and Kelvin H. Wagner, "Operator Notational Analysis of a Photorefractive Phased Array Processor," OSA Optics in Computing, April, 1999.
6. Andrew Kiruluta and Paulo E. X. Silveira and Greg Kriehn and Sam Weaver and Kelvin Wagner, "Photorefractive Phased Array Beamforming with True-Time-Delay Processing," Proc. IEEE International Topical Meeting on Microwave Photonics, October, 1998, pp. 103-106.
7. Jim Vian, Pete Kirkpatrick, Zoya Popovic, "An optically controlled transmit/receive active antenna," to be presented at PSAA 99, Feb 1999.
8. Shawn Stone, Jim Vian, Zoya Popovic, "Photonicly tuned slot antenna," to be presented at PSAA 99, Feb 1999.
9. P. M. Techau, J. R. Guerci, T. H. Slocumb, and L. J. Griffiths, "Site-specific Performance Bounds for Interference Mitigation in Airborne Radar Systems," to appear in Proc. ASAP '99, Lincoln Laboratory, March, 1999.
10. P. M. Techau, J. R. Guerci, T. H. Slocumb, and L. J. Griffiths, "Performance Bounds for Interference Mitigation in Radar Systems," submitted to IEEE Trans. on Aerospace Electronic Systems, June, 1999. Revised submission, November, 1999.
11. V. Shkunov, V. Damiao, E. Fotheringham, L. Czia, D. Z. Anderson, "Photorefractive oscillators in disks and spheres," CLEO 99, Anaheim.
12. K. D. Merkel and W. R. Babbitt, "Chirped Pulse Programming of Spatial-Spectral Holographic True-Time Delays", The Eighth Annual DARPA Symposium on Photonic Systems for Antenna Applications, January 14-16, 1998, DTIC# ADB 223444 PAA.
13. K. D. Merkel and W. R. Babbitt, "Optical coherent transient continuously programmed continuous true-time-delay processor", To be presented at PSAA-99.

14. K. D. Merkel and W. R. Babbitt, "Optical coherent transient continuously programmed continuous processor ", Accepted for publication in Optics Letters.
15. K. D. Merkel and W. R. Babbitt, "Optical coherent transient continuously programmed continuous signal processor ", submitted to Snowmass OIC.

2.6 Patents and Applications

2.6.1 Patents and Applications 2002

1. Invention disclosure submitted: P. Smith, D. Anderson, Z. Popovic, E. Fotheringham, "A dynamic system implementation of analog optical independent component analysis."
2. K. D. Merkel, Z. Cole, K. Rupavaratham, W. R. Babbitt and K. H. Wagner, US Patent Application No. PCT/US03/14,612, "Method and Apparatus for Processing High Time-Bandwidth Signals Using a Material with Inhomogeneously Broadened Absorption Spectrum."

2.6.2 Patents and Applications 2001

1. Joint Invention of Montana State University and Univ. of Colorado "Method and Apparatus for variable time delay optical coherent transient signal processing" International Application No. PCT/US00/24813.

2.6.3 Patents and Applications 2000

1. K. D. Merkel, W. R. Babbitt, K. Anderson, and K. Wagner, "Variable Time Delay Optical Coherent Transient Signal Processing," Provisional Patent Filed September 15, 1999. [DEPCOR]
2. "In-Line Polymeric Construct for Modulators, Filters, Switches and Other Electro-Optic Devices," U.S. Patent No. 6,047,095, Awarded to: Knoesen, A.; Yankelevich, D. R.; Hamilton, S. A.; Abbot, N. L., Hill, R. A. and Bjorklund, G. C., April 4, 2000.

