

FINAL REPORT

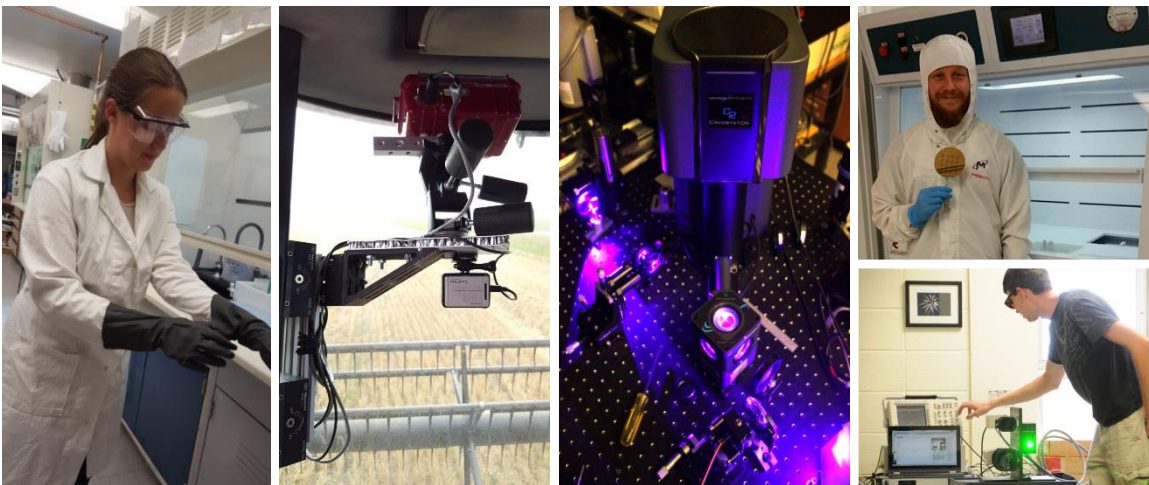
# Optics and Photonics Research for Montana Economic Development

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## Table of Contents

Executive Summary	1
Subproject Reports	
1. Ultra-compact spectral imagers for precision agriculture, wildfire mapping, and natural resources	10
2. High-performance, real-time image processing for hyperspectral imaging	15
3. Remote Sensing Algorithms for Precision Agriculture	19
4. Machine Vision Algorithms for Precision Agriculture	21
5. Microcavity sensors for hyperspectral imaging	23
6. Hyperspectral imaging for monitoring cell growth	27
7. Translational research to commercialize micro-mirror technology	29
8. Active waveguides and integrated optical circuits	32
9. Optical parametric oscillator for tunable lasers	43
10. Nonlinear optical detection of surface contaminants	45

## Executive Summary

The purpose of the *Optics and Photonics Research for Montana Economic Development* project was to focus the impressive capabilities in optics and photonics research at Montana State University (MSU) on projects with high promise to benefit Montana companies through technology development and commercialization. This was a unique opportunity to focus the researchers' efforts on problems that lay mostly in the gap that routinely exists between academic research and commercial products. This gap arises because traditional research funding is rarely, if ever, available to refine basic research to a point where it can be transitioned successfully to commercial products or services. Conversely, the companies rarely, if ever, have sufficient means to 'reach back' far enough to pull the nascent results from a research lab up to the company for refinement and commercialization. Therefore, this MREDI effort had rapid and substantial positive impact on the growth and strength of the Montana economy.

The project included ten subprojects, with commercial potential ranging from immediate to longer-term promise. This suite of activities was also designed to create new partnerships between optical remote sensing and agricultural researchers through several subprojects in precision agriculture. The project was so designed to expand already strong optical remote sensing research expertise into new areas that benefit the broader Montana economy. Each subproject was led by a faculty member at MSU or by a Montana company president and included one or more Montana companies as direct or indirect partners where the technology potentially could be commercialized (see Table 1).

*Table 1. Organization of the Optics and Photonics Research for Montana Economic Development project.*

<i>Subproject</i>	<i>Leader</i>	<i>Montana Businesses</i>
1. Ultra-compact spectral imagers for precision agriculture, wildfire mapping, and natural resources	Dr. Joseph Shaw – MSU Electrical & Computer Engineering (ECE)	NWB Sensors, Inc. Freeman Farms Nugent Farms Meridian Flying Svcs.
2. High-performance, real-time image processing for hyperspectral imaging	Dr. Ross Snider – MSU ECE	Resonon, Inc. Flat Earth, Inc.
3. Remote sensing algorithms for precision agriculture	Dr. Rick Lawrence – MSU Land Resources & Env. Sci.	Resonon, Inc.
4. Machine Vision Algorithms for Precision Agriculture	Dr. Neda Nategh – MSU ECE	Resonon, Inc. NWB Sensors, Inc.
5. Microcavity sensors for hyperspectral imaging	Dr. Zeb Barber – MSU Spectrum Lab	Advanced Microcavity Sensors, LLC
6. Hyperspectral imaging for monitoring cell growth	Dr. Ed Dratz – MSU Chemistry & Biochemistry	Resonon, Inc.
7. Translational research to commercialize micro-mirror technology	Chris Arrasmith – Revibro Optics	Revibro Optics
8. Active waveguides and integrated optical circuits	Dr. Rufus Cone and Dr. Charles Thiel – MSU Physics and Spectrum Lab	S2 Corp. AdvR, Inc. Scientific Materials Montana Instruments
9. Optical parametric oscillator for tunable lasers	Dr. Kevin Repasky – MSU ECE	AdvR, Inc.
10. Nonlinear optical detection of surface contaminants	Dr. Rob Walker – MSU Chemistry & Biochemistry	Altos Photonics

## Long-term impact

The following specific goals were proposed to ensure long-term impact of this investment.

1. Launch two new Montana optics and photonics companies that then existed on paper only (*Advanced Microcavity Sensors, LLC, and Revibro Optics*).
2. Enable new products for eight Montana optics and photonics companies (*Advanced Microcavity Sensors; Revibro Optics; Resonon, Inc.; NWB Sensors, Inc; AdvR, Inc; FLIR/Scientific Materials Corp.; S2 Corp; Montana Instruments*).
3. Create new collaborations that bring together optics and photonics researchers and companies with Montana farmers for precision agriculture.
4. Expand MSU optics and photonics research capabilities to help solve important Montana problems in agriculture, energy, natural resources, and health and biomedical sciences.
5. Assist in recruiting and supporting top faculty and graduate students in optics and photonics, which in the long term will provide the largest return on investment by establishing stronger and broader university research capacity and by training students in the advanced science and technology necessary to establish and grow optics and photonics companies.

All subproject objectives or milestones were met, with a few small modifications made necessary by the naturally unpredictable nature of research. In all cases, these modifications led to comparable results, and almost always stronger results than anticipated in the original proposal.

The long-term impact can be demonstrated numerous ways, but here we cite three examples. First, this effort led to several totally new collaborative relationships between Montana academic organizations and companies, especially in the field of precision agriculture. This is a collaboration that was literally created by the Montana Research and Economic Development Initiative (MREDI), which will continue to grow and serve the diverse needs of both new and traditional segments of the Montana economy.

Second, this effort created stronger partnerships between academic researchers and Montana companies, leading to lasting benefits through the creation of new commercial products and progress toward future commercial products.

A third example, and the final one given here, is the long-term impact of training students in research with commercialization in mind. The MREDI project allowed us to more successfully recruit and retain excellent graduate students for university-industry collaborative research. Our recent history shows clearly that this kind of training produces graduates who start new high-technology companies or become employees of and leaders in such companies. This process, by which we have created more than thirty optics and photonics companies in Montana, and the role of the MSU Optical Technology Center (OpTeC) in it, was recognized in September 2015 with an *award of excellence in talent development* presented by the University Economic Development Association (UEDA). Figure ES.1 is a photograph of this award being accepted in Anchorage, Alaska, by Dr. Joseph Shaw, MSU OpTeC Director and principal investigator of this MREDI project.



**Figure ES.1** Dr. Joseph Shaw accepting the *award of excellence in talent development* from the University Economic Development Association (UEDA) at their annual meeting in Anchorage, Alaska, in Sept. 2015.

## New businesses

A primary objective of this MREDI project was to launch two new companies, and by its conclusion those two companies have grown and become solidified because of the MREDI activities and financial support, while a third company also was established partially as a result of this effort.

- Revibro Optics (Bozeman, MT)
- Microcavity Sensors, LLC (Bozeman, MT)
- Beartooth Scientific (Bozeman, MT)

## Commercial products or progress toward products

Another key objective of this project was to create eight new products in Montana companies. This was achieved, along with significant progress that could lead to even more products in coming years.

Method of mapping weeds in grain fields using low-cost cameras – licensed to NWB Sensors, Inc. (Bozeman, MT) and in process of being commercialized.

FPGA smart-camera system being commercialized at Flat Earth, Inc. (Bozeman, MT) for use by Resonon, Inc. (Bozeman, MT) in real-time hyperspectral image processing applications.

Demonstrated feasibility and advantages of narrow-band spectral imaging for airborne weed mapping, which will result in an expanded market for the recently upgraded airborne hyperspectral imaging systems sold by Resonon, Inc.

LCAM hyperspectral sensing technology being commercialized by Microcavity Sensors, LLC (Bozeman, MT).

Hyperspectral imaging microscope with integrated microfluidic cell nutrient dosing system for Resonon, Inc. (Bozeman, MT).

Adjustable-focus mirrors – Revibro Optics (Bozeman, MT)

Spectroscopic testing of new laser materials produced by Scientific Materials Corp. (Bozeman, MT).

Channel waveguides in LiNbO<sub>3</sub> – AdvR, Inc. (Bozeman, MT)

Lithium niobate crystal incorporating thulium ions for photonic signal processing, also with magnesium ions to increase the optical damage threshold – S2 Corp. (Bozeman, MT)

Lithium niobate and lithium tantalite crystals – Scientific Materials Corp. (Bozeman, MT)

Major progress toward commercially viable sub-micron periodically poled nano-photonic devices - AdvR, Inc. (Bozeman, MT)

Nondestructive method of testing optical waveguides using frequency-chirped lasers – AdvR, Inc. and possibly broader applications for Bridger Photonics, Inc. (Bozeman, MT).

Major progress toward new lasers for gas sensing using nonlinear optical techniques – AdvR, Inc. (Bozeman, MT).

#### Patents and other technology transfer

License to NWB Sensors, Inc. (Bozeman, MT): *Mapping grain fields using low-cost, GPS-enabled cameras during existing farm activities*

License to Revibro Optics (Bozeman, MT): Patent 7,494,233 - *Off-axis variable focus and aberration control mirrors and method.*

Patent for Liquid Crystal Arrayed Microcavity (LCAM) sensors: Patent WO 2016057125 A9 - *Microcavity Array for Spectral Imaging* (2016).

Patent for micro-machined focus-control mirrors licensed to Revibro Optics

Provisional patent application in preparation for enhanced thermal contact with insulating optical materials to allow increased operating powers in a cryogenic environment

#### Jobs created

The Montana optics and photonics industry is growing at a high rate (estimated in surveys given by the Montana Photonics Industry Alliance to be approximately 8-13% annually in recent years) and during 2015-2017 the MREDI funding has been a critical element helping to drive this growth (it is only one element, but a very important one). Therefore, although it is generally difficult to clearly identify which jobs arose because of MREDI support, in some cases we can link new jobs to MREDI funding and results of this research. Those jobs, summarized below, are mostly occupied by holders of advanced science and engineering degrees. There were many more jobs created in this industry, but at least these are known to be somehow related to the MREDI project.

#### Company positions (10):

- 1 engineer at Flat Earth, Inc.
- 3 scientists/engineers at Advanced Microcavity Sensors, LLC
- 2 permanent engineers and 1 temporary commercialization person at NWB Sensors, Inc.
- 2 full-time and 1 part-time engineer at Revibro Optics, Inc.
- 2 engineers/scientists at AdvR, Inc.

#### University positions (48):

- 20 graduate students
- 22 undergrad students
- 1 Research Engineer
- 3 Research Scientists
- 2 Postdoctoral scholars

#### Graduate degrees completed with MREDI support

One of the most important products of university research is graduates who are trained with highly specialized skills. In optics and photonics research, the strongest training occurs in graduate school.

Therefore, a very important product of the MREDI support is the following list of graduate students who received either MS or PhD degrees during the two-year MREDI period (other students participated in MREDI research while pursuing degrees, but only those who finished during this period are listed).

Briana Jones	MS	Electrical Engineering	Repasky group	Dec. 2015
David Riesland	MS	Optics & Photonics	Shaw group	Dec. 2016
Monica Whitaker	MS	EE	Snider group	Dec. 2016
Aaron Marsh	MS	Physics	Cone group	May 2017
Conner Dack	MS	EE	Snider group	May 2017
Chat Chantjaroen	PhD	Engineering (ECE)	Repasky group	May 2017
Cooper McCann	PhD	Physics	Repasky group	May 2017
Christine Gobrogge	PhD	Chemistry	Walker group	May 2017
Michael Roddewig	PhD	Engineering (ECE)	Shaw group	May 2017

#### New grant funding to MSU and industry (\$20.83M)

The MREDI project not only focused some of our attention on technology commercialization opportunities, but also helped us continue to grow and diversify our research activities, as shown by the following list of new grants and sales made possible in full or in part by the MREDI work.

- \$80k NPS – *Development and testing LIDAR to study insect responses to light and noise* – awarded May 2017 (Shaw)
- \$98,800 USDA/NIFA - *Creating an advanced, economical, environmentally friendly measurement of snow water equivalence using observed GPS signals beneath the snowpack*
- \$30,000 MT State Matching Funds Program – (NWB Sensors, Inc. – Bozeman, MT)
- \$99,850 USDA/NIFA - *Intelligent mapping of the farm using low-cost, GPS-enabled cameras during existing farm activities* (NWB Sensors, Inc. – Bozeman, MT)
- \$300k NIH/SBIR – *Development of an open speech signal processing platform*, R44 DC015443-01 (Snider, SBIR Phase I with Flat Earth, Inc. – Bozeman, MT)
- \$12.5k MT Ag Exp’t Station (Lawrence)
- \$172k NSF – *A biologically inspired algorithm to detect, segment and track moving objects with observer motion”* (Nategh)
- \$75k NASA EPSCoR (Nategh)
- \$77.7k Air Force STTR (Barber with Spectral Molecular Imaging, Inc., Beverly Hills, CA)
- \$209k MBRCT (Barber with AMS, LLC)
- \$150k NIH (Phase-1 SBIR with AMS, LLC)
- \$750k NIH (Phase-2 SBIR with AMS, LLC)
- \$129k MBRCT (Barber with AMS, LLC)
- \$25k National Academy of Sciences (Dratz PhD student fellowship)
- \$225k NSF – *High-power laser compatible MEMS deformable mirrors for confocal and two-photon microscopy* (Phase-1 SBIR to Revibro Optics)
- \$40k commercial sales for newly founded Revibro Optics
- \$60k S2 Corp. – *Efficient photonic computational engine for selection and filtering* (Barber)
- \$4.5M ONR – *Full-spectrum staring receiver* (Barber)
- \$800k S2 AFRL – *Instantaneous wideband 10 GHz time difference of arrival* (SBIR with S2 Corp)
- \$50k NASA – *Nanoscale poling and structuring in nonlinear optical materials* (Himmer and Nakagawa)

- \$500k NSF – *Photonics enabled extreme bandwidth wireless communications receiver* (Phase-IIB SBIR with S2 Corp.)
- \$1M IARPA – Efficient, high-data-rate photonic computational engine for 2-D image processing (Babbitt with S2 Corp).
- \$81k MBRCT – *Internally cooled laser trapped particles for ultra-high sensitivity accelerometry*
- \$27k ONR – *Functionalization of optically levitated particles*
- \$1.59M NSF – *Development of a micropulse DIAL (MPD) testbed for sensing lower tropospheric water vapor profiles* (Repasky).
- \$363.5k ARO – *Organic enrichment at aqueous interfaces: Cooperative adsorption and its role in atmospheric science* (Walker).
- \$426.2k NSF – *Nonlinear optical studies of high temperature surface chemistry in energy conversion systems* (Walker).
- \$345k ONR – *Operando optical studies of electrochemical oxidation and materials degradation in high temperature solid oxide fuel cells* (Walker).
- \$8.6M of related funding to S2 Corp.
- \$50k of sales of new rare-earth-activated materials developed at Scientific Materials Corp. in collaboration with MSU.

#### Pending grants (\$24.8M)

The impact of the MREDI work will continue to grow in the future, as illustrated by the following list of grants that are pending as of the writing of this report. Some of these, such as the first one on the list, are proposals for direct follow-on work in areas where we did not previously have suitable experience.

- \$200k USDA - *Hyperspectral imaging: A Remote-Scouting IPM tool for Early Detection of Herbicide-Resistant Weed In-crop* – Jha and Shaw, submitted May 2017
- \$314.7k Industry - *Hyperspectral Imaging and Spatial Learning for Produce Monitoring* – Shaw and Sheppard, submitted June 2017
- \$20M NSF – *CREWS: Convergent Research on Environmental Water* – Multiple investigators throughout the MUS with Shaw, to be submitted July 2017
- \$188k NASA – *Space debris identification and tracking system based on a real-time, adaptive motion processing algorithm* (Nategh)
- \$2M NIH/SBIR – *Development of an open speech signal processing platform*, Phase-2 SBIR – Flat Earth, Inc. (Bozeman, MT) with Snider
- \$1.25M USGS - *Improved Biophysical and Geophysical Data Extraction Using Agnostic Image Analyses and Super Ensembles* (Lawrence)
- \$750k NSF (Phase-2 SBIR with AMS)
- \$150k DARPA (Phase-1 SBIR with AMS)
- \$1.8M NIH – *Early detection of Alzheimer’s disease by combining blood-based assays with molecular imaging* (Dratz).



