Optics and Photonics Research for Montana Economic Development - MREDI Project

Quarter 2 Report – February 5, 2016

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Introduction

The project is on track and is already helping create new jobs in the Montana optics and photonics industry. The following report documents progress toward the milestones and objectives for each subproject.

Subproject 1: Ultra-compact spectral imagers for precision agriculture and mapping of wildfires and natural resources (Joseph Shaw, joseph.shaw@montana.edu 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

Activities to date

Weeds typically are managed with multiple herbicide applications throughout the year. One of these applications is post-harvest, usually with a focus on quack grass and other perennial weeds. In this project we are working toward a weed mapping solution using combine-mounted imagers to allow farmers to target specific regions of their field for herbicide application and to provide an annual record of problem regions.

Our approach is based on the use of low-cost, multi-spectral cameras with red, green, and near infrared (NIR) channels, connected to a GPS receiver to create geo-tagged images of the grain crop and weeds during harvest. Post processing of these images produces a map showing weed detections in the field. This second quarterly report demonstrates our progress to date in both the automated detection algorithm and mapping capabilities. It also addresses improvements that will be made to the system to prepare it for an improved second mapping effort during the grain harvest in 2016.

- Our primary milestone for this quarter was to complete initial weed maps from the 2015 harvest. We report here the development of a computer vision algorithm based on a support vector machine (SVM) for automatically detecting weeds in grain crops. SVM's are trainable signal classification algorithms that have been shown to provide some of the best signal classification and are commonly used for problems such as automated handwriting detection. The groundwork for this training algorithm was completed by three undergraduate electrical engineering students, Amber Geer, Seth Laurie, and Allison Walsh as part of their Senior Capstone project. This work includes hand classifying images to produce a data set that could be used to train the SVM. The SVM uses properties of the color and brightness pixel/region to classify it as a weed, clean crop, or something else. An example is shown in Figure 1 as a three-dimension normalized color vector for thousands of pixels identified as weeds, clean crop, harvested crop, and center-pivot tracks.

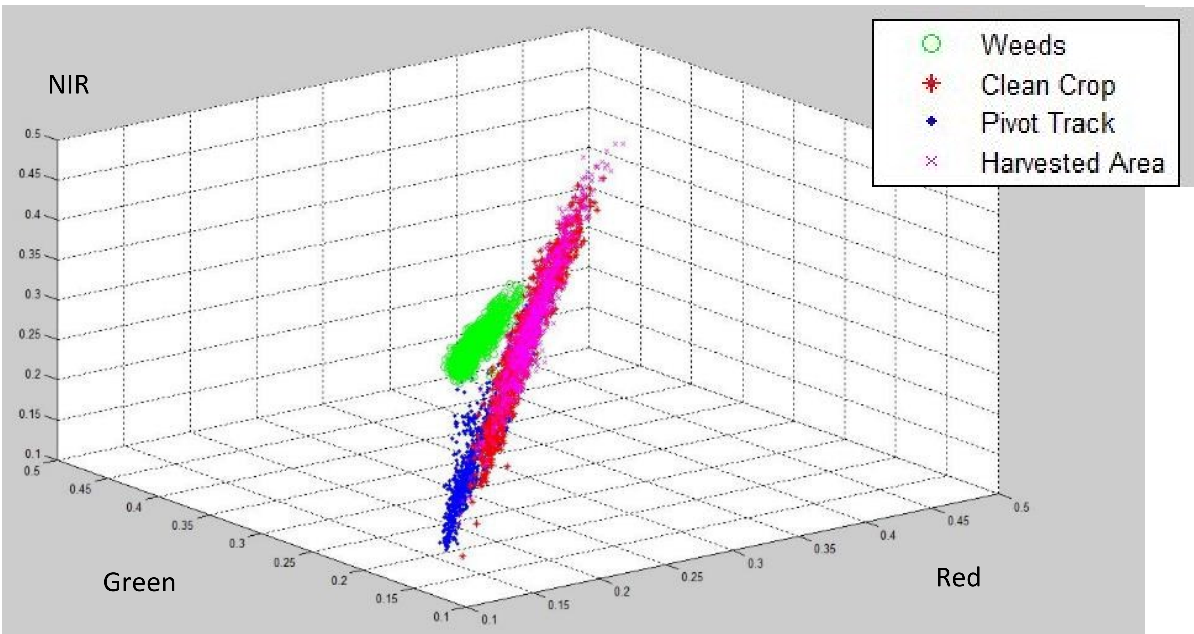

Figure 1. Colors present in a set of images for four different types of objects that appear in the crop images. In this three-dimensional space the weeds (green) are distinct from the other objects, which enables their detection.