2.6.4 Patents and Applications 1999

1. K. D. Merkel and W. R. Babbitt, "Optical Coherent Transient Continuous Processor," Provisional Patent Filed December 22, 1998. [AFOSR/MURI]
2. W. R. Babbitt and T. W. Mossberg, "Apparatus and methods for routing of optical beams via time-domain spatial-spectral filtering," U. S. Patent No. 5,812,318 (September 22, 1998). [AFOSR]
3. K. D. Merkel and W. R. Babbitt, "Variable Time Delay Optical Coherent Transient Signal Processing," Provisional Patent Filed September 15, 1999. [DEPSCOR]

2.7 Classes Taught by the PIs relating to the MURI research

2.7.1 2001-2002 AY

1. Dr. Wagner and Dr. Anderson jointly taught a graduate-level Advanced Optics Lab in Fall of 2001 developed for interdisciplinary students with interests in Chemistry, Physics, and Electrical Engineering. Several of the MURI graduate students were involved either as TAs or in taking the class.
2. Zoya Popović taught a class in RF-optical techniques at the Technical University in Munich in 2001. This was a part of an ongoing collaboration. She will teach again in the summer of 2003.
3. Kelvin Wagner taught CU ECEN 6006, Applied Photonics, new course developed to be the second course in the new core optics curriculum. Spring 2002.
4. Kelvin Wagner taught CU ECEN 4016/5016, Fundamentals of Photonics, new introductory course developed as an introduction to the optics core curriculum. This was the second offering of this course, and the first by Prof. Wagner.
5. Randy Babbitt taught MSU Physics 353, Holography-Laser Photography, Spring 2001, undergraduate. Spring 01 (Randy Babbitt), Spring 02 (Randy Reibel taught it, Randy Babbitt was the mentor).

2.7.2 2000-2001 AY

Dr. Wagner and Dr. Anderson jointly taught a graduate-level Advanced Optics Lab in Fall of 2001 developed for interdisciplinary students with interests in Chemistry, Physics, and Electrical Engineering. Several of the MURI graduate students were involved either as TAs or in taking the class.

Last year Prof. Popović taught a new special topics graduate course *RF/optical techniques*, that covered some common methods and components used at both RF and optical frequencies (wavelengths). The objective of the course was to present two different views of the same electromagnetic technique, phenomenon, or circuit component. Examples of methods that were compared include: Fourier optics and antenna analysis, Gaussian beams at optical and millimeter waves, diffraction theory, and basic field theorems. Examples of components that are compared include: polarizers, lenses, waveguides, directional couplers, retroreflectors, phase conjugators, and soliton transmission structures. The course concluded with a conference where students presented projects they worked on during the last month of the course. The presentations were judged by industry members, and Best Paper Award was given. A digest of this mini conference was published for assessment purposes (available upon request).

Zoya Popović taught a class in rf-optical techniques at the Technical University in Munich during her sabbatical. A part of the class was shared with Prof. Andreas Cangellaris from the University of Illinois at Urbana-Champaign. It was taken by around 15 graduate students.

1. Wagner, CU ECEN 5696, Fourier Optics, Fall 2000, graduate.
2. Wagner and Anderson, CU ECEN 5606, Advanced Optics Lab , Fall 2001, graduate.
3. Popović, CU ECEN 5004, RF/optical techniques, Spring 1999, graduate.
4. Popović, CU ECEN , Transmission/Antenna Lab, Fall 2001, graduate.
5. Babbitt, MSU Physics 222, Honors General and Modern Physics, Spring 2001, undergraduate.
6. Babbitt, MSU Physics 500, Optical Signal Processing Seminar Spring 2001, graduate.

7. Babbitt, MSU Physics 500, Optical Signal Processing Seminar Fall 2001, graduate.
8. Babbitt, MSU Physics 500-14, Optical Coherent Transient Seminar Spring 2001, graduate.
9. Babbitt, MSU Physics 500-14, Optical Coherent Transient Seminar Fall 2001, graduate.
10. Babbitt, MSU Physics 353, Holography-Laser Photography, Spring 2001, undergraduate.
11. Knoesen, UC Davis EEC236, Nonlinear Optical Applications, Fall 2001, graduate.