### Partnerships formed, strengthened, or expanded

Through working together, we formed stronger and expanded partnerships between MSU and the following organizations.

- NWB Sensors, Inc. (Bozeman, MT)
- Freeman Farms (Fairfield, MT)
- Nugent Farms (Fairfield, MT)
- Quadrocopter, LLC (Columbia Falls, MT)
- Flat Earth, Inc. (Bozeman, MT)
- Advanced Microcavity Sensors, LLC (Bozeman, MT)
- Resonon, Inc. (Bozeman, MT)
- Revibro, Inc. (Bozeman, MT)
- AdvR, Inc. (Bozeman, MT)
- S2 Corp. (Bozeman, MT)
- Montana Instruments (Bozeman, MT)
- Scientific Materials Corp./FLIR (Bozeman, MT)
- University of Calgary
- Spectral Molecular Imaging Inc. (Beverly Hills, CA)

### Peer-reviewed journal publications

Another major output of all research programs is publication of results in the peer-reviewed literature. The following papers have been published or submitted during the MREDI period.

M. R. Roddewig, F. R. Hauer, J. H. Churnside, P. E. Bigelow, and J. A. Shaw, "Airborne lidar detection and mapping of lake trout spawning sites in Yellowstone Lake," *Appl. Opt.* (in review 5/17).

M. R. Roddewig, J. H. Churnside, and J. A. Shaw, "Airborne lidar detection of an underwater thermal vents," *J. Appl. Rem. Sensing* (in press 7/17).

M. R. Roddewig, N. J. Pust, J. H. Churnside, and J. A. Shaw, "Dual-polarization airborne lidar for freshwater fisheries management and research," *Opt. Eng.* **56**(3), 031221 (2017).

M. Vollmer and J. A. Shaw, "Atmospheric optics in the near infrared," *Appl. Opt.* **56**(19), G145-G155 (2017).

J. A. Shaw, "Inflight observations of Bottlinger's rings," *Appl. Opt.* **56**(19), G113-G119 (2017).

J. A. Shaw and M. Vollmer, "Blue sun glints on water viewed through a polarizer," *Appl. Opt.* **56**(19), G36-G41 (2017).

Z. W. Barber, C. Harrington, R. K. Mohan, T. Jackson, C. Stiffler, P. B. Sellin, and K. D. Merkel, "Spatial-Spectral Holographic Real-Time Correlative Optical Processor with >100 Gb/s Throughput," *Applied Optics* **56**(19), 5398-5406 (2017). doi:10.1364/AO.56.005398

C. Stoltzfus, R. Barbour, D. Atherton, and Z. Barber, "Micro-Sized Tunable Liquid Crystal Optical Filters," *Optics Letters* **42**(11), 2090-2093 (2017). doi:10.1364/OL.42.002090

- R. E. Latterman, S. Birrell, P. A. Sullivan, and R. A. Walker, "Improved pulsed laser operation with engineered nanomaterials" *ACS Applied Materials and Interfaces* **8** (30) 19724-19731 (2016).
- C. A. Gobrogge, V. A. Kong and R. A. Walker, "Unusual Temperature Dependent Solvation and Partitioning in Phospholipid Membranes" *J. Phys. Chem. B* **120** (8) 1805-1812 (2016).
- S. M. Burrows, E. A. Gobrogge, L. Fu, K. A. Link, S. M. Elliott, H. F. Wang, and R. A. Walker "OCEANFILMS-2: Representing co-adsorption of saccharides in marine films improves agreement of modelled and observed marine aerosol chemistry" *Geophys. Res. Lett.* **143** (15) 8306-8313 (2016).
- C. A. Gobrogge, H. S. Blanchard, and R. A. Walker "Temperature Dependent Partitioning of Coumarin 152 in Phosphatidylcholine Lipid Bilayers" *J. Phys. Chem. B*, **121** (16) 4061-4070 (2017).
- C. A. Gobrogge and R. A. Walker "Quantifying Solute Partitioning in Phosphatidylcholine Membranes" *submitted to Analytical Chemistry*.
- C. A. Gobrogge, V. A. Kong and R. A. Walker "Temperature Dependent Partitioning of C152 in Binary Phosphatidylcholine Membranes and Mixed Phosphatidylcholine/Phosphatidylethanolamine Membranes" *in revision with J. Phys. Chem. A* (invited for Veronica Vaida Festschrift).
- T. Lutz, L. Veissier, C. W. Thiel, P. J. T. Woodburn, R. L. Cone, P. E. Barclay, and W. Tittel, "Effects of mechanical processing and annealing on optical coherence properties of Er<sup>3+</sup>:LiNbO<sub>3</sub> powders," *Journal of Luminescence*, In Press, available online (2017) doi: 10.1016/j.jlumin.2017.03.027.
- N. Sinclair, D. Oblak, C. W. Thiel, R. L. Cone, and W. Tittel, "Enhanced properties of a rare-earth-ion-doped waveguide at sub-Kelvin temperatures for quantum signal processing," *Physical Review Letters* **118** (2017) 100504.
- S. Welinski, C. W. Thiel, J. Dajczgewand, A. Ferrier, R. L. Cone, R. M. Macfarlane, T. Chanelière, A. Louchet-Chauvet, and P. Goldner, "Effects of disorder on optical and electron spin linewidths in Er<sup>3+</sup>, Sc<sup>3+</sup>:Y<sub>2</sub>SiO<sub>5</sub>," *Optical Materials* **63** (2017) 69.
- L. Veissier, C. W. Thiel, T. Lutz, P. E. Barclay, W. Tittel, and R. L. Cone, "Quadratic Zeeman effect and spin-lattice relaxation of Tm<sup>3+</sup>:YAG at high magnetic fields," *Physical Review B* **94** (2016) 205133.
- T. Lutz, L. Veissier, C. W. Thiel, P. J. T. Woodburn, R. L. Cone, P. E. Barclay, and W. Tittel, "Effects of fabrication methods on spin relaxation and crystallite quality in Tm-doped Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> powders studied using spectral hole burning," *Science and Technology of Advanced Materials* **17** (2016) 63.
- T. Böttger, C. W. Thiel, R. L. Cone, Y. Sun, and A. Faraon, "Optical spectroscopy and decoherence studies of Yb<sup>3+</sup>:YAG at 968 nm," *Physical Review B* **94** (2016) 045134.
- T. Lutz, L. Veissier, C. W. Thiel, R. L. Cone, P. E. Barclay, and W. Tittel, "Modification of phonon processes in nanostructured rare-earth-ion-doped crystals," *Physical Review A* **94** (2016) 013801.
- L. Veissier, M. Falamarzi, T. Lutz, E. Saglamyurek, C. W. Thiel, R. L. Cone, and W. Tittel, "Optical decoherence and spectral diffusion in an erbium-doped silica glass fiber featuring long-lived spin sublevels," *Physical Review B* **94** (2016) 195138.

N. Kunkel, A. Ferrier, C. W. Thiel, M. O. Ramírez, L. E. Bausá, R. L. Cone, A. Ikesue, and P. Goldner, "Rare-earth doped transparent ceramics for spectral filtering and quantum information processing," *APL Materials* 3 (2015) 096103.

E. Saglamyurek, T. Lutz, L. Veissier, M. P. Hedges, C. W. Thiel, R. L. Cone, and W. Tittel, "Efficient and long-lived Zeeman-sublevel atomic population storage in an erbium-doped glass fiber," *Physical Review B* 92 (2015) 241111(R).

S. Spuler, K. Repasky, B. Morley, D. Moen, M. Hayman, A. Nehrir, "Field deployable diode laser based differential absorption lidar for profiling water vapor," *Atmospheric Measurement Technology*, **8**, 1073-1087 (2015).

T. N. Ashour, E. Dratz, S. Halonen, "Use of human induced pluripotent stem cell-derived neurons as a model for Cerebral Toxoplasmosis," *Microbes Infect.* **18**(7-8), 496-504 (2016).  
doi: 10.1016/j.micinf.2016.03.012. Epub 2016 Apr 12 PMID: 27083472

N. Tanaka, E. Dratz, S. Halonen, S. "Use of human induced pluripotent stem cell-derived neurons as a model for Cerebral Toxoplasmosis," *Microbes Infect*, **18**(7-8), 496-504 (2016).

R. J. Usselman, C. Chavarriaga, P. R. Castello, M. Procopio, M. Ritz, E. Dratz, D. J. Singel, C. F. Martino, "The Quantum Biology of Reactive Oxygen Species Partitioning Impacts Cellular Bioenergetics," *Sci Rep.* **6**:38543 (2016). doi: 10.1038/srep38543.

C. McCann, K. S. Repasky, M. Morin, R. Lawrence, and S. Powell, "A novel histogram based unsupervised classification technique to determine natural classes from biophysically relevant fit parameters to hyperspectral data," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 99:1-11 (2017).

C. McCann, K. S. Repasky, M. Morin, R. Lawrence, and S. Powell, "Using Landsat surface reflectance (LaSRC) data as a reference target for multi-swath hyperspectral data collected over mixed agricultural rangeland areas," *IEEE Transactions on Geoscience and Remote Sensing* (in press).

C. McCann, K. Repasky, R. Lawrence, and S. Powell, "Multi-Temporal Mesoscale Radiometrically Referenced Hyperspectral Data of Mixed Agricultural and Grassland Regions for Vegetation Health Monitoring," *ISPRS Journal of Photogrammetry and Remote Sensing* (in review).

M. Morin, R. Lawrence, K. Repasky, T. Sterling, C. McCann, and S. Powell, "Agreement analysis and spatial sensitivity of multispectral and hyperspectral sensors in detecting vegetation stress at management scales," *Journal of Applied Remote Sensing* (in review).

Laffoon, Masters, Dratz, and Roberts, "Deep-proteomic screen of plasma proteins reveals biomarkers for Alzheimer's disease that are dependent on sex and APOE genotype," *Alzheimer's Research and Therapy* (in review).

Laffoon, Masters, Dratz, Roberts, "The Australian imaging, biomarker and lifestyle study: ApoE-all complex in the proteomic comparison of plasma HEPSEPH binding proteins from homozygous ApoE carriers," to be submitted in July 2017.

**Subproject 1: Ultra-compact spectral imagers for precision agriculture and mapping of wildfires and natural resources** (Joseph Shaw with NWB Sensors, Inc.). Development of ultra-compact imaging systems for weed mapping in precision agriculture, UAV mapping of wildfires, and a wide variety of ground-based and airborne remote sensing. The sensor systems will be commercialized through NWB Sensors, Inc. and tested for precision agriculture at Montana farms in Fairfield, MT and Sidney, MT with Meridian Flying Services from Sidney, MT.

### Milestones

- a) September 30, 2015: Initial agricultural data collection completed
- b) December 31, 2015: Initial weed maps complete
- c) June 30, 2016: Prepare a refined imaging system and application-specific algorithm
- d) December 31, 2016: Complete results of summer 2016 harvest experiment
- e) June 30, 2017: Finish imaging system and algorithms and transfer to private partner

### Accomplishments

The purpose of this subproject was to develop ultra-compact optical imaging systems for remote sensing in important Montana applications. The primary focus was on mapping weeds during grain harvest, with secondary areas of ultra-compact thermal imagers and compact lidar systems for use in applications ranging from natural resource management to ecological studies. All milestones were met, and along the way we learned that off-the-shelf action cameras could be used with machine-vision algorithms to map weeds at harvest, with comparable performance to that achieved with the visible-and-near-infrared camera systems we built in our lab. For example, an off-the-shelf GoPro camera correctly detected weeds or lack of weeds 93% of the time relative to expert observers viewing the same images. An off-the-shelf Garmin camera performed the same task with 97% accuracy relative to the same expert observers. In these experiments, the cameras were mounted in the cab of a combine and recorded images during harvest on multiple Montana farms (Fig. 1.1). This weed-mapping method has been licensed to NWB Sensors, Inc. of Bozeman, MT, who are further refining it for commercial application. An example weed map from this method is shown in Fig. 1.2.



**Fig. 1.1** Custom and off-the-shelf cameras mounted in a combine during harvest.

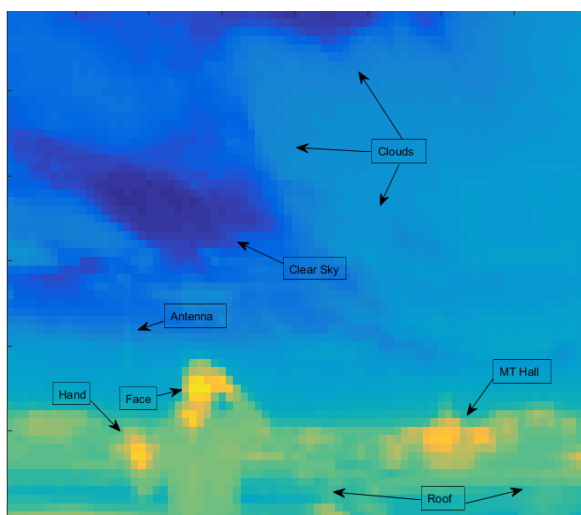


**Fig. 1.2** Weed map created from images obtained during harvest on a Montana grain farm.

We also developed methods to provide quantitatively calibrate thermal images from ultra-compact imaging modules with rapidly increasing capabilities and falling costs. Their small size and low cost make them extremely attractive for drone-based remote sensing and bring thermal imaging down to the consumer market. However, they provide notoriously poor stability and accuracy, resulting in images that are only qualitatively useful without our calibration methods. We have demonstrated that these modules can be calibrated successfully, resulting in greatly increased stability and accuracy. For example, calibration of a FLIR Lepton module resulted in an RMS uncertainty of  $1.57 \text{ W}/(\text{m}^2 \text{ sr})$  using our standard microbolometer calibration methods. Using an exponential-based algorithm that accounted for temperature compensation vs time, the uncertainty was further reduced to  $1.31 \text{ W}/(\text{m}^2 \text{ sr})$ . This shows that even ultra-low-cost IR imaging modules can be calibrated sufficiently for many quantitative remote sensing measurements. An example of these ultra-compact, low-cost imaging modules is the tiny chip on the right-hand side of Fig. 1.3, which is a photograph of uncooled thermal infrared imagers we have worked with at MSU since 2001. An example thermal image from this tiny module is shown in Fig. 1.4.



**Fig. 1.3** Uncooled thermal infrared imagers used in our lab since 2001. The current study uses the tiny imaging module sitting in a plastic dish on the right-hand side.

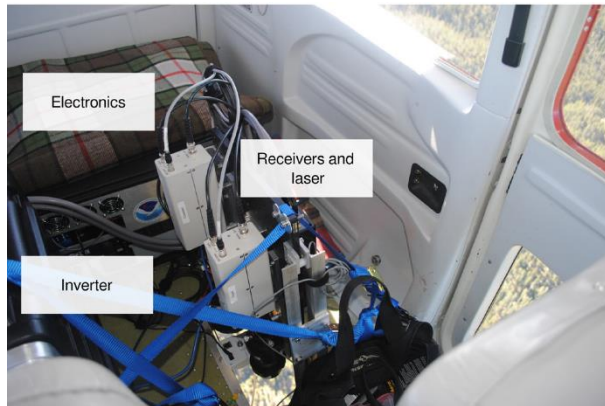


**Fig. 1.4** Thermal image recorded with ultra-compact thermal imaging module, showing person, a distant building, and clouds.

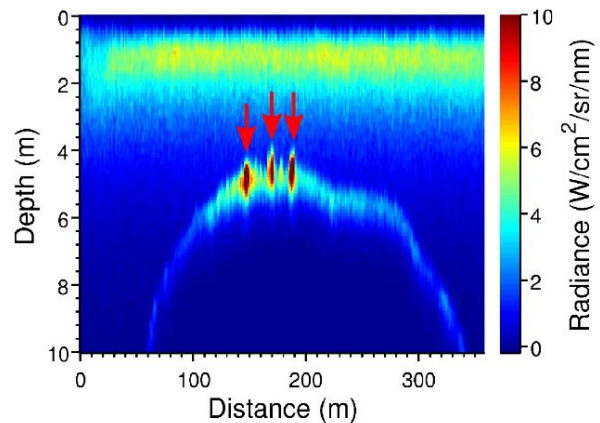
The final technology we developed further in this subproject was a compact airborne lidar system that can fly in a small, single-engine airplane for studies of lake and river ecology. We refined the prototype system and used it to help map spawning locations of invasive lake trout that threaten the ecological balance in and around Yellowstone Lake, which has great implications for the Montana tourism and recreation economic segments. We also demonstrated that this system can provide useful measurements ranging from profiling of underwater thermal vents to monitoring water quality through range-resolved measurements of water turbidity and plankton distributions. Figure 1.5 shows a photograph of this system mounted in the airplane and Fig. 1.6 is a time-height plot of the signal from Yellowstone Lake, showing a dome-shaped bottom feature with underwater thermal vents (seen as reddish streaks here) whose outflow appears to have attracted a thin layer of plankton (seen as a yellow band near the water surface).