- This training process has successfully produced a classifier that works for one of the two imaging systems deployed during the 2015 harvest. This system (designated System 1) operated in the same combine with the same software configuration throughout the harvest. A second system (designated System 2) was moved between multiple combines, and had software modifications implemented throughout the harvest. Thus the data from System 2 contains much more variety that has impaired the algorithm training accuracy. This provides a realistic data set that will lead to an improved, more robust processing algorithm, to be implemented in spring 2016.

- Mapping software using the SVM classifier has been implemented using Matlab for data processing and geo-referencing and using Google Earth Pro for displaying the maps. Currently all data collected with System 1 have been processed and maps have been produced. These data were collected over seven operating days between 11 August 2015 and 21 August 2015 and covered approximately 400 acres of irrigated wheat and barley. Figures 2 and 3 show two of these maps. In both images the red region shows the field and the green dots show the GPS locations of identified weeds. The landowner has been shown both these maps and has indicated that these locations generally match his notes of problem spots in the fields.

Figure 2. Weed detection map of an 80 acre field in Fairfield, Montana, with wheat in the north 40 acres and barley in the south 40 acres. The red region is the field and the green dots show the weed locations.

Figure 3. Weed detection map of a 23-acre field of barley. The red region is the field and the green dots show the weed locations.

- A problem with GPS accuracy was identified and solved. The GPS selected for the tests provided a 1 Hz georeference and was specified to be accurate to within 1.8 meters, sufficient for the project. Pre-harvest testing with the device placed on a car's dashboard and driving at highway speeds determined that it was within the specified accuracy. However, when deployed during harvest inside the cab of the combines, a much lower accuracy was obtained, estimated at worse than ±10 m. Recent tests on top of Cobleigh hall confirmed that at low speeds, or when not moving, that specific GPS device did not perform well. To improve performance before the summer 2016 harvest, an antenna was added to the GPS that can be placed on top of the combine rather than inside the cab. The external antenna greatly reduced the uncertainty of the stationary receiver by more than a factor of ten. Table *1* summarizes the results of this test and Figure 4 graphically illustrates them with red dots that mark the GPS-determined locations of the stationary receiver without an antenna (left) and with the external antenna (right).

Table 1. Results with and without the GPS antenna

Parameter	No Antenna	With Antenna	Units
Observations	378	377	images
Mean Error	6.67	0.62	Meters
Max Offset	32.52	1.74	Meters
Standard Deviation	4.42	0.33	Meters

Figure 4. GPS-determined locations for stationary receiver (a) without external antenna and (b) with the external antenna.

Projected next quarter activities

Our third-quarter activities will focus on preparing improved spectral imaging systems for deployment on combines before, during, and after the 2016 grain harvest.

Expenditures to date

Salaries $35,744.48, Benefits $7,437.78, Operations $11,688.00, total Expenditures $54,870.26.

Subproject 2: High-performance, real-time image processing for hyperspectral imaging (Ross Snider, rksnider@ece.montana.edu 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

Activities to date

- The senior design group has developed an algorithm to compute the center of mass of a falling object in real-time with data coming from a line scan camera imaging. They are now starting to implement the algorithm in Simulink that will then be converted to VHDL to be processed by an Altera Arria V FPGA.
- Capturing high speed imaging data is needed for test, verification, and debugging. We are developing a high speech image capturing system that will use mSATA high capacity very fast flash drives for storage. We have purchased a SATA protocol analyzer for development purposes.
- We are creating high speed serial interface links to transmit data between two FPGA boards which is the Altera Arria V FPGA and an Arria 10 board that will be used to processing hyperspectral data. This is how the edge information will be fused with the hyperspectral information.