2.7.3 1999-2000 AY

Prof. Popović's new book "Introductory Electromagnetics" was published this year and has already been used at CU and adopted by several other Universities.

Dr. Wagner and Dr. Anderson jointly taught a highly revised graduate-level Advanced Optics Lab in Fall of 1999 developed for interdisciplinary students with interests in Physics and Electrical Engineering. Several of the MURI graduate students were involved either as TAs or in taking the class.

Last year Prof. Popović taught a new special topics graduate course *RF/optical techniques*, that covered some common methods and components used at both RF and optical frequencies (wavelengths). The objective of the course was to present two different views of the same electromagnetic technique, phenomenon, or circuit component. Examples of methods that were compared include: Fourier optics and antenna analysis, Gaussian beams at optical and millimeter waves, diffraction theory, and basic field theorems. Examples of components that are compared include: polarizers, lenses, waveguides, directional couplers, retroreflectors, phase conjugators, and soliton transmission structures. The course concluded with a conference where students presented projects they worked on during the last month of the course. The presentations were judged by industry members, and Best Paper Award was given. A digest of this mini conference was published for assessment purposes (available upon request).

1. Wagner, CU ECEN 5696, Fourier Optics, Fall 2000, graduate.

2. Wagner, CU ECEN 6006, Nonlinear Optics, Spring 2000, graduate.
3. Wagner, CU ECEN 5156, Physical Optics, Fall 1999, graduate.
4. Wagner and Anderson, CU ECEN 5606, Fall 1999, graduate.
5. Anderson, CU PHYS 4510, Fall 1999, undergraduate.
6. Popović, CU ECEN 5004, RF/optical techniques, Spring 1999, graduate.
7. Popović, CU ECEN , Transmission/Antenna Lab, Fall 1999, graduate.
8. Babbitt, MSU Physics 500-14, Optical Coherent Transient Seminar Spring 2000, graduate.
9. Babbitt, MSU Physics 500-14, Optical Coherent Transient Seminar Fall 1999, graduate.
10. Babbitt, MSU Physics 353, Holography-Laser Photography, Spring 2000, undergraduate.
11. Knoesen, UC Davis EEC236, Nonlinear Optical Applications, Fall 1999, graduate.

2.7.4 1998-1999 AY

Dr. Popovic developed and taught a new class titled "RF/Optical Techniques" during Spring 1999 for this MURI as part of the optics and microwaves curriculum in Electrical and Computer Engineering at CU-Boulder. The entire CU MURI team including students, postdocs, and professors attended this unique course.

In addition Prof. Popovic's new book "Introductory Electromagnetics" was published this year and has already been used at CU and adopted by several other Universities.

Dr. Wagner and Dr. Anderson jointly taught a highly revised graduate-level Advanced Optics Lab in Fall of 99 developed for interdisciplinary students with interests in Physics and Electrical Engineering.

Prof. Anderson has again taught Introductory Optics to a large crop of Physics undergraduate students at CU.

1. Wagner, CU ECEN 5696, Fourier Optics, Spring 1999, graduate.

2. Wagner, CU ECEN 5156, Physical Optics, Fall 1999, graduate.
3. Wagner and Anderson, CU ECEN 5606, Fall 1999, graduate.
4. Anderson, CU PHYS 4510, Fall 1999, undergrad.
5. Popovic, CU ECEN 5004, RF/optical techniques, Spring 1999, graduate.
6. Popovic, CU ECEN , Transmission/Antenna Lab, Fall 1999, graduate.
7. Babbitt, MSU Physics 500-14, Opt. Coh. Trans. Seminar 1 3 S99, graduate.
8. Babbitt, MSU Physics 500-14, Opt. Coh. Trans. Seminar 1 5 F99, graduate.

2.7.5 1997-1998 AY

Dr. Popovic has developed a new class as part of the optics and microwaves curriculum in Electrical and Computer Engineering at CU-Boulder. The class is titled "RF/Optical Techniques" and will be taught as ECE 5004 in the Spring of 1999. Many of the CU-Boulder graduate students will be taking this course.