The most economically feasible and promising of these technologies is real-time weed mapping with GPS-enabled cameras. As part of this MREDI effort, our commercial partner (NWB Sensors, Inc. of Bozeman, MT) conducted a commercialization study that revealed promising aspects of the market for this technology as a commercial product or service. Their summary report begins after Figures 1.5 and 1.6.





**Fig. 1.5** Compact lidar system mounted in a single-engine airplane during flights over Flathead Lake.



**Fig. 1.6** Time-height plot of lidar signal, showing underwater thermal vents in Yellowstone Lake and what appears to be an overlying plankton layer near the water surface.

## Commercialization Study Summary Report by NWB Sensors, Inc.

### *Summary of MREDI Business Outcomes*

The MREDI program has provided opportunities to NWB Sensors, Inc. that may not have existed without this program. Over the last year NWB Sensors has established a licensed the weed mapping technology and associated data sets developed at MSU, and has successfully acquired federal funding to commercialize this technology through a USDA/NIFA Small Business Innovative Research (SBIR) grant. This grant and the commercial opportunity we have identified through the MREDI program has allowed NWB Sensors to add one full time and one half-time employee, thus going from 2 to 3.5 employees nearly doubling the size of our business. In addition to these benefits, the work conducted through the MREDI program has led to both new business contacts and a better understanding of the precision agriculture industry, largely through our collaborations and conversations with MMEC and MSU agricultural researchers.

### *Executive Summary*

With the advent of precision/smart agriculture, farming is changing. Technologies exist to add precision to all aspects of the farm. Through "mapping the farm," precision management strategies can be implemented such as: targeted herbicide application, targeted soil management, variable rate fertilizer application, improved yield predictions, improved water management, etc. In principle, this saves time and money while increasing crop yield and quality. Unfortunately, these practices require information that is generally not readily available to the small farm as current mapping technology is time consuming and expensive, putting it out of reach of all but the largest farms. However, by augmenting existing farm activities high quality field maps can be generated for a fraction of the cost. By leveraging the times that a farmer drives the whole field, such as tilling the soil, seeding the crop, spraying for weeds or pests, or harvesting the crop, and adding low cost GPS enabled cameras to the machinery then advances in machine vision can be utilized to map weeds and other objects of interest.

### *Proof of Concept*

Initial proof of principle of the Field Mapper technology was demonstrated during the 2015 and 2016 harvest seasons. Cameras were deployed by Montana State University on combines during August 2015 and August 2016 and over 500,000 images were collected. Machine vision software was developed to identify weeds and weed types from these images. Initial real-world results showed promise, as the system correctly identified patches of weeds with an accuracy of more than 98% with an overall weed detection accuracy of 92%. The system was additionally able to determine the species of these weeds approximately 78% of the time. Other features were also detected within the imagers, with un-ripe green crop at a rate of 74% accuracy, tracks in the field at 72% accuracy, and manmade objects at 78% accuracy. These metrics can be greatly improved with a more diverse data set, including more data on different vehicles at different farms, and a broad set of features extracted from the data. This accuracy is sufficient to be above the economic threshold for weed management in cereal grains.

### *Current Technology*

While there are current technology-based mapping techniques, such as drones and aircraft that can theoretically map the farm at any time and provide spatial resolution on the order of 5 cm, the expense of these technologies is still around \$1000 per flight. As imaging technology advances these platforms will have the ability to utilize more advanced sensors, though at additional cost. This is opposed to freely available satellite data that only images a farm with a very coarse resolution at set times regardless of weather or other considerations, and has long return intervals on the order of 1-2 weeks, making it less than ideal for timely decision making. The next generation of satellites is projected to image every location on earth daily, though with spatial resolutions far larger than what would be necessary for accurate weed detection. The final option is the human option, which while highly accurate suffers from high costs either in money or time making it a difficult option to implement on larger farms. Given these options the Field Mapper technology is an attractive option from the price standpoint as well as ease of adoption.

### *The Precision Agriculture Market*

The global precision agriculture market was estimated at 3.2 billion (USD) in 2015 and is forecasted for rapid growth with an expected market size between of 10.2 billion (USD) and 11.5 billion (USD) by 2025, demonstrating a growth rate near 13%. This market is significantly outpacing the global economic growth rate near 3.5%. Within this market the weed mapping technology fits into many aspects of the industry, but fits best in the crop scouting applications with account for approximately 10% of the total market. In the United States, the adoption of precision agricultural methods has been slow but steadily growing. Currently, more than 60% of the cropped land is maintained using at least one precision agricultural technology, most prominently auto-steer. Of the farmers surveyed during this study this trend was roughly supported with 66% using at least one precision agriculture technique. More importantly all would consider an automated weed mapping system and 75% have a specific desire for weed mapping to aid in farm management. The desire for site-specific management was shown, in that 70% of those interviewed were implementing site-specific management through spot spraying. The value of the automated mapping system was shown in the fact that 30% were already using some type of weed mapping program requiring user input. The most common of these was manually adding GPS targets for weeds, a feature of many auto-steer systems.

### *Pricing for the Technology*

Further market analysis needs to be done to determine an appropriate price point for effective technology adoption, but initial estimates based on a \$500 camera and approximately \$1500 software licensing cost which gives a three-year amortized cost for a 500-acre farm (cost of \$1.33 / acre for the system). When farmers were polled for information on how much they would spend for weed mapping applications most who had precise answers ranged from \$5-15/ acre.

Utilizing the weed map to do site-specific weed management (SSWM) in conventional farming has an annual benefit range of \$6.50 to \$20.00 /acre for corn, \$10.00 to \$24.00 /acre for soybean, and \$2.50 to \$8.50 /acre for wheat. These numbers are based on 1995 data adjusted for inflation and crop prices. This places the technology within reach of Montana wheat farmers, but this is just at the economic limit for the technology. This in part explains the slow adoption of SSWM by conventional farming, and the inability of aircraft and drones to economically act as a tool for SSWM.

### *Identified Target for Market Entry*

NWB Sensors, Inc. has identified organic grain production as the most likely point of entry of for the weed mapping technology into the precision agriculture market. Approximately 1% of grain production in the United States uses organic farming techniques. The number of acres in organic production continues to increase annually, greatly outpacing growth of other agricultural sectors.

In organic farming, SSWM is one of the tools available to the farmer, and can include herbicide application as a last resort. In the case where herbicide is applied to a weed patch that has been deemed unmanageable via organic methods that location and a buffer zone are removed from organic production for at minimum three years. The need for locating and identifying weeds and weed patches in organic farming was expressed by nearly all organic growers we contacted. Organic wheat is sold at a premium that varies between 200% to 300% of the conventional wheat price. Despite this premium, organic wheat tends to be at a slight economic disadvantage to conventional wheat due to increase production costs, primarily labor costs. However, growth in organic wheat production continues to outpace growth both in organic corn and organic soybeans.

Knowledge of the location of perennial weed patches, such as Canada thistle, bindweed, and quack grass has the potential to decrease labor costs bringing significant benefit to the grower. A quantified economic benefit for this type of management is largely not studied in the literature and not easily identifiable by the grower we contacted.

### *Hurdles to Adoption*

Historically, precision agriculture products have not been widely adopted by smaller farms. Some of this can be attributed to cost, which this product addresses, but the social aspect of technology adoption needs to be better understood before bringing the product to market. These two understanding gaps should be addressable through continued conversations with farmers and coops and discussions with the distributors who would market the system. Expanding the research base to include organic farmers will be a key factor as organic farming is a growing industry and to be successful organic farmers want more information about their farm ecosystem as compared to other traditional farmers.



### *Value Added Approach*

The value-added nature of the system is that the imagery can be used to determine many other valuable pieces of data at different times throughout the growing season such as the following times:

- During harvest in addition to weed mapping, it could show crop yield (by counting heads of grain) and crop height (used to determine harvest index which speaks to stressed areas of the field)
- During seeding it could be used to scout the early season weeds in the fields (if present) aiding in herbicide selection decisions for conventional agriculture.
- During spraying it could show stages of weed growth (setting a timetable for spraying before they go to seed) and nitrogen deficiency (to aid in variable rate fertilization) as well a measure of the initial success of site specific management of weeds from the previous year's weed map.
- During tilling it could show soil moisture content (allowing for more intelligent seed planting timing), in addition be used to identify and map weed patch.

This is a brief example of the many other valuable data points that can be used to improve crop yield, crop quality, and ultimately increase profits. These data products can be part of a software package upgrade (and additional cameras as necessary) that is slowly rolled out as the company grows. Eventually the offering will be a large-scale farm management system.

### Expenditures

Salaries \$193,581.76, Benefits \$49,448.55, Sub Award \$273,999.99, Operations \$135,750.32, total Expenditures \$652,780.62.

**Subproject 2: High-performance, real-time image processing for hyperspectral imaging** (Ross Snider with Resonon, Inc.). Design a high-speed hyperspectral waterfall sorting system to fuse object edge information with hyperspectral data to sort agricultural products quickly and efficiently using Resonon's Hyperspectral Imagers and remove rejected items via airjets. The goal is to perform the data fusion, accept/reject decision, and removal all in real-time using FPGA technology.

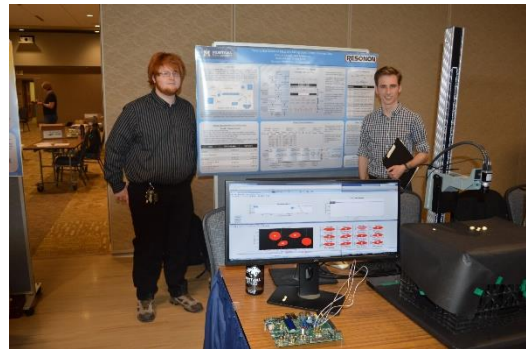
### Milestones

- a) February 1, 2016: Determination of center of mass of each food item in image/line scan
- b) September 1, 2016: Determine trajectory of food item for precise timing removal
- c) February 1, 2017: Integrate hyperspectral data within food item edge boundaries
- d) June 31, 2017: Use hyperspectral data within food item edges to classify food item as accept/reject
- e) June 31, 2017: Time air jets to remove rejected food items
- f) June 31, 2017: Final report emphasizing commercial products and potential

### Accomplishments

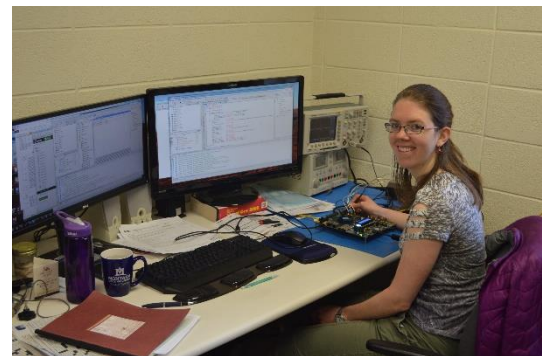
We have accomplished the milestones, as discussed below.

Milestones 1&2 were met by two Electrical and Computer Engineering Seniors Tyler de Caussin and Alex Matejunas (Fig. 2.1), who developed a real-time, FPGA-based algorithm for computing the center of mass of a falling object from data coming from a high-speed line scan camera generating data at 640 Mbytes/s. The team presented their design at the MSU COE Engineering Design Fair on April 28, 2016.

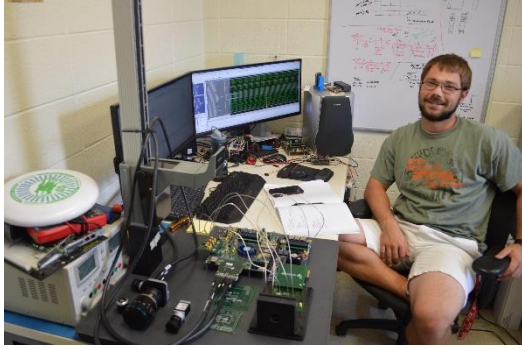


**Figure 2.1** MSU undergraduate students who developed a real-time, FPGA-based algorithm for tracking a falling object in high-speed images.

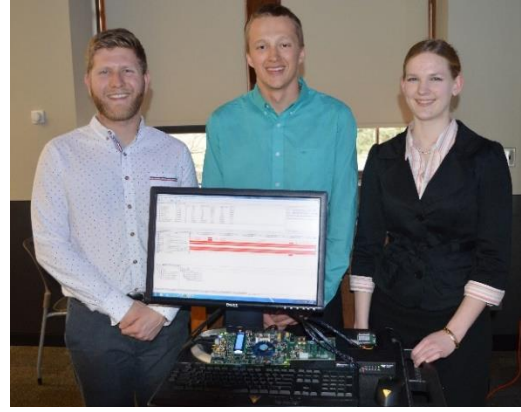
Milestones 3&4 were met by two Electrical Engineering graduate students Monica Whitaker (Fig. 2.2) and Connor Dack (Fig. 2.3) who got their Master's degrees implementing real-time classification and sorting algorithms in FPGAs. Monica Whitaker's Master's Thesis was *Development of a Smart Camera System on an FPGA* that integrated data from both a hyperspectral camera and a monochrome line scan camera and is capable of scanning objects in freefall and deciding within milliseconds whether to keep the object. Connor Dack's Master's Thesis was *Development of a Smart Camera System Using a System-On-Module FPGA* where he took the work that Monica had done and focused on system integration using Intel's new Arria 10 FPGAs and creating custom camera interfaces to stream image data directly to FPGAs. There is still some camera integration work to be done to get data to the FPGAs.



**Figure 2.2** MSU graduate student who developed real-time classification and sorting algorithms.



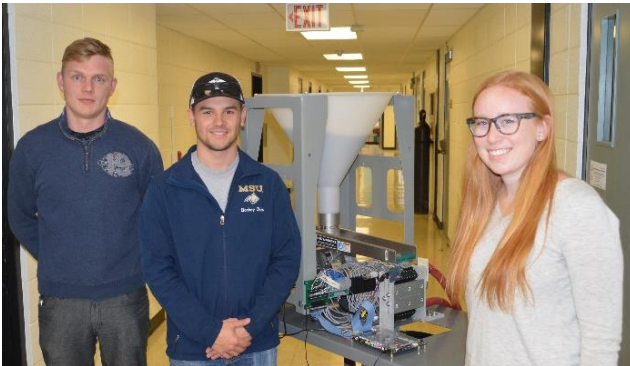
**Figure 2.3** MSU graduate student who developed real-time classification and sorting algorithms.



**Figure 2.4** MSU undergraduate students who developed mSATA FPGA controller for high-bandwidth data collection.

Associated with Milestone 4 (classification of food items) is training the classification system and the need to record data for machine learning. This requires a way to save high bandwidth imaging data. To accomplish this, three Electrical and Computer Engineering Seniors Nick Lapp, Hendrick Haataja, and Hannah Mohr developed a mSATA FPGA Controller that can stream data to a SSD drive at 200 Mbytes/sec (Fig. 2.4). This will be used to store imaging data to be used for machine learning classification purposes.

Milestone 5 was met by three Electrical and Computer Engineering Seniors, Sam Kyser, Phillip Lowther, and Molly Tomlinson (Fig. 2.5), who developed a waterfall testbed sorting platform (Fig 2.6) where we will be able to test the real-time sorting algorithms that are run in FPGAs. The system has 32 independently controlled air valves where each air valve can open and shut in milliseconds. The goal was to be able to eject unwanted lentils as they fall.



**Figure 2.5** MSU undergraduate students who developed a waterfall sorting testbed to test real-time sorting algorithms.



**Figure 2.6** Waterfall sorting testbed.

### *Additional Funding*

The MREDI grant allowed us to build expertise and show that we can develop FPGA-based systems. With this experience, we received NIH funding for the following FPGA-related work.

NIH/SBIR Fast Track (R. Snider & Ray Weber) R44 Phase 1 (funded): \$300K; Phase 2 (pending): \$2M

This proposal will create an open speech signal processing platform. The open computational framework will be used for developing algorithms that will help accelerate acoustic and hearing science research. The open framework will leverage a new class of computational devices that represent the future for embedded systems needing significant digital signal processing (DSP) capability. These devices, known as system-on-chip field programmable gate arrays (SoC FPGAs), enable algorithms to run with deterministic and extremely low-latency abilities that are not possible with conventional CPUs. The open platform will enable creation of next-generation hearing aids and sound processors.

#### *Partnerships formed*

We are working with Flat Earth, Inc. to commercialize this technology to be used by Resonon.

#### *Licensing or technology transfer*

We are working with MSU technology transfer office to license this technology to Flat Earth, Inc.

#### *Progress toward products*

The goal is for Flat Earth, Inc to create a Smart FPGA Camera that Resonon can use to process their hyperspectral data in real-time.

#### *Jobs Created*

Conner Dack graduated spring 2017 with his Master's degree and was hired by Flat Earth, Inc. to develop FPGA systems for Resonon.