Projected next quarter activities

- Continue with physically integrate line scan camera to Arria V FPGA board.
- Develop Simulink model that will be used to generate the VHDL component used to process data.
- Get high speed serial link communication working between FPGA boards (3 Gbps).

Expenditures to date

Salaries $3,878.20, Benefits $149.31, Operations $15,216.44, Capital $4,845.00 total expenditures $24,088.95

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.

Milestones

a) July 31, 2016: Collect invasive weed field data
b) August 31, 2016: Collect hyperspectral image data
c) October 31, 2016: Complete image preprocessing
d) January 31, 2017: Complete analysis of spectral band optimization and weed species mapping
e) June 30, 2017: Final report, including applications for commercial site-specific agriculture

Activities to Date

- Methods for geometric and radiometric correction of multi-swath hyperspectral imagery have been developed and refined with sample data in anticipation the 2016 field season and meeting the needs for Milestone c.
- Competing approaches for band optimization are currently being analyzed, providing the framework needed for Milestone d.
- Coordination has begun for identifying and obtaining access to field sites for the 2016 field season.

Discussion

Hyperspectral imagery collections at adequate spatial resolution for analysis of cropland weeds commonly requires multiple flight lines over targeted areas. This results in imagery that lacks precise spatial consistency and the high level of spatial accuracy to identify field plots for correlation to image spectral responses. The imagery also suffers from radiometric inconsistencies among flight lines because of bidirectional reflectance issues and changing solar illumination. Work led by Cooper McCann (Physics PhD student advised by Dr. Kevin Repasky) had resulted in a processing stream that, through several steps, achieves relatively high and consistent geometric correction. Subsequent steps use free, moderate-resolution Landsat imagery as a pseudo-calibration target to achieve high radiometric quality and consistency across an area of interest. *Figure 5* shows the obvious geometric issues present in a single flight line before any corrections. *Figure 6* illustrates the results of full geometric corrections, while radiometric inconsistencies between flight lines are evident. *Figure 7* demonstrates visually the effects of full geometric and radiometric corrections.

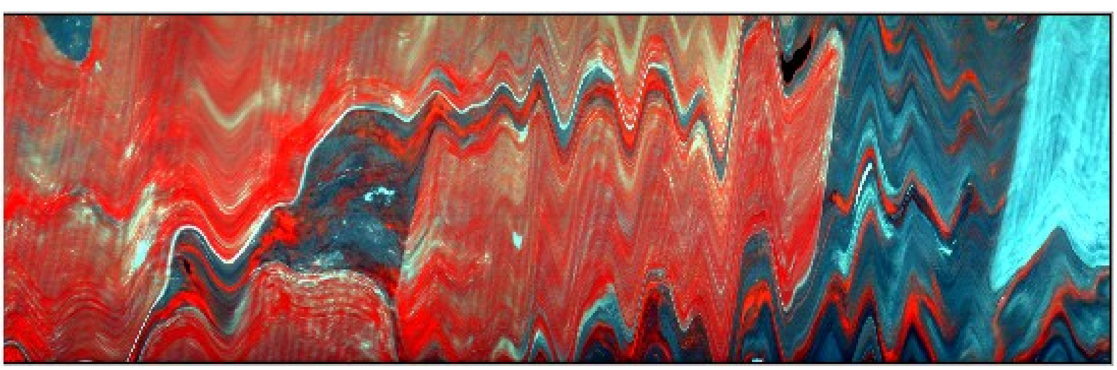

Figure 5. A single hyperspectral flight line demonstrating geometric issues associated with airplane roll, pitch, and yaw.

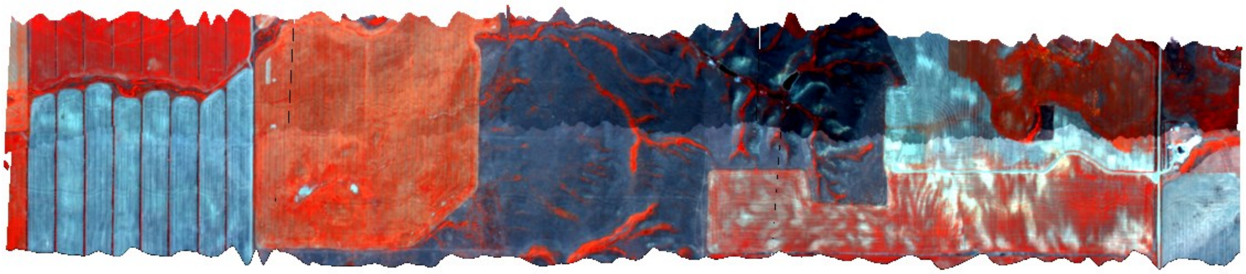

Figure 6. Two swaths showing the effects of differing illumination conditions.