Dr. Anderson taught a new class on photorefractive optics during Fall of 1997 just as the MURI was getting started primarily to a number of the CU MURI students. This class allowed a wide variety of students to communicate efficiently using the powerful tools developed by Prof. Anderson for describing systems such as those he is investigating under this MURI.

Dr. Wagner taught the Graduate Optics Lab in Spring 98, to a wide range of graduate students, including MURI students. He taught Physical Optics in Fall 98 to many MURI students as well.

Randy Babbitt has taught Holography to a huge class of interested undergraduates at MSU. Similarly Prof. Anderson has taught Introductory Optics to a large crop of Physics undergraduate students at CU.

3 Summary of University Equipment Matching Expenditures

In the RF Photonics MURI proposal to ONR in 1997, the University of Colorado team promised a contribution of \$307,202 which represented 49.5% of the CU equipment acquisition costs and Prof W. R. Babbitt of Montana State University promised a contribution of \$126,824 which represented 15% of the MSU equipment and 15% of Prof. Babbitt's AY salary. The change of the subcontracts from Optivision to Photonics Data Systems and finally to the University of California Davis for the PILF work did not include any matching. And the descoping of the work at George Mason University by Lloyd Griffiths during the course of the project effectively negated the small matching commitment by GMU in the original proposal. This total matching commitment represented approximately 10% of the original MURI budget, and the fully funded commitments at CU and MSU were fully honored as is documented and listed in the following tables.

Record of spending on 1648005 34-10106-10837 ST 27956

| Reference | Journal DaPO No. | Item Desc. | Vendor | Amount |
|-------------------|------------------|--|---------------------------|---------------------------|
| Lab & Tech Shop | | Olympus Digital Camera, 32 MB SmartMedia Card, NiMH Batteries, Adapter | PTK*Publish Perfect | \$1,756.75 |
| Supply/Service | 04/06/00 | CHA-1263 | | |
| Equipment <\$5000 | 05/01/00 | 201732 | Creative Computers | \$2,721.00 |
| Equipment <\$5000 | 05/01/00 | 201732 | Creative Computers | \$139.00 |
| Equipment <\$5000 | 05/01/00 | 201732 | Creative Computers | \$310.00 |
| Equipment <\$5000 | 05/05/00 | 201732 | Creative Computers | \$77.00 |
| Lab & Tech Shop | | Olympus P-33 Personal Photo Printer | B&H Photo-Video-Pro Audio | \$447.65 |
| Supply/Service | 05/10/00 | CHA-1367 | | |
| Printers <\$5000 | 05/30/00 | CHA-1362 | WMI*MAC Warehouse | \$1,008.08 |
| Equipment <\$5000 | 02/28/01 | CHD-057 | Apple | \$3,655.00 |
| Equipment <\$5000 | 05/07/01 | CHD-057 | Apple | \$600.00 |
| Total: | | | | <u>\$10,714.48</u> |

Table 7: Additional \$10K matching obligation by Prof. Anderson satisfied with \$10K of purchases on his matching account to support his MURI research.



Wm. Randall Babbitt
Director of Spectrum Lab
Professor of Physics

Department of Physics
Montana State University
Bozeman, Montana 59717-3840

Telephone 406-994-6156
FAX 406-994-4452
Email: babbitt@physics.montana.edu

DRAFT

To:
Kelvin Wagner
University of Colorado

November 29, 2003

Subject: Cost-Sharing report for MURI grant

I am writing to report that MSU has fully met our cost-sharing commitment for the MURI grant.

The attached spread sheet gives a year by year breakdown of the proposed and actual cost-sharing by MSU.