#### Expenditures

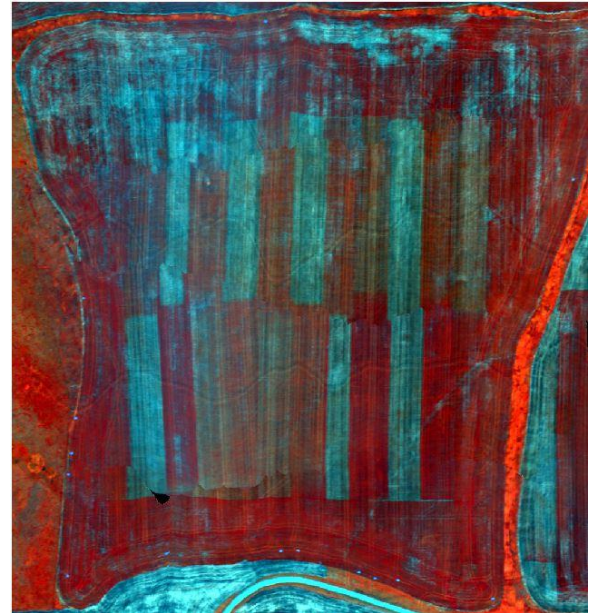
Salaries \$112,355.40, Benefits \$9182.60, Operations \$105,768.32, total Expenditures \$227,306.32.

**Subproject 3: Remote Sensing Algorithms for Precision Agriculture** (Rick Lawrence with Resonon, Inc.)  
Develop and apply a methodology using hyperspectral imagery for determining optimal narrow spectral band combinations for identifying targeted invasive weeds in specific crops.

### Accomplishments

The objective of this subproject was to evaluate the use of narrow spectral bands for identifying invasive weeds in crops. Broad spectral bands (such as blue, green, red, and near infrared) can each be divided into much narrower bands, for example we can examine 10 or more spectral bands within the red portion of the spectrum. If narrow spectral bands can out-perform the more traditional broad bands, this would allow our collaborators to develop and market improved, more sensitive sensors to be placed on board tractors to identify weeds.

Narrow-band, on-tractor sensors do not yet exist; therefore, we partnered with Resonon, Inc. (Bozeman, MT), who developed the Pika II hyperspectral instrument, which enabled us to image fields using 80 narrow spectral bands in the blue, green, red, and near infrared portions of the spectrum. The sensor was flown over one field in Cascade County, Montana, and two fields in Gallatin County, Montana, thanks to the cooperation of local farmers. Weed infested and non-infested areas were identified and marked with tarps prior to flight to enable positive location on the imagery. Flights were conducted in early May and June based on farmer's herbicide spray schedule. Field data were collected on the same day as hyperspectral flights. Figure 3.1 shows a processed image from the June flight campaign in false color infrared, where red represents vegetation.

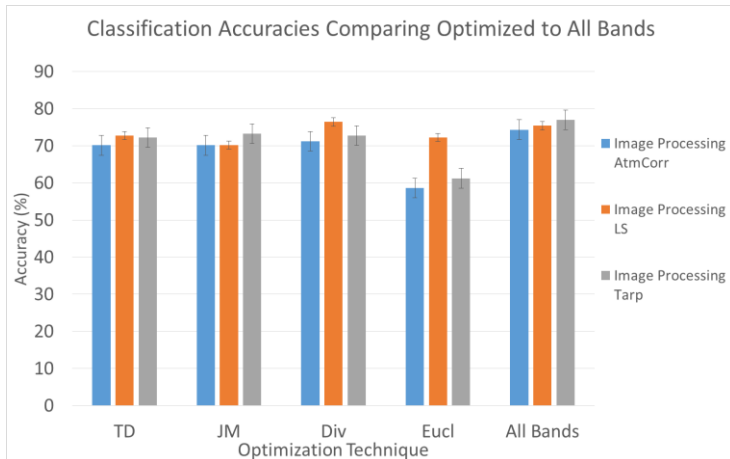


**Figure 3.1** False color IR image of one of the study fields located in the Gallatin Valley, near Bozeman, MT.

Pixels containing infested and un-infested locations were used to select for optimal bands capable of separating weeds and crops. Multiple statistical analyses were tested to evaluate the best approach for identifying narrow spectral bands for weed identification. The use of all 80 bands from the Pika II provided a baseline for the highest accuracies that we could expect. Many of the analyses using a limited number of bands, as would be practical for on-tractor sensors, resulted in substantially reduced accuracies; however, we demonstrated that, with the right approach and combination of bands, the reduced number of bands could achieve comparable accuracies to using all 80 bands (Fig. 3.2). A map using one set of optimal bands can be seen in figure 3.3 in red, compared with a map using all 80 available bands in yellow.

Our analyses of the effects of using narrow bands vs broad bands demonstrated that in airborne studies, narrow bands resulted in much higher accuracies (Fig. 3.4). Common broad-band filters could range from 50-100 nm, while the Pika II produces 6 nm wide bands. The results indicate that narrow-band sensors have the ability to provide substantially higher accuracy in differentiating weeds from crops than broad-band sensors.





**Figure 3.2** Comparison of analyses using reduced numbers of bands (the first four sets of bars) to using all 80 bands provided by hyperspectral sensor (the last set of bars). Most results for the reduced bands are below using all bands, but the best results show that comparable accuracies are possible using reduced bands.

This research has important implications for our associated research developing on-tractor sensors for invasive weed management. Competing technologies have relied on broad band sensors. Using our narrow-band selection techniques, it will be possible to develop on-tractor sensors with significantly improved ability to detect weeds within crops. In addition to this resulting in a higher-value sensing instrument, increased detection accuracies should result in improved crop management, reducing the use of herbicides where weeds are not present, while at the same time reducing the numbers of weeds that are missed using these devices.



**Figure 3.3** Weed maps using hyperspectral data: red using 3 optimal bands, yellow using all 80 available bands.

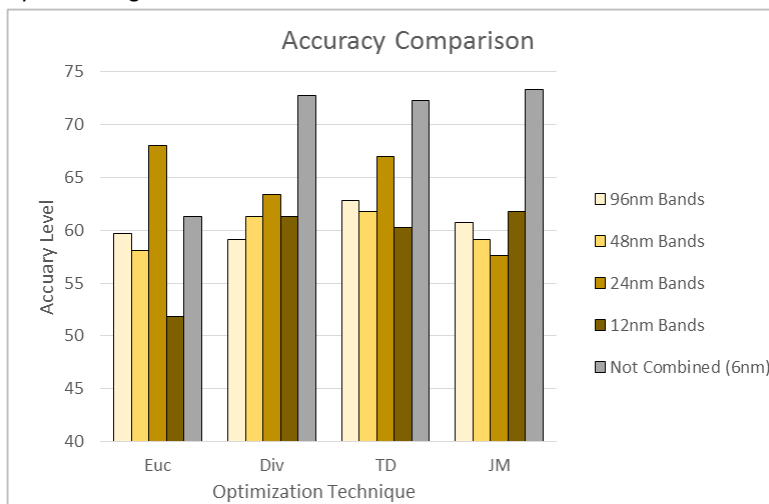
*Additional grant funding received*

\$12,500 from Montana Agricultural Experiment Station

*Additional proposals in progress*  
USGS for \$1,250,000

*Partnerships*

We strengthened and enhanced our long-term relationship with Resonon, Inc., of Bozeman, MT



**Figure 3.4** Comparison of estimated accuracy as bands are widened to 2, 4, 8, and 12 bands. Creating new bands 12, 24, 48, and 96 nm wide.

*Commercial products*

Improved, on-tractor weed sensors using narrow-band technologies; we have demonstrated the feasibility and advantages of this approach

*Jobs created*

One graduate student trained.

Expenditures

Salaries \$83,646.92, Benefits \$7912.87, Operations \$15,841.95, total Expenditures \$ 107,401.74.

**Subproject 4: Machine Vision Algorithms for Precision Agriculture** (Neda Nategh with Resonon and NWB Sensors, Inc.) Develop machine vision algorithms for weed detection and food sorting using spectral imaging data.

#### Milestones

- a) Nov. 31, 2015 Formalize strategy for machine vision research in collaboration with spectral imaging team.
- b) May 31, 2016 Initial machine vision algorithms developed.
- c) Sep. 30, 2016 Initial testing of machine vision algorithms complete.
- d) May 31, 2017 Final testing and development complete.
- e) June 30, 2017 Final report completed.

#### Summary of Accomplishments

The high spectral images from subprojects 1 and 2 were created by the corresponding teams. The students were involved in analyzing these images for classification purposes. Appropriate statistical methods for clustering and labeling the data were discussed and utilized to classify different images into meaningful groups for several purposes. Examples of applications that were using the results of such classification included precision agriculture and automated systems for processing agricultural products. The specified project milestones have been accomplished in a timely manner.

The analyses developed as part of this project were used for applications specified in subprojects 1, and 2. The precision agriculture application included weed detection that was purposed to be integrated with spectral imagers developed by NWB Sensors, Inc. to enable imaging systems for weed mapping at Montana farms. Refer to the subproject 1 report for commercialization of the sensor systems through NWB Sensors, Inc.

The project also aimed for applications developed under subproject 2 to develop high-performance, real-time image processing for hyperspectral imaging in collaboration with Resonon, Inc. Specifically, the project resulted in designing a high-speed hyperspectral waterfall sorting system to fuse object edge information with hyperspectral data to sort agricultural products quickly and efficiently using Resonon's Hyperspectral Imagers and remove rejected items via airjets. Refer to the subproject 2 report for commercialization of this system through Resonon, Inc.

#### Summary of long-term impact (including future activities enabled by MREDI)

The students who were trained and educated for conducting the project goals will fulfill the expertise needs of the labs in their future research. The student training aspect of this project will also contribute to Montana's workforce needs while simultaneously broadening participation of students with science, technology, engineering, and mathematics (STEM) disciplines. The continuation of the developments initiated by this project will open new opportunities for existing and future local spinoffs and startups and also for university research development.

List of the following:

- Total related grant funding received
  - \$187k from NSF
  - \$75K from NASA EPSCoR
  - Total additional proposals in progress

One grant proposal with NASA Dual-Use Technology Development with NASA Marshall Space Flight Center.

- Partnerships formed, strengthened, or expanded  
The project invigorated existing collaborations between MSU and two Montana-based companies, Resonon, Inc. and NWB Sensors, Inc. to enhance their capabilities in the spectral imaging solutions for a variety of **industrial, remote sensing, and laboratory applications. Moreover, this project opportunity resulted in establishing a collaboration between the PI of this project with two other faculty members in the Department of Electrical and Computer Engineering, which would promise new collaborative opportunities for the continuation of the MREDI-initiated projects or for possible new lines of multidisciplinary research on MSU campus or across institutions.**
- New business created  
In future phases, this project has the potential to develop the domain expertise for MSU to start up or partner with Montana-based optics companies to create novel imaging systems and technology.
- Other licensing or technology transfer  
This project focuses on enhancing the technology for the analysis of spectral imaging data, which is inherently ripe with opportunities to transfer to industry. The team collaborated with Montana-based Resonon, Inc., a leader in completely integrated hyperspectral imaging solutions. The result of this project was used to integrate to their hyperspectral imaging cameras aiming to add autonomy to their use their food sorting technology solution. The team also established a collaboration with NWB Sensors, Inc., a remote sensing technology company in Bozeman, which builds a variety of thermal camera system. The spectral image processing developed as part of this project aimed to integrate to their camera systems for weed detection application.
- Commercial products or progress toward products  
Refer to the products reported by subprojects 1 and 2, which were the users of the result of these analyses.
- Jobs created (categorized by private sector, research scientists/engineers, technicians, students, faculty, postdocs, etc.)  
Refer to the products reported by subprojects, which were the users of the result of these analyses.

### Expenditures

Salaries \$81,204.03, Benefits \$7012.84, Operations \$10,802.90, total Expenditures \$ 99,019.77.



**Subproject 5: Microcavity sensors for hyperspectral imaging** (Zeb Barber with Advanced Microcavity Sensors LLC). Advance MSU/Advanced Microcavity Sensors LLC (AMS) technology on microcavity hyperspectral imaging sensors toward commercial applications in agriculture and engineering tests to determine feasibility of mounting sensor technology on UAV; secondary objective solving MT problems in agriculture and biomedical (skin cancer). The primary objective focused on MREDI goal #2: creating private sector jobs.

#### Milestones

- a) June 1, 2016: Investigate non-circular symmetric micro-cavity mirrors for transverse mode manipulation
- b) September 1, 2016: Evaluate Microcavity Hyperspectral Imaging prototype system for early crop disease/weed detection
- c) December 30, 2016: Determine engineering specifications for use of Hyperspectral Sensor on UAV
- d) June 30, 2017: Submit final report specifying technical accomplishments and outlining commercial potential.

#### Accomplishments

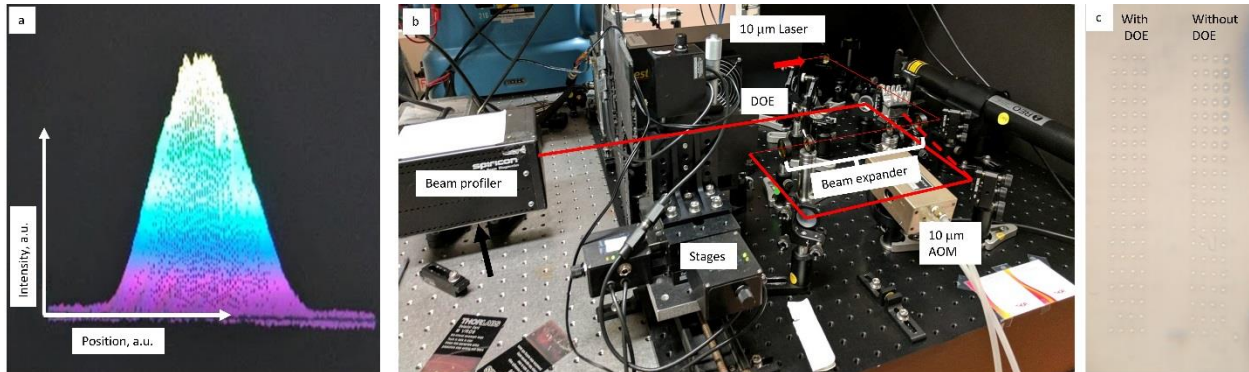
This project was successful on several fronts, including strengthening the prospects of Advanced Microcavity Sensors, creating jobs, securing additional funding, and accomplishing the technical objectives and milestones. All milestones were accomplished; however, for milestone b) in our evaluation process we determined that the strength of the microcavity technology, or Liquid Crystal Arrayed Microcavities (LCAM), is in its ability to provide high spectral resolution in a small package. While high spectral resolution is necessary for many applications including some specialized agricultural research applications, for field agricultural sensing high resolution may be unnecessary and the trade-off between sensitivity and resolution makes the LCAM technology less competitive for agricultural applications. For this reason, we shifted this objective and milestone toward other applications including atmospheric gas sensing including using the sun as a light source.

Technical accomplishments include improving the laser ablation process for making the microcavity mirrors, performing measurements with an LCAM device using the sun as a source, and designing and testing a compact packaging for the LCAM devices suitable to portable applications, such as mounting on UAV's.

#### *Summary of Technical Progress by Objective*

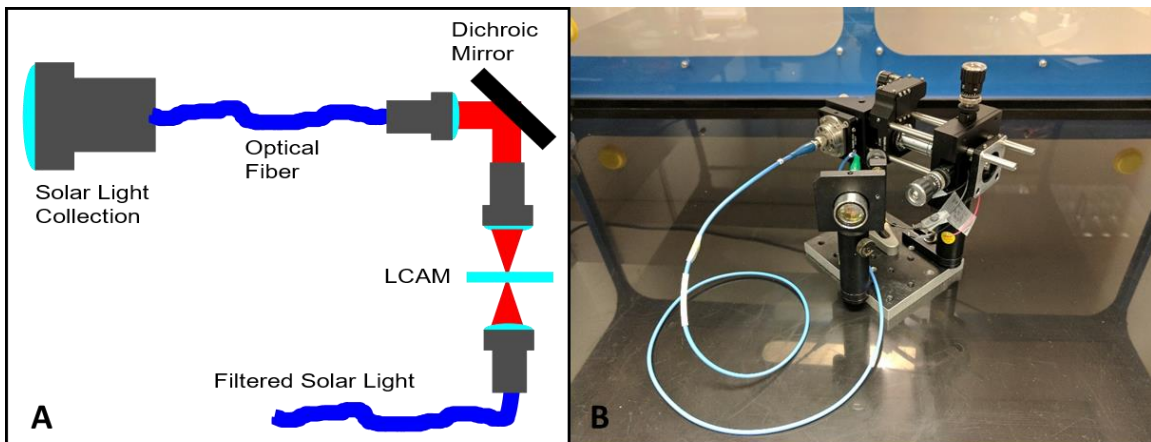
- a) Under this task we investigated many aspects of the laser ablation process of the microcavity mirrors to improve the overall operation of the LCAM devices. This includes improving the consistency of the laser ablation process by adding an Acousto-Optic switch to control the laser and minimizing the debris left over from the ablation process. To minimize the transverse optical modes present in the transmission of LCAM cavities, we integrated a diffractive optical element (DOE) into the ablation system (Fig. 5.1b) used to make the curved mirror surfaces. The DOE increases the radius of curvature of the ablated curved mirror surfaces by changing the ablation laser beam profile (Fig. 5.1a) from a Gaussian to a top hat profile. The DOE should provide a 30  $\mu\text{m}$  diameter top hat beam at the focus of the 15 mm lens used in the ablation setup. Since the top hat occurs only at the focus of the lens, where the beam is the smallest, we cannot resolve the intensity profile with our beam profiler. Thus, to test the performance of top

hat craters, compared to Gaussian craters, we have ablated arrays of craters (Fig. 5.1c) and will test the performance of LCAMS constructed using the two types of craters.