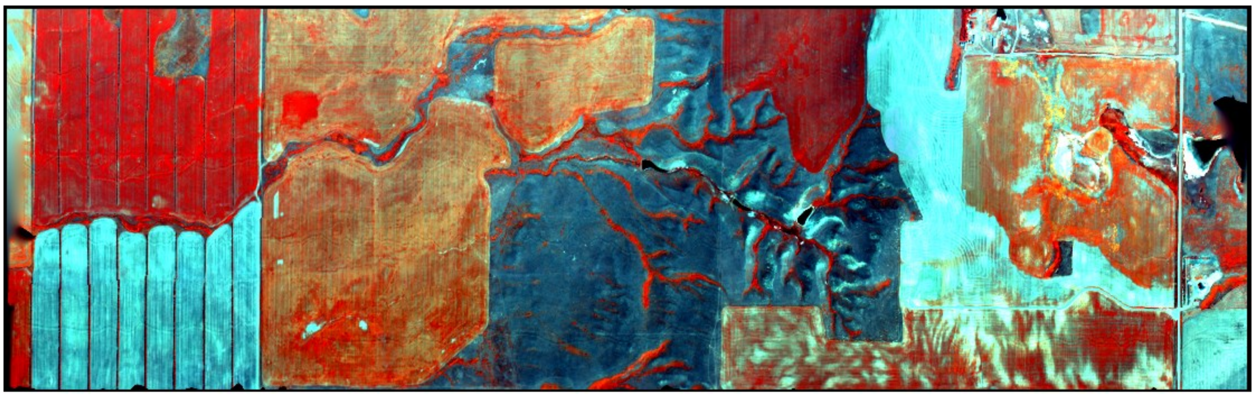

Figure 7. Mosaicked image demonstrating the effects of full geometric and radiometric preprocessing.

Expenditures to date
Salaries $1,622.51, Benefits $62.61, Operations $0, total Expenditures $ 1685.12

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
- May 31, 2016 Initial machine vision algorithms developed.
- Sep. 30, 2016 Initial testing of machine vision algorithms complete.
- May 31, 2017 final testing and development complete.
- June 30, 2017 Final report completed

Activities to date
- Strategy was formalized and estimated timeline was discussed for machine vision research in collaboration with spectral imaging team (Resonan, Dr. Snider, Dr. Ratz).

Expenditures to date
Salaries $9,600.00, Benefits $51.28, Operations $0, total Expenditures $9651.28

Subproject 5: Microcavity sensors for hyperspectral imaging (Zeb Barber with Advanced Microcavity Sensors LLC). Advance MSU/Advanced Microcavity Sensors LLC (AMS) technology on microcavtity 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.

Activities to date

Program (Non-Technical) Highlights:

- Advanced Microcavity Sensors (AMS) was awarded by NSF an SBIR Phase I to develop the microcavity hyperspectral imaging technology for biomedical applications. This $150,000 9-month award started January 1, 2016 and includes a sub-contract to MSU Spectrum Lab in the amount of $24,960.
- Dr. Russell Barbour (Founder of AMS) with the NSF funding has left MSU to focus full time at AMS to commercialize the technology.
- AMS has hired Mr. Austin Beard, a Montana native and MSU Electrical and Computer Engineering alumnus. Mr. Beard will be paid by funds on the NSF award.

Technical Progress toward Objectives:

Significant effort has been placed on AF STTR and MBRCT sources of funding for the technology development effort so far. The MSU Spectrum Lab work on the AF STTR funds has demonstrated minimal degradation of cavity Q due to intracavity liquid crystal, which was a key risk mitigation for the overall technology.