We proposed \$48,565 in cost-sharing on equipment and we spent \$48,566 in cost-sharing on equipment. We proposed that Prof. Babbitt would spend 6.75 months of his academic year salary as cost-shared time on the grant for a total cost of \$78,259 and Prof. Babbitt actually spend 7.47 months of his academic year salary as cost-shared time for a total cost-share of \$78,603. All cost-sharing occurred within the performance period of the grant, which included a no-cost extension to November 2003.

Sincerely,

Wm. Randall Babbitt

DRAFT

| | Year 1 | Year 2 | Year 3 | 3 year Total | Year 4 | Year 5 | 2 year Total | 5 year TOTAL | |
|--|-----------|-----------|-----------|-----------------|-----------|-----------|-----------------|-----------------|---------|
| Proposed Cost Sharing | | | | | | | | | |
| VP of Research Contribution | | | | | | | | | |
| Prof. Babbitt's Start-up Funds | | | | | | | | | |
| 15% of Equipment Cost in year 1,2, 15% | 21,210 | 16,705 | 2,840 | 40,755 | | | 0 | 40,755 | |
| Prof. Babbitt's IDC funds | | | | | | | | | |
| 15% of Equipment Cost in years 4 and 5 | | | | 0 | 3,000 | 4,810 | 7,810 | 7,810 | |
| | | | | | | | | 48,565 | |
| Physics Department Contribution | | | | | | | | | |
| Prof. Babbitt's salary during acad. year | months | 1.35 | 1.35 | 1.35 | 4.05 | 1.35 | 1.35 | 2.70 | 6.75 |
| 15% for 9 months each year | 15% | 9.0 | 8,250 | 8,580 | 8,923 | 25,753 | 9,280 | 9,651 | 18,931 |
| Fringe Benefits on above salary | 26% | | 2,145 | 2,231 | 2,320 | 6,696 | 2,413 | 2,509 | 4,922 |
| Indirect Costs on above salary | | | 4,054 | 4,216 | 4,385 | 12,655 | 4,560 | 4,742 | 9,302 |
| | | | 14,449 | 15,027 | 15,628 | 45,104 | 16,253 | 16,902 | 33,155 |
| | | | | | | | | | 78,259 |
| Total cost share | | | 35,659 | 31,732 | 18,468 | 85,859 | 19,253 | 21,712 | 40,965 |
| | | | | | | | | | 126,824 |

| Reported by FY (July-June) | FY98 97-98 | FY99 98-99 | FY00 99-00 | 3 year Total | FY01 00-01 | FY02 01-02 | FY03 02-03 | 3 year Total | 6 year TOTAL |
|--|---------------|---------------|---------------|-----------------|---------------|---------------|---------------|-----------------|-----------------|
| Actual Cost Sharing | | | | | | | | | |
| Prof. Babbitt's Start-up Funds (436260) | | | | | | | | | |
| Equipment | | 24847 | 15849 | 40696 | | | | | |
| Minor equipment | | | 60 | 60 | | | | | |
| | | | | 40756 | | | | | 40,756 |
| MBRCT grant (426008) | | | | | | | | | |
| Equipment | | | | | | 7,810 | | | 7,810 |
| | | | | | | | | | 48,566 |
| Physics Department Contribution | | | | | | | | | |
| Prof. Babbitt's salary during acad. year | months | 2.63 | 2.13 | 0.00 | 4.76 | 1.36 | 0.00 | 1.35 | 2.71 |
| | | 15,354 | 12,943 | 0 | 8,295 | 0 | 8,847 | | |
| Fringe Benefits on above salary | 25% | 3,839 | 3,236 | 0 | 2,074 | 0 | 2,162 | | |
| Indirect Costs on above salary | 39% | 7,485 | 6,310 | 0 | 4,044 | 0 | 4,215 | | |
| | | 26,678 | 22,489 | 0 | 49,166 | 14,413 | 0 | 15,024 | 29,437 |
| | | | | | | | | | 78,603 |
| | | | | | | | | | 127,169 |

Table 8: MSU cost sharing commitment and expenditures showing full compliance with the cost sharing obligation