**Figure 5.1** The ablation beam profile (a) has a Gaussian shape outside the focus of the ablation lens. The ablation setup (b) includes a diffractive optical element (DOE), a 10  $\mu\text{m}$  AOM, and beam expansion and collimation optics. The ablation beam path is shown by the red line in b. When viewed with a microscope, the craters (c) burned with the DOE element in the beam path and without look very similar.

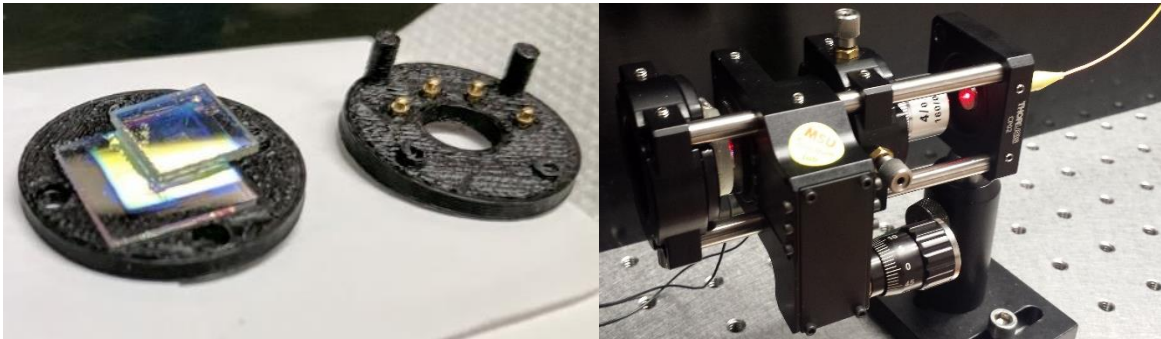
b) For this objective, we decided to investigate the use of LCAM units for atmospheric monitoring. The general idea was that the sun is a very bright light source and it should be relatively simple to gather its light and filter the light with an LCAM. Various chemicals and elements in the atmosphere absorb solar light, so we looked for relevant spectral absorption signatures. Illustrated in Fig. 5.2a is the instrument we built for this effort. The first prototype is pictured in Fig. 5.2b. A 1" fiber coupler was used to gather solar radiation and couple it to a single mode optical fiber. The light from the fiber was collimated and incident on a 45° mirror with the same high-reflectivity coating as the LCAM. The purpose of this was to filter out solar light not within the band of the LCAM. The light was then focused and coupled into the LCAM. After the LCAM, the filtered light was coupled to an optical fiber to make it available for transport to a variety of optical detectors. The instrument was mounted onto a tracking telescope for easy tracking of the sun throughout the day.



**Figure 5.2** LCAM instrument layout used for solar absorption measurements. We could see a solar signal while the Sun was unobstructed by clouds, but the solar background fluctuated significantly and sporadically due to clouds passing between the sun and the instrument.

c) For mounting to a UAV, the most important aspect was robustness to environmental perturbations, including temperature and vibrations. We made significant progress in the manufacturability and

compactness of the LCAM (Fig. 5.3). This new design allowed the LCAM to fit in a standard 1" optic holder to easily make electrical contacts using spring-loaded contacts. This, combined with more compact input and output coupling optics, made for a compact and robust system.



**Figure 5.3** (Left) Compact holder for the LCAM with spring loaded electric contacts. (Right) Compact characterization setup for the LCAM.

In addition, in this final quarter we determined that the liquid crystal tuning approach is much superior to piezo-electric tuning for long-term and short-term stability and robustness to vibrations. The piezo-electric tuning requires a mount that allows the two sides of the microcavity to move relative to one another, making for a more complex mounting system that becomes susceptible to thermal drifts and vibrations. With the liquid-crystal-tuned LCAM, the two sides of the cavity are glued together with a layer of epoxy only 2  $\mu\text{m}$  thick, which makes the dimensional stability and stiffness very good. With the liquid-crystal-tuned design, the main stability issues come from the input and output coupling optics, which could be made more robust using permanently mounted optics like microlenses.

#### *Long-Term Impacts*

There are several long-term impacts of this project. The first and foremost impact has been the strengthening of the LCAM technology that directly benefits the commercial interests of Advanced Microcavity Sensors LLC, which is licensing the technology from MSU for commercial applications. Before this project, AMS was just getting started and this funding enabled AMS to focus on the commercial and business side of the technology. The technology is currently under the patent review process and AMS has committed to prosecuting the patent in the US, Canada, and the EU.

The second impact is that the LCAM technology has attracted significant funding for commercialization through the SBIR and STTR programs and support from the Montana Board of Research and Commercialization Technology. Almost **\$900K** has been invested in the technology in MT from other sources during the MREDI project. A list of additional funding for MSU Spectrum Lab and Advanced Microcavity Sensors (AMS) includes:

- \$77,682 for (8/15 – 3/16) from a Phase 1 STTR contract with the Air Force. The prime on this contract is Spectral Molecular Imaging Inc (SMI). of Beverly Hills, CA.
- \$59,482 for (8/15 – 10/16) from an AMS research contract with the Montana Board of Commercialization and Technology (MBRCT). The total project was funded at \$209,015 between AMS and MSU. The AF STTR project above also represents matching funds for the MBRCT effort.
- \$24,960 for (1/16 – 6/16) from Advanced Microcavity Sensors (AMS) on an NSF \$150,000 SBIR Phase I to develop the microcavity hyperspectral imaging technology for biomedical applications.
- \$230,540 for (8/16 – 7/18) from a Phase 2 STTR contract with SMI and AMS as a continuation of the Phase 1. The total contract value is \$750K with another ~\$100K as a subcontract to AMS.

- \$65,495 for (10/16 – 10/17) from AMS under another Montana Board of Research and Commercialization Technology (MBRCT) grant entitled, “Light Emitting Diode Pumped Laser Array for Ultra-Spectral Imaging.” The total funding between AMS and MSU is \$129,168.
- In addition, AMS and MSU have applied for the NSF Phase 2 SBIR program and a Phase 1 DARPA SBIR which could represent an **additional \$900K** investment in the LCAM technology in MT.

The third major impact of this project is that it has supported jobs at MSU and the Bozeman optics industry. In the first place, Dr. Russell Barbour who is the co-inventor of the technology at MSU, has through the MBRCT and NSF funding, been able to form his company AMS, where he works full time on commercializing the microcavity technology. In addition, two PhD hires, Dr. David Atherton and Dr. Caleb Stoltzfus, were made at MSU Spectrum Lab due to the strength of the funding on this project. Dr. Atherton received his degree in Physics from MSU and a PhD and MBA from the University of Nevada-Reno. Dr. Atherton is continuing to work the MREDI project and additionally is pursuing a new technology area based on laser particle levitation for high performance accelerometry and force sensing that should have markets in the energy sector. Dr. Stoltzfus is a MT native and received both his undergraduate degree and PhD in Physics from MSU. His PhD emphasis in biophotonics under Prof. Alex Rebane is an asset to the project. At AMS, in addition to Dr. Barbour, the NSF funding provided employment for Mr. Austin Beard, a MT native and MSU electrical engineering graduate.

#### Expenditures

Salaries \$68,552.65, Benefits \$24776.94, Operations \$6,684.06, total Expenditures \$ 100,013.65.

**Subproject 6: Hyperspectral imaging for monitoring cell growth** (Ed Dratz with Resonon, Inc.). Design a hyperspectral imaging system for monitoring the metabolic state of live cells in culture. Applications to stem cells for understanding disease mechanisms in individuals, drug testing in cells from individuals, potentially optimize personal nutrition, and solve Montanan's health problems.

#### Milestones

- a) February 1, 2016: Complete design and testing of proof of principle prototype hyperspectral imager with improved cost/benefit, prototype interface for cell hyperspectral analysis, and development of stem cell labeling
- b) May 1, 2016: Integrate the prototype systems for advanced analysis of stem cell metabolism with hardware and software control. Test for evaluation of optimization of selected nutrients
- c) October 1, 2016: Refine and improve software and operating conditions of real time hardware and software for variations of metabolic state for culture optimization
- d) February 1, 2017: Enhance user interface to control system and software to control and optimize nutrient composition; evaluate possible changes in microscope system for improved performance
- e) June 30, 2017: Proof of principle for feedback control of nutrient optimization with nutrient dosing control system. Investigate biochemical individuality in pilot experiment
- f) June 30, 2017: Submit grant proposals to leverage additional support. Final report to MUS that summarizes accomplishments and commercial potential

#### Accomplishments

All milestones were completed, assembling and testing a fully functional hyperspectral imaging microscope, with integrated microfluidic cell nutrient dosing system. The final milestone on feedback control of nutrient optimization with the nutrient dosing system has been initiated, but is not fully complete. The new microscope is a central, foundational tool for investigation/optimization of the nutrient requirements for individual human subject's stem cell reprogramming, renewal and function.

Stem cells located all over the human body replace worn out and damaged cells with fresh cells and need the optimum balance of nutrient building blocks to produce fully functioning replacement cells. We have preliminary evidence that the nutrients in different individual's blood plasma samples need to be supplemented in different ways for the optimization of that individual's stem cell renewal and function. A goal is to make this nutrient optimization of stem cell culture into a biomedical assessment of individual, personalized nutrient optimization, which has tremendous commercial potential that is expected to generate several major patent applications, when it has further advanced.

#### *Long-term impact*

This new approach, enabled by the microscope system created with MREDI support, promises to make personalized, preventative medicine much more rational and effective. The current medical system relies primarily on pharmaceuticals which suppress symptoms of disease but do not prevent disease. Our new approach promises to enable the design of nutrient supplements that are compounded to complement the diets and life styles of individuals to provide much more optimum stem cell function and thus greatly improve long term health—counteracting rising health care costs as well as substantially overcoming the current persistence and increasing incidence of many chronic diseases. Thus, we expect that this new tool will generate very substantial grant and commercial support. We will seek to pilot the clinical application of this new system in Montana, first benefitting citizens of Montana.

#### *Additional grant funding received*

The graduate student in Chemistry and Biochemistry, Elizabeth Corbin, who has been the principal worker on the biological aspects of this project, has been awarded a very prestigious Ford Foundation Graduate Fellowship from the US National Academy of Sciences, starting July 1, 2017, for the completion of her PhD thesis work. This is the first Ford Foundation Graduate Fellowship that has been awarded at MSU and will provide \$25k support.

#### *Additional proposals in progress*

An NIH STTR proposal for further work toward enhancing optical design and commercialization is in preparation and will be submitted soon. In addition, we expect to be able to secure very substantial NIH and Foundation funding to use this microscope for R&D to greatly enhance preventative medicine, improve health, reduce chronic disease, and reduce health care costs.

#### *Partnerships formed, strengthened, or expanded*

Greatly expanded and strengthened partnerships between Resonon, Inc. in Bozeman, the Dratz and Usselman research groups in Chemistry and Biochemistry at MSU, and the Snider research group in Electrical and Computer Engineering at MSU. We also have had very close cooperation with Applied Scientific Instrumentation in Eugene, OR, who provided many of the optical components, and Sigma Millipore, who provided the basic microfluidic cell growth chambers integrated into the new system.

#### *Commercial products or progress toward products*

An excellent start has been made on developing commercial products, as described above.

#### *Jobs created*

This project has provided jobs for two graduate students, one PhD student in Chemistry and Biochemistry and one Masters student in Electrical and Computer Engineering, has occupied one faculty member in Chemistry and Biochemistry and one in Electrical and Computer Engineering, and has engaged a Research Assistant Professor in Chemistry and Biochemistry. The project has also provided a paid internship for an accomplished undergraduate in optical engineering in the private sector. Grant proposals in preparation will engage several staff in the private sector and in the University for additional development and commercialization.

#### Expenditures

Salaries \$57,388.56, Benefits \$9074.88, Operations \$133,536.56, total Expenditures \$ 200,000.

**Subproject 7: Translational research to commercialize micro-mirror technology** (Chris Arrasmith at Revibro Optics). Translate MSU-developed deformable mirror technology to a commercially sustainable product.

#### Milestones

- a) Refine production to achieve a repeatable fabrication process. This milestone will involve a redesign of fabrication masks, purchase of new wafer bonding equipment, and refinement of wafer bonding process (June 30, 2016).
- b) Obtain funding from another source. Revibro will pursue funding through commercial sales and commercial R&D efforts (June 2016), and through SBIR/STTR or similar government funding (June 2017).
- c) Create 2 full time Montana jobs: One job will be created immediately to sustain the founder of Revibro (August 2015); Technical and/or sales and marketing hire (December 2015).

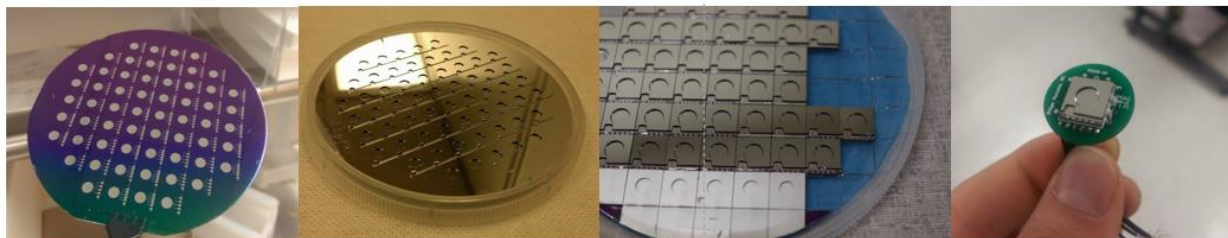
#### Accomplishments

Revibro Optics successfully accomplished all three milestones. Funding from the MREDI has been critical to provide a good foundation for this new startup company, allowing us to improve our fabrication processes and obtain both commercial and federal funding for continued success of the company.

#### *Milestone A:*

Fabrication of our unique deformable mirrors relies on standard Micro-Electro-Mechanical-Systems (MEMS) processes that can be done at the Montana Microfabrication Facility (MMF) at MSU.

At the start of the MREDI project in 2015, Revibro was using the fabrication process previously developed by MSU for fabrication of our 4-mm-diameter deformable mirrors. While this process was a good starting point, there were many issues with the repeatability of several fabrication steps, resulting in poor device yield. Out of the 60 potential mirrors per wafer, we typically yielded 4-6 quality (sellable) mirrors. Fig. 7.1 shows photos from various stages of our fab process for reference.



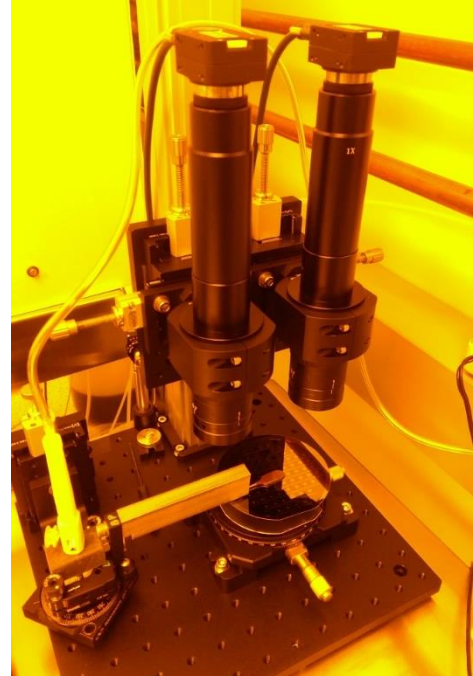
**Figure 7.1** Photos from Revibro's fabrication process: wafer with electrodes (left), wafer with released mirrors (left middle), diced wafer with individual mirrors (right middle), single mirror mounted for testing (right).

The first step to improve repeatability was to redesign the fabrication masks. We designed new mask sets for both 4-mm and 2-mm diameter mirrors, incorporating several innovative ideas to help with mask alignment and mirror flatness. The individual die size was changed from 10 mm x 11 mm to 8 mm x 8 mm, resulting in 79 available die per wafer instead of 60. Also, several critical steps, including through-wafer etching and thin film deposition, were optimized to produce very repeatable results for these steps.

We initially proposed to purchase new wafer bonder equipment to address the most problematic step in our process. However, after evaluating suitable bonders, we found the cost to be much more than anticipated (~\$150k), and much greater than the budget for this equipment. So, we focused on leveraging



our existing bonding apparatus and method by designing a new bond alignment fixture. Our fabrication process uses a stacked wafer approach with electrodes on the bottom wafer and the thin membrane mirror on the top wafer, and requires good alignment of the two wafers prior to bonding to ensure the mirrors are centered over the electrodes. The new alignment system uses two cameras and a 5-axis alignment fixture to align the mirror wafer over the electrode substrate. As summarized in our Q7 report, this new alignment system, along with the use of a spacer layer material, has allowed us to improve our device yield from around 10% to greater than 50%, drastically reducing the cost per device and providing us with many sellable-quality mirrors. A photo of the new alignment system in the Montana Microfabrication Facility (MMF) is shown in Fig. 7.2. We are continuing to work with the MMF to pursue funding from other sources to purchase a new wafer bonder. This bonder will benefit Revibro, as well as several other research groups at MSU.



**Figure 7.2** Photograph of new alignment system used in fabrication of micro-mirrors.

*Milestone B:*

This milestone involved pursuing additional funding from both commercial and government sources. Revibro is pleased to report the receipt of our first two commercial orders in the fall of 2016. This interest from early adopters is a good indication of the commercial viability for this technology. We successfully completed the orders early in 2017 and have been in close contact with both customers to provide support and obtain valuable feedback from the use of our mirrors in their microscope systems.