- AMS is improving the laser ablation based micro-crater cavity mirror template writing, including for making constructing non-circular symmetric micro-cavity mirrors. MSU Spectrum Lab has used scanning electron microscope (SEM) to image the micro-cavity mirrors created by AMS and then high reflection coated to MSU Spectrum Lab's specifications by a contract coating company (see Figure 8). We are currently investigating if the debris on the surface and in the craters is dust that can be cleaned or debris from the laser ablation formation of the microcavities. Even with the debris inside the craters we can achieve high cavity Q.

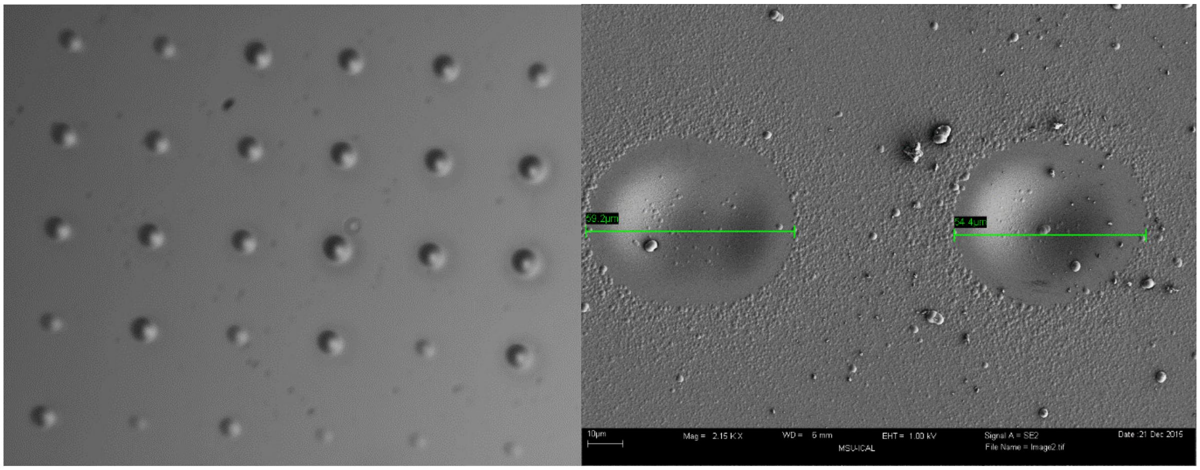

Figure 8. (Left) Microscope image of the microcavity craters, showing a section of a 10 x 10 array. (Right) SEM image of microcavity mirrors. The most interesting thing to note about this SEM image is that the surface of the micro-craters is significantly smoother than the glass surface on which they were formed.

- Liquid crystal filled cavity filters constructed on AF STTR and MBRCT funded efforts have shown insensitivity to vibrations. This indicates vibrations due to mounting on UAV will not be significant issue for the micro-cavity based hyperspectral imaging sensor.

Expenditures to date
Salaries $4,762.52, Benefits $1,703.96, Operations $198.20, total expenditures $6,664.68

Subproject 6: Hyperspectral imaging for monitoring cell growth (Ed Dratz, dratz@chemistry.montana.edu 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

Activities to date

- Excellent progress has been made in the Dratz lab on introducing optogenetic probes of the oxidation/reduction state into human adult stem cells in culture. The probes have been transferred to new carrier vectors that are providing increased efficiency of probe introduction. A graduate student in the Dratz lab is devoting full effort to working with the optogenetic probes, assisted by a research undergraduate, two postdoctorals in the Reijo Pera lab, and a Reseach Assistant Professor in the Singel lab, all in the Chemistry and Biochemistry Department. An advanced undergraduate Electrical and Computer Engineering (ECE) Design Team in the Snider lab in ECE is continuing to design the microscope stage controller system and the controller for the cell culture environmental control system. A graduate student in the Snider lab is devoting full effort to the high speed hyperspectral imaging analysis software and will be working on this crucial aspect of this project into the next year.
- Prof Dratz and Prof. Snider have finalized access to the Onyx CellAsic microfluidic cell culture control and observation software after extensive negotiations with the parent company, EMD Millipore Corporation, and a written agreement executed. The Onyx CellAsic microfluidic cell culture control and observation system has been ordered and delivered. An older but excellent Zeiss laser-excited confocal fluorescence microscope has been upgraded with the latest computer and software and moved to the Dratz lab in the Chemistry and Biochemistry Building. This is important for this project since we need a standard of performance comparison with the Resonon Hyperspectral system being designed and built for this project. Also, it is impractical to transfer the cell cultures across campus for testing on other microscopes because of the delicate nature of their metabolic balance and having this excellent microscope in the cell culture lab will greatly facilitate this work.
- The upright microscope test system from the Dratz Lab that has been moved to the Resonon facility is being used for initial testing of the excitation laser system for hyperspectral imaging, which is a major goal that needs to be fully worked out and tested. Alternative concepts have been formulated for coupling the laser excitation beam to the excitation telescope system. Additional work is needed to test the concept and begin development.
- The personnel include two graduate students devoting full effort to the project, two advanced undergraduates on an ECE Design team.

Expenditures to date

Salaries $17,198.15, Benefits $1148.13, Operations $6,587.10, Capital $29,261.20total expenditures $54,194.58.

Subproject 7: Translational research to commercialize micro-mirror technology (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).

Activities to date

- Technical measurements of mirror performance. These measurements will be used to focus new fabrication efforts in Q3.
- A comprehensive product datasheet is underway using performance measured during Q2.
- Revibro Optics has registered for Photonics West in February 2015. This will be an important opportunity for generating commercial revenue.
- A review of current DoD SBIR topics is under review for possible application by February 17.
- Business students were engaged in Q2 via the BMGT475R class. These students helped Revibro Optics develop marketing materials and a plan for engaging "early adopter" customers.
- Investigated wafer bonding equipment options.
- Chris Arrasmith, founder of Revibro Optics, is employed full time thanks to the MREDI project. In the coming year, Chris will be searching for another hire in the next year to help with sales and marketing or technical development of the deformable mirror products.

Discussion

Related to Milestones a) and b), we made important progress in the characterization of our variable-focus mirrors. Previously we have performed basic measurements of mirror defocus versus voltage for operation at relatively slow speeds. Metrology efforts during Q2 aimed at measuring the high-speed response of the mirrors. These high-speed measurements are firstly in response to desired specifications for potential customers in the fields of microscopy and neurology, and secondly to have a clear understanding of current mirror performance so we can make appropriate improvements during our next fabrication run.

Revibro Optics worked with undergraduate and graduate student at MSU to measure the new performance values. Data will be used both in an MSU publication on current deformable optics technology, as well as in a comprehensive product datasheet for Revibro Optics' products. To define the high-speed performance, the mirrors were actuated with a square-wave voltage. A pulsed laser phase shifting interferometer was then used to capture the rise and fall (step response) times for the mirror under test. The first step response tests captured the response to large-scale defocus, providing information on how quickly the mirrors can change over a large focal length range. The settling time for these defocus steps is below 100 µs, as shown in *Figure 9* (left). This result means the our technology is 10-100 times faster than competing focus control technologies, giving our technology a very competitive edge for high-speed focus control. The second test measured the aberration correcting time response of our mirrors. The mirror was biased to given defocus value, and the shape of the mirror changed to realize many different spherical aberration values. The settling time for these experiments is also less than 100 µs. *Figure 9* (right) shows the step response for a 400 nm spherical aberration step. These two results can be shared with interested customers, and will also be used to create a substantial specification sheet for our product.