MREDI funding also has allowed us to exhibit at several trade shows, including Photonics West in San Francisco and Laser World of Photonics in Munich, Germany. These trade shows have been very useful to identify new markets and perform market research. They have also allowed Revibro to find distributors in Europe and Asia that are well positioned to represent our product in these markets. A photo of our booth from the recent Laser World of Photonics is shown in Fig. 7.3.



**Figure 7.3** Photograph of Revibro Optics booth at Laser World of Photonics in June 2017.

Revibro also successfully obtained an SBIR Phase I award through the National Science Foundation. This award, which started February 1<sup>st</sup>, will sustain the business for the next year and provide us funding to develop new metal coatings for our mirrors. The new gold and protected silver coatings are necessary to handle the high-power lasers commonly used in Two-Photon Microscopy (TPM), which is a leading market for our technology.

*Milestone C:*

Through MREDI funding Revibro hired its first full time employee in addition to Chris Arrasmith, the founder, in October of 2016. We now have two full-time and one part-time engineer, and are in the process of hiring



a third full-time engineer to push our technology development. The funding from MREDI and corresponding SBIR funding has been critical to hiring technical staff and getting Revibro Optics off the ground.

Below is a summary of important results from MREDI funding:

- New business created!
- First commercial sales of ~\$40k
- Phase I SBIR award of \$225k (in progress)
- Patent licensed from MSU
- Critical development of our mirrors completed resulting in a prototype kit available to early adopters
- Identification of key future developments toward a first product, which will be accomplished through the SBIR award
- Two full-time and one part-time engineering job created. A third full-time job created by SBIR funding received as a result of the MREDI funding.

#### Expenditures

Sub Award from 41W410 -Total Expenditures \$ 273,999.99.

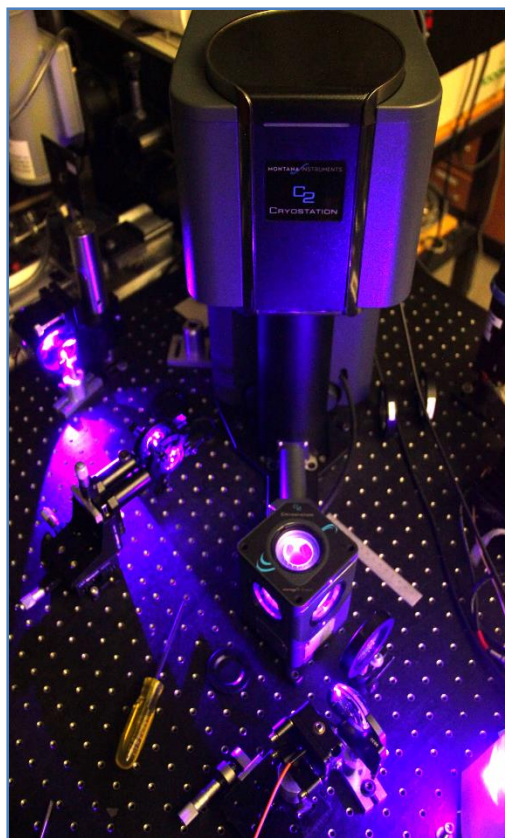
**Subproject 8: Active waveguides and integrated optical circuits** (Rufus Cone, collaborating with Babbitt, Nakagawa, Barber, Himmer, Avci, and Thiel with S2 Corp., AdvR, FLIR/Scientific Materials, and Montana Instruments). Integrate Montana products, expertise, and capabilities to improve marketability, performance, and enable additional products: Build interdisciplinary connections among MUS and Montana optics industries to integrate (a) optical crystals by FLIR/Scientific Materials Corp. (SMC); (b) waveguide photonic components of AdvR, Inc.; (c) Montana Instruments (MI) cryogenic systems; and (d) S2 Corp. (S2C) signal processing devices.

#### Milestones

- a) Fall 2015: Fabrication of rare earth doped optical waveguide suitable for optical signal processing applications
- b) Summer 2016: Integration of an optical waveguide into a cryostat
- c) Spring 2017: Demonstration of SSH processing in a cryogenic waveguide
- d) June 2017: Final report summarizing technical results and emphasizing commercial potential.

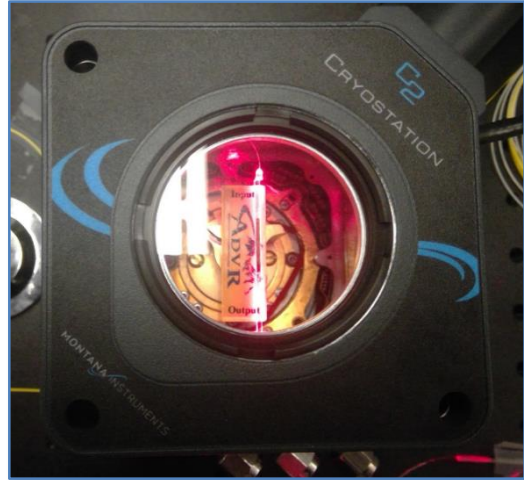
#### Accomplishments

Our vision for this MREDI sub-project was to employ special rare-earth-activated crystals produced by Scientific Materials-FLIR with the waveguide design and the miniature packaging capabilities of AdvR, Inc., all integrated with Montana Instruments Corp. low temperature systems to enable photonic signal processing systems produced by S2 Corp., leading to new products and capabilities for each company as well as the university research program. This collaborative, interdisciplinary, Montana-focused effort was uniquely made possible by the MREDI program, opening completely new opportunities to leverage Montana technologies towards research and development efforts that are beyond the capabilities of individual research groups or companies. During our MREDI effort, all project objectives were successfully completed. MSU researchers worked with AdvR, Inc. to perform optical lithography in the Montana Microfabrication Facility and produce optical waveguides suitable for integration into photonic devices. Methods for activating waveguides with rare-earth ions were also developed and tested at MSU, identifying which processes produced materials suitable for optical signal processing applications at MSU and S2 Corp., as well as which techniques were not suitable due to undesired effects on the optical interactions with the material or the properties of the incorporated ions. The fabricated waveguides were studied in detail for both channel (1-D) and planar (2-D) configurations, and waveguides were successfully integrated with a Montana Instruments cryogenic system at temperatures below 4K to evaluate their properties for integrated optical signal processing and other photonic applications (examples shown in Fig. 8.1 and Fig. 8.2).



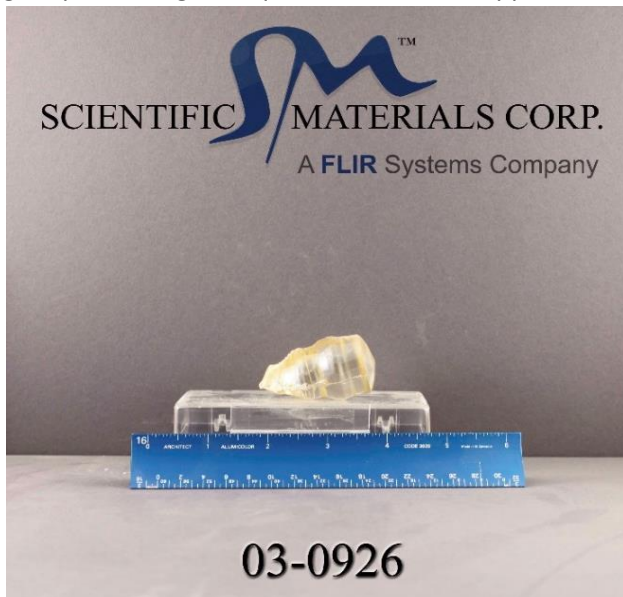
**Figure 8.1** Coupling of laser light into a rare-earth-activated waveguide at 3K in a Montana Instruments Cryostation.

MSU personnel and students also worked closely with Scientific Materials Corp./FLIR to improve the growth of rare-earth-activated lithium niobate crystal materials required both for current S2 Corp. signal processing applications, as well as for producing ion-doped crystal wafers for waveguide fabrication. Students worked with Scientific Materials to develop a method for improved control of thermal gradients during the growth process, allowing larger and higher-quality lithium niobate crystals to be produced (an example crystal is shown in Fig. 8.3). Materials with different chemical compositions were also grown, enabling new properties for improved performance in optical signal processing applications. Based in part on our MREDI results, new international customers have already inquired into purchasing these special materials from Scientific Materials Corp.

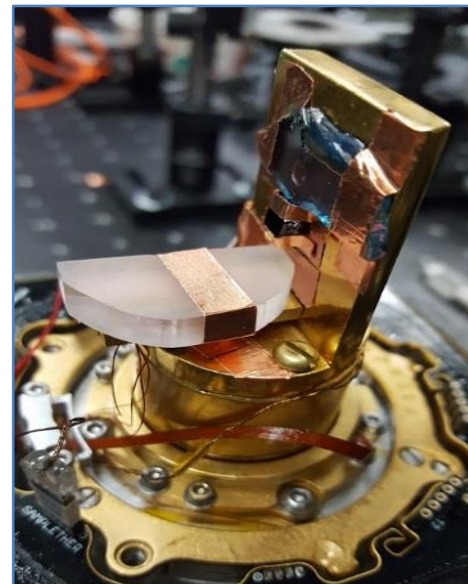


**Figure 8.2** Example of optical fiber coupling of an AdvR Inc. waveguide within a Montana Instruments Cryostation.

During the process of integrating waveguides and bulk crystal samples into the Montana Instruments cryocooler, MSU personnel and students interacted regularly with Montana Instruments personnel on planning and optimizing mounting strategies for these specialized samples. For example, general purpose cryogenic samples holders designed by MSU students were shared with Montana Instruments for potential use by other customers. This effort enabled the successful study and demonstration of optical signal processing in both waveguide and bulk rare-earth-activated crystals. In particular, spectral hole burning processes used in photonic spectrum analysis applications were demonstrated for planar waveguide structures at 3K using a Montana Instruments cryocooler in Tm:YAG, a principal material system used by S2 Corp. for their current products. Optical coherent transient processes used for photonic signal processing and quantum network applications were



**Figure 8.3** One of the new single-crystal boules of lithium niobate doped with thulium and magnesium ions that was grown by Scientific Materials Corp. with assistance from MSU researchers and students.



**Figure 8.4** A single crystal produced by Scientific Materials Corp. mounted in a Montana Instruments Cryostation for study at MSU, where its properties are evaluated for photonic signal processing products developed by S2 Corp.

also demonstrated in Tm:LiNbO<sub>3</sub> channel waveguides in collaboration with researchers at the University of Calgary, which is another promising optical signal processing system. As another example, Fig. 8.4 shows a crystal grown by Scientific Materials Corp. that we engineered to have a significantly increased optical signal processing speed; in the Figure, it is being studied at MSU using a Montana Instruments cryocooler.

Over the course of the MREDI project, many technical goals and innovations were achieved. Some of these successes and developments have been summarized in our quarterly project reports, with several significant accomplishments briefly highlighted in the following partial list.

- Optical coupling of waveguides held at 4K in mechanical cryocoolers
- Testing of Montana Instruments and S2 Corporation mechanical cryocoolers
- Spectroscopic testing of new laser materials produced by Scientific Materials Corp
- Development of a new technology for nondestructive characterization of optical waveguides
- Optical study of waveguide properties at cryogenic temperatures
- Development of sub-micron periodically-poled nano-photonic devices
- Testing vibrationally induced coherence loss in closed-cycle optical cryostats
- Development of improved laser characterization capabilities at new wavelengths
- Study of the effects of chemical processing on optical spectra of crystals
- Optical lithography and waveguide fabrication in lithium niobate crystal wafers
- Lithium niobate opto-electronic crystal growth
- Diffusion doping of rare-earth ions into lithium niobate crystals
- Fabrication of proton exchanged waveguides in rare-earth-activated crystals at MSU
- Theoretical analysis of the effects of spectral hole burning on optical waveguides
- Material and waveguide chemical composition characterization at MSU physics and ICAL
- Development of new cryogenic sample mounting hardware
- Optical waveguide theoretical modeling and computer simulations using COMSOL Multiphysics

In addition to the critical technological and scientific impacts, the MREDI effort also had many significant educational and economic impacts, some of which are described in the following sections.

#### *Impact on New University Research Funding*

This MREDI project has already had a significant impact on new research funding at Montana State University by nurturing new ideas in their early stages, providing new experimental and computational capabilities, generating new ideas from the interdisciplinary collaborations, and illuminating opportunities for new technologies from interactions with the local Montana optics industry. While we expect the impact of our MREDI effort on academic and industrial research and development to continue to increase well beyond the end of the project, there have already been a significant number of new research projects funded at the university over the course of the project that are briefly outlined below. ***MREDI provided key support, capabilities, and technologies for these projects totaling \$1,554,000 of new research funding for MSU.***

- **\$60,000** awarded to MSU from S2 Corporation for extending the project “Efficient Photonic Computational Engine for Selection and Filtering” (PI: Barber) for the period 12/2015 to 3/2016.
- **\$763,000** awarded to MSU over three years (11/2015 – 11/2018) as part of a >\$11 million contract with the Office of Naval Research in the area of Electronic Warfare for the project “Full-Spectrum Staring Receiver (FSSR)” (PI: Barber). This project is led by BAE Systems or Nashua, NH. The core of the system is based on the S2-SA technology that was developed at MSU and S2 Corporation. In total,

**\$4.5 M of this contract is for Montana-based entities.** The MSU press release can be found at <http://www.montana.edu/news/16038/s2-corporation-and-msu-jointly-announce-contract-to-provide-wideband-sensor-capability-to-u-s-navy> and a TV segment filmed and produced by KXLF-TV can be viewed at: <https://www.youtube.com/watch?v=k9TnY49tvyc&feature=youtu.be>

- **\$181,000** awarded to MSU over 1 year (8/2016 – 6/2017) as a subcontract from S2 Corporation on a SBIR project from Air Force Research Labs (AFRL) called “Instantaneous Wideband 10 GHz Time Difference of Arrival” (PI: Barber).
- **\$50,000** awarded to MSU over 4/1/16 to 12/31/16 for the project “Nanoscale Poling and Structuring in Nonlinear Optical Materials,” (PI: Himmer and Nakagawa) funded by the NASA Montana Space Grant Consortium.
- **\$148,000** awarded to MSU over two years (Q1 2017 – Q1 2019) as part of a NSF Phase IIB SBIR project “Photonics Enabled Extreme Bandwidth Wireless Communications Receiver” (PI: Barber). The goal of this project is to implement the waveguide integration techniques developed on MREDI into S2-SA and S2 processor applications at S2 Corp.
- **\$244,000** awarded to MSU over one year (Q1 2017 – Q1 2018) from IARPA as part of a joint \$1M effort between S2 Corporation and Spectrum Lab effort on “Efficient, High-data rate Photonic Computational Engine for 2-D Image Processing” (PI: Babbitt) to apply the S2 processing to 2D image analysis. This new optical computing research brings \$1M of federal funding to Montana and was highlighted recently in the Bozeman Daily Chronicle newspaper: [http://www.bozemandailychronicle.com/news/montana\\_state\\_university/s-corporation-and-msu-announce-new-contract-for-big-data/article\\_76cd45e3-ab4f-5ccc-867e-ba9350f5e187.html](http://www.bozemandailychronicle.com/news/montana_state_university/s-corporation-and-msu-announce-new-contract-for-big-data/article_76cd45e3-ab4f-5ccc-867e-ba9350f5e187.html)
- **\$81,000** awarded to MSU over one year (Q3 2017 – Q2 2018) by the Montana Board of Research and Commercialization Technology for “Internally Cooled Laser Trapped Particles for Ultra-High Sensitivity Accelerometry” that will build on our expertise in rare-earth-activated materials to enable a new area of research in Montana.
- **\$27,000** awarded to MSU over one year (Q3 2017 – Q2 2018) by the Office of Naval Research for “Functionalization of Optically Levitated Particles” to use rare-earth-doped micro-crystals for new military sensing applications.

A number of other funding proposals are being prepared based on the results of our MREDI efforts and the new research capabilities and partnerships developed during this project.

#### *Impact on Montana Industry Funding*

While the technologies developed during our MREDI effort have broad economic impact on the Montana optics and photonics industry, one of the more easily quantifiable measures of economic impact is new federal contracts and research funding brought into the state. While MREDI is supporting the university research and development efforts and does not directly support new projects at the commercial businesses, our work provides the foundation for the continued growth of the state industries through the early-stage technologies and expertise being advanced to the point where transfer to Montana companies is practical.

In particular, our MREDI efforts on developing cryogenic optical waveguide technology are crucial for the next level of integration and miniaturization of the photonic signal processing devices being developed at S2 Corporation. Just over the course of our MREDI effort, S2 Corporation has secured significant federal funding in the amount of **\$8,608,000** to develop the S2 technology, as outlined by the table in Table 8.1 that was provided by S2 Corporation. While this funding is not a direct result of the MREDI project, it



shows the significant continued interest and development of the S2 technology, with our MREDI effort providing the seed technologies required to develop the next generation of S2 technology.

Table 8.1 Recent federal funding secured by S2 Corp. to develop the S2 technology for defense applications (courtesy of Dr. Kris Merkel, CEO and President of S2 Corp).

Funding Agency		S2 prime	Start date
Office of Naval Research (ONR) - Electronic Warfare (BAE Systems prime contractor)	ONR base Y1	\$ 1,870,000	
	ONR adds	\$ 600,000	Jun-15
Air Force Research Labs Sensors Division Phase III SBIR and DARPA - S2 System Build and Delivery	AF Sys bld	\$ 1,604,000	Oct-15
Air Force Research Labs Sensors Division Phase III SBIR and ONR - Field Testing	VH2	\$ 800,000	Jan-16
National Science Foundation Phase 2B SBIR	NSF Ph2B	\$ 500,000	Jan-17
Air Force Research Labs Sensors Division Phase III SBIR and ONR - Time Difference of Arrival Demo	TDOA	\$ 920,000	Jun-16
Army Rapid Innovation Fund - S2 System Improvements and Tests	Army RIF	\$ 1,300,000	Jun-16
IARPA High Throughput 2D Image Correlation	IARPA 2-D	\$ 1,014,000	Feb-17
	SUM	\$ 8,608,000	

In addition to the impact on S2 Corp., our collaborative efforts with Scientific Materials Corp. have also resulted in additional international business opportunities. In particular, there have already been inquiries regarding the purchase of the new lithium niobate materials produced as a part of our joint effort. In addition, as a direct result of our MREDI efforts, **\$50,000** of another rare-earth-activated material developed with MSU is being purchased by a customer in Canada for applications closely related to the photonic signal processing applications developed in Montana.

Impact on Montana Student Education, Training, and Employment:

The MREDI effort has provided a unique educational opportunity for Montanans at all levels of education. In addition to the senior university personnel, we have had **3 research scientists, 2 postdoctoral students, 6 graduate students, and 6 undergraduate students** all working on this MREDI sub-project, with 2 students receiving BS degrees and 1 student receiving an MS degree over the course of the effort. As part of the MREDI group effort, there have been **more than 10 public presentations and colloquia by students** working on MREDI where they have presented their research. In addition, several of the students and faculty members working on our MREDI effort volunteered for public outreach and education (an example is shown in Fig. 8.5), providing an important service for the Montana community.

During this effort MSU collaborated with the local optics company, AdvR, Inc., to learn and develop processes to define channel (1D optical propagation channels in an optical crystal) waveguides in LiNbO<sub>3</sub>, which is a material for RF and optical signal processing applications. As a result of this MREDI-enabled collaboration, MSU personnel (Fig. 8.6) gained new expertise in key processes include design of optical lithographic masks, spin-coating and curing of photoresist, UV exposure and development of the photoresist, metal deposition, and chemical etching. This training resulted in the production of channel LiNbO<sub>3</sub> waveguides using proton exchange that was performed in AdvR’s facilities.

The particular and unusual focus of MREDI on developing new technologies with direct economic impact has exposed the students to ideas and practical



Figure 8.5 Example of STEM outreach at Montana schools by MREDI researchers.

issues critical for entrepreneurial careers. Undergraduate and graduate students are working in close collaboration with professionals in the local optics industry, with benefits for all involved. Students regularly visited the local companies to use their specialized equipment, such as the M-lines waveguide characterization system and wafer dicing saw at AdvR, Inc. and the crystal X-ray diffraction system at Scientific Materials Corp. During these exchanges, the students gained remarkable insight into industry and business while the companies also learned more about capabilities and expertise available at the university. ***These valuable relationships lead to career opportunities for the students and encourage them to remain in Montana and contribute their skills to the development of the local community.*** The relationships fostered by MREDI will continue to be developed and strengthened, leading to opportunities for future collaborative research and development efforts.



**Figure 8.6** Research engineer Tia Sharpe in the Montana Micro-fabrication Facility working on waveguide fabrication in collaboration with AdvR, Inc.

#### *Impact on Student Employment in Montana Industries*

Employment in the optics and photonics industry has continued to expand at a rapid pace, with new personnel recently being hired at all of our partner companies. In particular, management at both S2 Corp. and Montana Instruments Corp. have said that their needs for employees is far surpassing the supply of workers being produced in the state. MREDI provided a key service in helping to make students aware of these career opportunities and encouraging them to enter these fields where the Montana economy is rapidly growing. This strong collaborative and invigorating environment also encourages more senior professionals to remain in the state. In one case, a senior researcher turned down a lucrative job offer in California to work on lighting system development to remain in Montana and work with MSU and local industry on this MREDI effort. In addition, the students that have graduated while working on this MREDI effort have all either found immediate employment in their chosen field or continued with their higher education in Montana.

Undergraduate student Kaitlin Poole completed her Bachelor's degree in Physics at MSU while working on this MREDI effort, and after graduating from MSU, she received a commission as an active duty second lieutenant and was deployed to the Information Directorate of the Air Force Research Lab (AFRL). Kaitlin and her family are residents of Bozeman, where her father works in health care.

Undergraduate student Brett Wilkins (Fig. 8.7) also completed his Bachelor's degree in Physics at MSU while working on this MREDI effort. After graduating from MSU, as a direct result of this MREDI effort Brett applied for a job at AdvR, Inc. in Bozeman, MT and was subsequently hired for a position to help with producing and characterizing their waveguide products. Brett has recently entered the physics graduate program at MSU and is continuing to work part time at AdvR Inc. while pursuing his MS degree.



**Figure 8.7** Brett Wilkins completed his MSU B.S. degree while working on MREDI and is now employed by AdvR, Inc., helping produce their optical waveguide products.

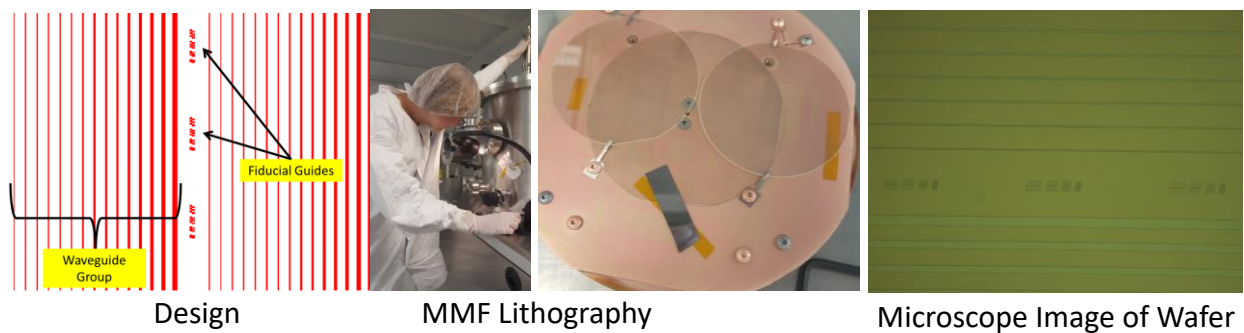
Postdoctoral researcher Caroline Richards who worked on this MREDI project, originally coming to Montana from France, also plans to enter the local Montana photonics industry once her postdoctoral work at MSU is completed.

Her work as part of MREDI provided essential experience that will help her to pursue a successful career in the local industry.

### *Impact on Montana University Competitiveness*

MREDI has had a significant positive impact on the educational and scientific competitiveness of the Montana University System. This project engendered a range of new collaborations between groups and departments within the university, as well as between the university and Montana industry. This led to innovative research and development as well as enhanced student involvement in interdisciplinary investigations. MREDI further enhanced the unparalleled educational training at MSU involving close collaboration with both academic and industrial researchers in the Montana photonics community. Furthermore, the new cutting-edge technologies studied as part of MREDI also provided a rich research environment for students at all stages of their education.

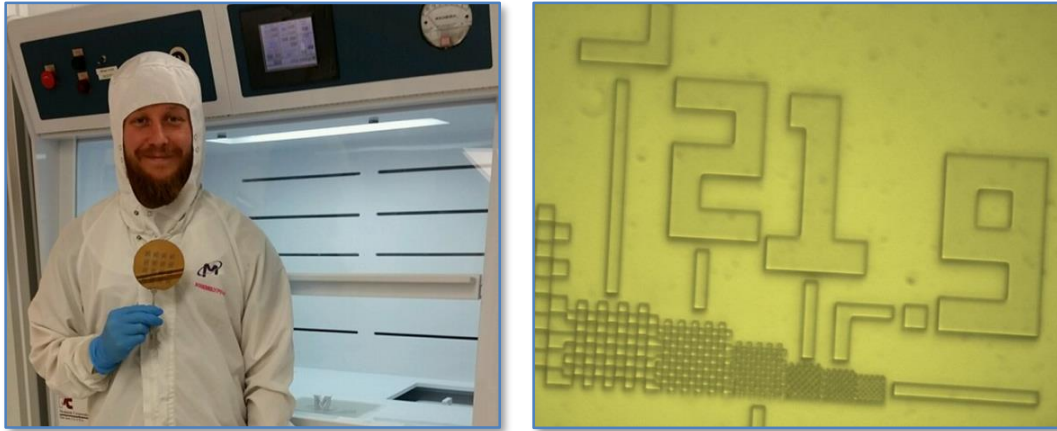
The integration of optical waveguide technology and rare-earth-activated materials during our MREDI effort has created expertise and infrastructure that supports a range of new research efforts. In particular, optical lithography (Fig. 8.8) is a key enabling technology for many integrated signal processing research and development areas, providing an essential foundation for new research programs being developed and expanded at MSU and in the local industry. Additional work under MREDI on the next generation of nano-photonic device fabrication (Fig. 8.9) will enable entirely new research avenues.



**Figure 8.8** Illustration of the optical waveguide fabrication process.

Our MREDI efforts have also made other significant contributions to the university research infrastructure. For example, integration of waveguide devices with cryogenic technology allows new properties of optical materials to be studied that previously could not be accessed. Advanced computational software that has been acquired as part of MREDI (such as Comsol Multiphysics) allows a wide range of photonic and nonlinear optical devices to be designed and simulated, enabling new research proposals that have been submitted. New capabilities for cutting very thin crystalline samples has allowed new optical materials to be studied and also has enabled new collaborative projects with local companies. A range of optical crystal growth and processing capabilities have been developed at MSU as part of MREDI, allowing us to produce entirely new samples of optical materials that are of both commercial and scientific interest. New laser systems have been built and new interferometric characterization systems have been built to study their properties.

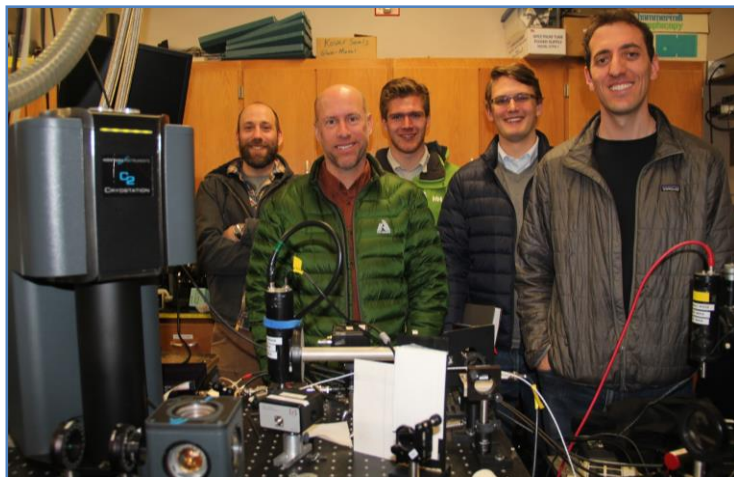




**Figure 8.9** Graduate student Torrey McLoughlin (left) in MSU's Microfabrication Lab, holding a patterned silicon wafer (right) that he produced as part of his experimental and theoretical studies of the potential for sub-micron lithographic structuring of optical materials for new photonic technologies.

### *Impact on Montana Industry Competitiveness*

In addition to developing new technologies that will lead to new products for Montana companies, our MREDI efforts have had a range of broader impacts on the local optics industry. For example, we have been working with Montana Instruments Corp. to evaluate the performance of their systems in a range of laboratory environments, providing essential feedback (Fig. 8.10). We have also been in discussion to test new prototype systems being developed by Montana Instruments, helping them to refine their product while also providing the university with a new cutting-edge technology beyond the capabilities of systems at other universities. The international exposure that we helped provide for their products has also helped to increase sales of their systems, with many researchers working in fields related to current MSU research programs now using Montana Instruments cryocoolers (for example, see work highlighted on the Montana Instruments web site at <http://montanainstruments.com/low-temperature-physics-research/spotlight-on-researchers/1200/Spectral-hole-memory-for-light-at-the-single-photon-level/>).



**Figure 8.10** Engineers and scientists from Montana Instruments visiting MSU to discuss our MREDI efforts and how their instruments are used in practical operation.

As part of MREDI we have also begun studies of how different spectroscopic properties of materials may be used to characterize the chemical and structural properties of optical waveguides produced by AdvR, Inc., potentially leading to additional future joint research efforts. We have also adapted the advanced remote sensing and ranging technologies used by the local companies Bridger Photonics and Blackmore Sensors and Analytics (Bozeman) to study the quality of optical waveguides and lithography of AdvR, Inc. products, potentially providing an improved non-destructive method for product quality control and optimization. Furthermore, we expect that our work on developing sub-micron periodically-poled nanophotonic devices will directly lead to an entirely new class of products for AdvR.

Tying everything together, our innovations and studies all directly impact the photonic signal processing devices under development at S2 Corporation. Each technology developed or improved as part of our MREDI work can be incorporated into the integrated signal processing devices, potentially improving system performance or providing alternative design options. As such, this work supplied key seedling technologies that will lead to continued product development, new funding, and increased revenue.

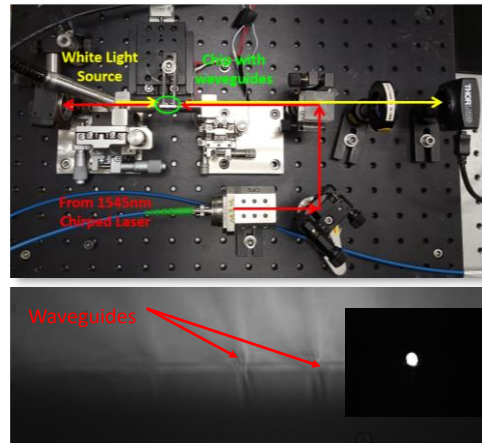
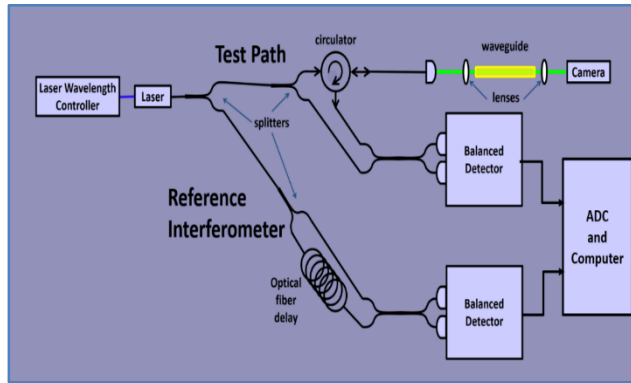
Our MREDI efforts have a range of broader impacts on the local optics industry. We have worked closely with Scientific Materials Corp. to develop a crucible after-heater design that reduces thermal gradients and crystal strain during crystal growth. This effort was led by MSU materials science graduate student Tino Woodburn and successfully enabled larger single crystals of the important optoelectronic crystal lithium niobate to be produced. Using this approach, Scientific Materials Corp. grew a new lithium niobate crystal that incorporates thulium ions for photonic signal processing at S2 as well as magnesium ions that increase the optical damage threshold of the material. Additional growths of lithium niobate and lithium tantalate crystals are underway. These new materials are vitally important to research efforts at MSU and to photonic signal processing applications at S2 Corporation. They are also of broader commercial interest as a product for Scientific Materials Corp., with inquiries by international customers regarding these materials already being received.

#### *Impact on New Technology Patents*

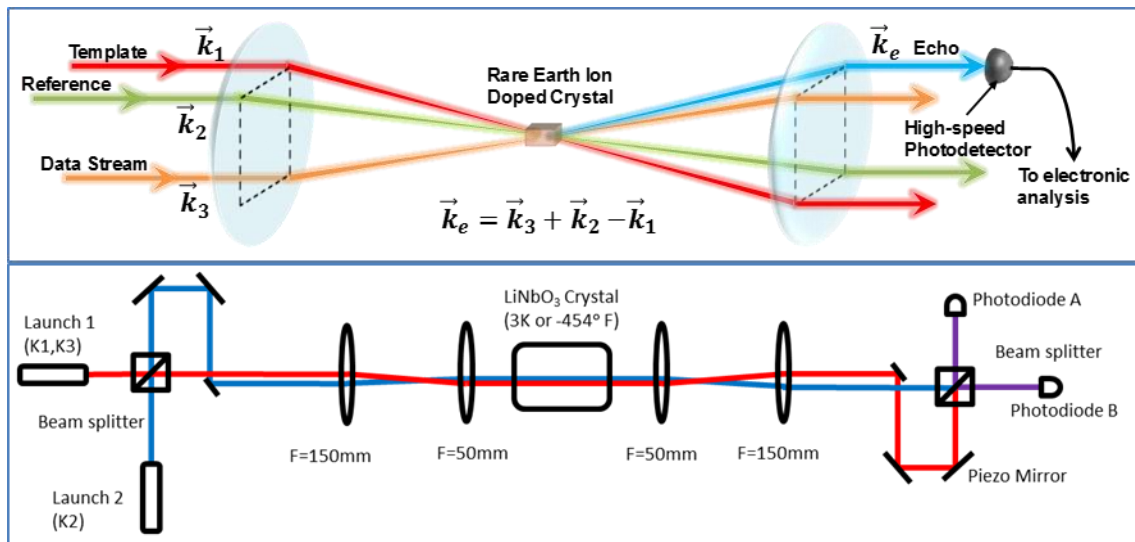
During our MREDI effort, a promising new technology was developed for providing enhanced thermal contact with insulating optical materials, allowing increased maximum system operating powers in the cryogenic environment. We are working with MSU TechLink to prepare a provisional patent application for this invention. We expect that this technology will directly impact several local Montana companies, including S2 Corp., Montana Instruments Corp., and Scientific Materials Corp., each for a different potential market segment (photonic signal processing, cryogenic systems, and high-power lasers, respectively) and licensing of the intellectual property to these companies will be pursued once the patent is filed.

Also during this project, we investigated using ultra-high resolution FMCW LADAR technology that Spectrum Lab developed with Montana company Bridger Photonics Inc. as a non-destructive method of determining waveguide propagation loss independent of input and output coupling losses. The optical waveguides fabricated by MSU Spectrum Lab in cooperation with AdvR, Inc. were tested using the nondestructive method (Fig. 8.11). This method uses a frequency chirped-laser, a reference fiber interferometer, and signal processing algorithms. With this method, we measure the back scattering in a waveguide to determine waveguide propagation losses without destroying the waveguide, as in the typical cut-back method. This technique could also be refined for other industrial measurement applications by Bridger Photonics Inc., for example. Consequently, this new technology is being investigated for potential patenting and eventual licensing opportunities.

In addition to these new technologies, as part of our MREDI effort, MSU Spectrum lab developed and tested a new photonic signal processing protocol that allows many complex holographic processes to be transferred to integrated waveguide device architectures. This novel technique (Fig. 8.12) allows optical programming and signal beams to be separated after passing through a waveguide by using interferometric methods, a key requirement for practical device implementations that would employ sophisticated photonic circuits. As this technology is further refined, we will evaluate opportunities to patent and license this new approach.



**Figure 8.11** Non-destructive characterization of waveguides fabricated by Spectrum Lab with AdvR Inc. assistance using an ultra-high resolution FMCW LADAR technology previously developed in collaboration with Bridger Photonics. (Left) Test Setup for nondestructive optical waveguide characterization. (Upper Right) Characterization setup. (Lower Right) Image of the front facet of the waveguide with inset of output facet with coupled laser light.



**Figure 8.12** (Top) Diagram of optical geometry used for correlative signal processing applications in bulk crystals. (Bottom) New interferometric signal processing geometry developed by MSU Spectrum Lab to enable correlative signal processing to be implemented using integrated waveguide devices.

### *Impact on International Promotion of Montana Science and Industry*

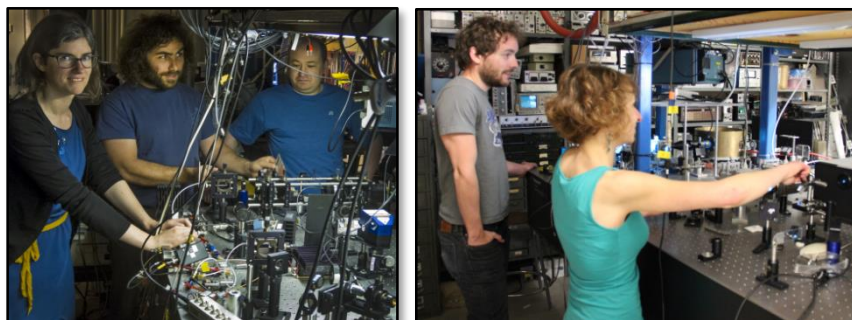
The extensive international collaborations involved in parts of our MREDI research have led to increased exposure of the local optics industry to international markets. We routinely arrange for visiting

researchers to tour several of the local companies whenever they visit Bozeman, increasing awareness of the impressive technological products produced here in Montana. Furthermore, presentations by MSU personnel at international professional conferences highlight the interaction with the local industry and the unique products available from them. During the course of this project, personnel working on this MREDI subproject have presented **18 invited talks, seminars, and colloquia**, with all travel expenses paid for with other funding sources. At many of these meetings, substantial excitement and interest was expressed by the audience regarding the Montana photonics industry and the products that they offer. Furthermore, our MREDI-supported research has already led to **10 publications in peer-reviewed scientific journals (5 more in preparation)**. These publications increase the international prestige and profile of the university research programs as well as the state of Montana more broadly.

Our MREDI research efforts continue to increase the exposure of the local optics industry to international markets. One activity toward this goal is the recent work by researchers and students at MSU on developing an exhibit for the American Computer Museum in Bozeman ([www.compustory.com](http://www.compustory.com)) to highlight the unique signal processing and quantum information research and industry present here in Montana. This public display will explain to the broader public how the technologies being developed and commercialized here in Montana will enable the next generation of computing and communications.

During this quarter the Cone research group also received a significant honor by one of their scientific publications on materials for optical signal processing and quantum information being included in a special issue of the Journal of Luminescence entitled “Luminescence Legacy” ([www.journals.elsevier.com/journal-of-luminescence/virtual-special-issues/luminescence-legacy](http://www.journals.elsevier.com/journal-of-luminescence/virtual-special-issues/luminescence-legacy)). This MSU research publication was one of only 15 chosen for this special issue; it was selected from more than 13,000 peer-reviewed publications spanning the 47-year history of the international journal.

The results and technologies resulting from our MREDI effort have also greatly enhanced our international scientific collaborations. Many aspects of our MREDI work are more broadly relevant to emerging fields such as secure quantum communications, leading to new interactions with other research groups and institutes. During MREDI, we hosted **24 international visitors** as part of collaborations with groups at California Institute of Technology, University of San Francisco, University of South Dakota, University of Calgary (Alberta, Canada), Australian National University (Australia), Chimie Paritech (France), AlphaNov (France), and University of Otago (New Zealand), some of which are shown in Fig. 8.13. No MREDI funds were used for any visits and all expenses were covered either by the visiting researchers or other sources.



**Figure 8.13** (left) Researchers and students working on MREDI efforts in the MSU Physics Department. (right) A visiting scientist and graduate student from University of Calgary working in the MSU Physics Department on characterizing new rare-earth materials for signal processing applications related to the MREDI effort.

#### Expenditures

Salaries \$423,501.52, Benefits \$106,676.78, Operations \$369,812.93, total Expenditures \$ 899,991.23.

### **Subproject 9: Optical parametric oscillator for tunable lasers** (Kevin Repasky with AdvR, Inc.).

Investigate optical parametric oscillator performance in support of characterizing large aperture periodically poled non-linear optical crystals and in support of continued development of large area methane detection.

#### Milestones

- a) December 2016: Model optical parametric oscillator performance using SNLO modeling tools
- b) June 30, 2017: Demonstrate singly resonant optical parametric oscillator pumped at 1064 nm and seeded at 1650 nm
- c) June 30, 2017: Final report including scientific merit and commercial products or potential

#### Accomplishments

The main goals of this research project involved developing a laser source for methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) differential absorption lidar (DIAL). The laser development was based on the nonlinear optical parametric oscillation (OPO) using an injection seeded singly resonant architecture. The development of the OPO for methane, operating near 1650 nm, was successfully completed by Briana Jones and is described in detail in her master's thesis titled "Development of a singly-resonant optical parametric oscillator for carbon cycle science." Since graduating with her master's degree in Electrical and Computer Engineering, Briana has been working at Advr, Inc., a Bozeman-based photonics company specializing in nonlinear optical materials and integrated waveguide structures. The development of the OPO for carbon dioxide, operating near 1570 nm, was completed by Chat Chantjaroen and is described in his Ph.D. thesis titled "Development of a micro pulsed lidar and a singly-resonant optical parametric oscillator for CO<sub>2</sub> dial for use in atmospheric studies."

The OPO developed for methane studies was based on large-aperture periodically-poled magnesium-oxide-doped lithium niobate as the nonlinear optical material. Results from the OPO indicate that energies on the order of 1 mJ are possible with the experimental setup presented when operating at 20 Hz repetition rate. The OPO produced a linewidth of 10.5 GHz, measured on a system with resolution of 6.6 GHz. Future work includes optimization of the OPO to increase the output energy from the system to 3 mJ by improving mode-matching into the cavity and increasing the energy into the system. Additionally, a method to precisely measure the linewidth of the OPO output is necessary as well as a pump laser that operates at 1 kHz to test the performance of the OPO at 1 kHz. The initial results show promise for the use of the OPO as the DIAL laser transmitter and with improvements, the OPO should meet the requirements for the DIAL system. Furthermore, the modeling efforts based on SNLO favorably compared with the measured performance of the OPO at 1650 nm validating the modeling efforts.

The OPO developed for carbon dioxide studies requires an output energy of 3-mJ at 1571 nm with a repetition rate of 1 kHz and a linewidth on the order of 3 MHz (24.7 fm) in order for a DIAL to meet an error of less than 2%. Our results indicate that an OPO is the best choice for the DIAL transmitter due to its high output energy at 1571 nm and narrow linewidth. With dither locking and a seeding injection of 160-mW power, the OPO produces a maximum measured output energy of 2 mJ at an input pump energy of 11.5 mJ and predicts a possible maximum output energy of 2.5 mJ at an input pump energy of 20-mJ. The steady state of the OPO occurs between the input pump energies of 5.5-7.5 mJ when the conversion efficiency reaches 20%. The achievable narrowest linewidth from the OPO is 11.4 GHz (0.0941 nm) measured with a 0.06 nm resolution. Although the DIAL transmitter requirements are not quite met, the close results suggest a potential success of an OPO, especially when there is still room for improvements. To achieve a higher output energy and narrower linewidth, the OPO can be improved

with a better choice of mirrors, better mode-matching, better locking, and higher-power seed laser. Without further narrowing the linewidth, the output energy can be increased with increased input pump energies. However, we must take precaution when tuning up the input pump energies as they shall not exceed the damage threshold of the crystal. Again, the modeling efforts based on SNLO favorably compared with the measured performance of the OPO at 1570 nm further validating the modeling efforts.

#### *Students working on this project*

Briana Jones graduated with a MS in Electrical and Computer Engineering. Since graduating, she has been employed by Advr, a Bozeman based photonics company. At Advr, Briana continues to work with nonlinear optical material similar to her thesis work.

Chat Chantjaroen graduated with his Ph.D. in Physics. Chat has accepted an academic position.

Students working on other MREDI projects:

Cooper McCann received his Ph.D. in physics titled “Mesoscale, radiometrically referenced, multi-temporal hyperspectral data for CO<sub>2</sub> leak detection by locating spatial variation of biophysically relevant parameters.” As part of his thesis work he collaborated with researchers working on MREDI-funded projects. Cooper has accepted a job at NWB Sensors, a Bozeman based spectral imaging company.

#### *Bozeman based companies worked with*

AdvR, Inc. – Developed laser sources for remote sensing applications based on nonlinear optical materials developed and sold by AdvR, Inc.

Resonon, Inc. – Developing spectral image processing techniques for large area mesoscale multi-temporal data sets.

#### *Funded follow-on grants*

“Development of a micro-pulse DIAL (MPD) testbed for sensing lower tropospheric water vapor profiles,” PI Kevin Repasky, NSF, \$1,588,646.

#### Expenditures

Salaries \$65,099.21, Benefits \$3525.02, Operations \$31,375.40, total Expenditures \$ 99,999.63.

**Subproject 10: Nonlinear optical detection of surface contaminants** (Rob Walker with Altos Photonics). Develop a new method for detecting organic contaminants that accumulate on the surface of water based on nonlinear vibrational overtone spectroscopy (NVOS).

#### Milestones

- a) December 2015: Demonstrate feasibility of using new spectroscopic method for surface detection of adsorbed species
- b) June 2016: Submit SBIR application with Altos to develop detection and monitoring instrument based on NVOS
- c) December 2016: Successful application of NVOS to environmentally relevant systems including contaminants on water surfaces and solid substrates
- d) June 2017: Final report summarizing technical accomplishments and commercial potential.

#### Accomplishments

Support from the MREDI program helped catalyze significant innovation and provided important support for personnel development, although the project's research direction did not directly follow the path originally anticipated. Nevertheless, MREDI support of this work has led directly to >\$1M of grant support that has been recommended for funding starting in August and September 2017. MREDI support has also enabled three graduate students and four undergraduates to pursue research related to the original MREDI project. Six publications have also cited MREDI support.

The work originally proposed for MREDI support intended to develop new, non-invasive, optical techniques for detecting organic contaminants that accumulate on water surfaces. The techniques themselves were based on surface specific, nonlinear vibrational methods that have been a cornerstone of Walker Group research for more than fifteen years.

Our efforts were not fully successful, but did lead to excellent follow-on funding. In part, attempts to develop nonlinear vibrational overtone spectroscopy ran into the simple challenge that these experiments are difficult and, even in the best of circumstances, signal levels were going to be low. Our efforts were also hampered by circumstances outside of our control, such as construction of a new dining hall located next to the Chemistry and Biochemistry Building. This activity included installation of a steam tunnel outside of our building and immediately adjacent to our optical laboratory. After a five-month delay when we were unable to perform measurements because our laboratories were shaking percussively as the steam tunnel was installed *and* the air quality in the lab was compromised by dust created by the construction, we turned our attention to developing new methods and analyses related those originally proposed and embarked on studies of bioaccumulation of contaminants in model cell membranes using time-resolved fluorescence and of the properties of high temperature material surfaces. The former project is closely related to the aims of our original plan, insofar as the project goals consider the fate of environmentally relevant contaminants and their ability to be taken up by cell membranes. This work led to several publications and a proposal to the Army Research Office that has been tentatively approved for a September 1, 2017 start. The second project – surface chemistry on high temperature materials – employs more mature nonlinear optical techniques and applies them to identifying changes in material composition and structure at temperatures approaching 800°C under strongly oxidizing and reducing environments. These systems are relevant for electrochemical energy conversion systems. This second thrust has led to two successful proposals starting in September 2017 – one from the Office of Naval Research and the other from the National Science Foundation's Chemistry Division.



### *Funded proposals related to MREDI sponsored research*

Army Research Office – \$363,456

*Organic Enrichment at Aqueous Interfaces: Cooperative Adsorption and Its Role in Atmospheric Science*  
Submitted to ARO in September 2016 (Recommended for funding, starting September, 2017)

National Science Foundation - \$426,169

*Nonlinear Optical Studies of High Temperature Surface Chemistry in Energy Conversion Systems*  
Submitted to NSF in October 2016 (Recommended for funding, starting in September 2017)

Office of Naval Research - \$345,000

*Operando Optical Studies of Electrochemical Oxidation and Materials Degradation in High Temperature Solid Oxide Fuel Cells*

Submitted to ONR in April 2017 (Recommended for funding starting in August 2017).

### *Publications citing MREDI Support (M-REDI supported personnel underlined)*

1. R. E. Latterman<sup>1</sup>, S. Birrell, P. A. Sullivan, and R. A. Walker, “Improved pulsed laser operation with engineered nanomaterials” *ACS Applied Materials and Interfaces* **8** (30) 19724-19731 (2016).
2. C. A. Gobrogge, V. A. Kong and R. A. Walker, “Unusual Temperature Dependent Solvation and Partitioning in Phospholipid Membranes” *J. Phys. Chem. B* **120** (8) 1805-1812 (2016).
3. S. M. Burrows, E. A. Gobrogge, L. Fu, K. A. Link, S. M. Elliott, H. F. Wang, and R. A. Walker “OCEANFILMS-2: Representing co-adsorption of saccharides in marine films improves agreement of modelled and observed marine aerosol chemistry” *Geophys. Res. Lett.* **143** (15) 8306-8313 (2016).
4. C. A. Gobrogge, H. S. Blanchard, and R. A. Walker “Temperature Dependent Partitioning of Coumarin 152 in Phosphatidylcholine Lipid Bilayers” *J. Phys. Chem. B*, **121** (16) 4061-4070 (2017).
5. C. A. Gobrogge and R. A. Walker “Quantifying Solute Partitioning in Phosphatidylcholine Membranes” *submitted to Analytical Chemistry*.
6. C. A. Gobrogge, V. A. Kong and R. A. Walker “Temperature Dependent Partitioning of C152 in Binary Phosphatidylcholine Membranes and Mixed Phosphatidylcholine/Phosphatidylethanolamine Membranes” *in revision with J. Phys. Chem. A* (invited for Veronica Vaida Festschrift).

### *Personnel Development*

MREDI resources supported –in part – the research of three PhD students, one of whom defended her dissertation in April 2017, and four undergraduate students.

Graduate students:

1. Dr. Christine Gobrogge (graduated May 2017)
2. Ms. Katie Link, currently 4<sup>th</sup> year graduate student in Chemistry and Biochemistry
3. Ms. Grace Purnell, currently 4<sup>th</sup> year graduate student in Chemistry and Biochemistry

Undergraduate students:

1. Alex Sherman (currently in chemistry graduate program at Purdue University)
2. Victoria Kong (currently in chemistry graduate program at Pitt)
3. James Young (currently seeking employment as Chemical Engineer)
4. Benjamin Gold (Graduated with B.Sc. in Chemistry, MSU, 2017)

### Expenditures

Salaries \$68,407.78, Benefits \$5384.81, Operations \$36,207.45, total Expenditures \$ 110,000.04.