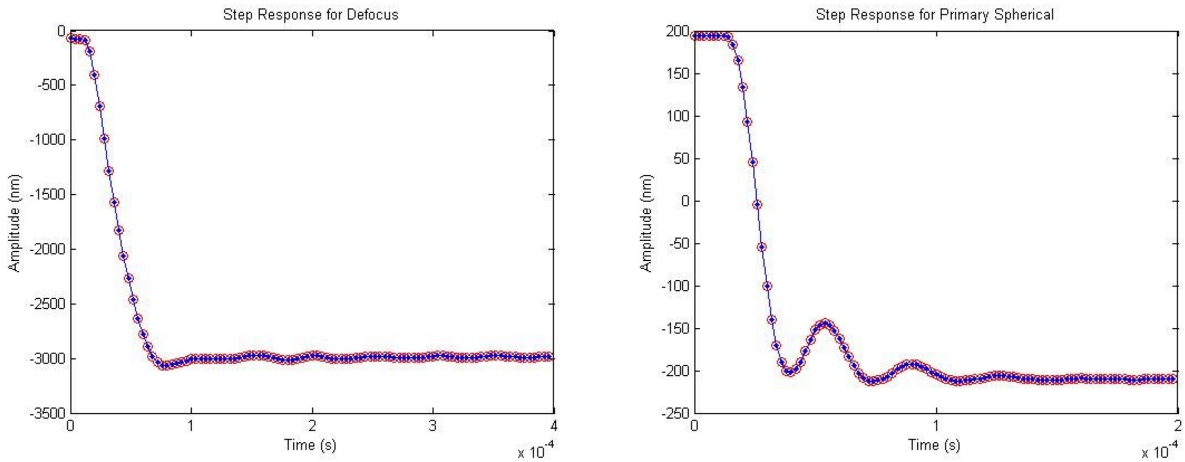

Figure 9. Plots of settling time (left) and step response (right) of miniature focus-control mirrors.

We also had the pleasure of engaging two MSU seniors during Q2 through the BMGT 475R course on Entrepreneurship. Through the interaction, the students gained valuable startup company experience, and were able to help develop a marketing plan and materials for Revibro Optics. The outcomes of the engagement included exciting new sales in the microscopy field, and the development of a newsletter to be used at future trade shows. This newsletter, shown in *Figure 10* will be valuable marketing material for the upcoming Photonics West trade show.

REVIBRO OPTICS

Revibro Optics Information Sheet — November 2015

Who Is Revibro Optics?

High speed focus control

Our MEMS based deformable mirror technology provides compact, high-speed focus control for demanding optical applications. Focusing is accomplished with a voltage selectable radius of curvature on the mirror surface. Available mirror diameters range from 2 mm to 5 mm. They are available in standard 1 inch diameter optical mounts, or may be provided in customer specific packages.

Our team at Revibro has expertise in optical system design, semiconductor manufacturing, and system integration.

REVIBRO OPTICS
Adjustable Focus Mirrors
Bozeman, Montana
www.revibrooptics.com

Telephone: 406-624-9068
E-mail: info@revibrooptics.com

Applications for fast focus control

Our variable focus mirrors are a valuable component for many optical systems including 2-Photon Microscopy, Confocal Microscopy, Interferometry, and Advanced Imaging systems. With the inherent ability for fast aberration correction, they may also be used in astronomy and imaging fields where optimal imaging with variable sample characteristics are encountered.

Q&A

Q: What size are the mirrors?
A: We have 4mm diameter mirrors available currently. Diameters between 2-5mm can be requested for special order.

Q: How fast are the mirrors?
A: They can operate at 3kHz with full stroke deflection, and much faster for small stroke operation.

Figure 10. Newsletter developed through interactions with BMGT 475R students at MSU-Bozeman.

The investigation into wafer bonding equipment hit a financial roadblock during Q2. The cost of quality wafer bonders is much higher than expected. As a reference, the EVG 501 is very popular research-grade bonder used at many universities. The used market price for this piece of equipment is between $100k-200k, which is well above the $30k budget for this project. We have been in discussion with the Montana Microfabrication Facility (MMF) at MSU about additional funding options, but have yet to secure the amount necessary for this grade of bonding equipment. We found one cheaper alternative from Idonus. They have many bonder configurations available, and can put together a basic bonding system for around $30k. However, the cheaper system is not much improved over our current bonding method using our custom fabricated bonding jig, so the cost/gain is not attractive. At this time we are holding off on the purchase of a bonder. We will continue looking for bonder options within the project budget, but hope to find a way to leverage our investment to purchase a system like the EVG 501 (see Figure 11).

Figure 11: Desired EVG 501 bonder (left), a cheaper alternative from Idonus (right).

Related to Milestone c), Revibro Optics will be searching for a new hire soon. During Q2 the interaction with BMGT 475R students filled the need for a marketing person. Currently we are evaluating what the biggest need is for the next year – either someone to push on fabrication and product development, or someone to help with sales and marketing of our mirrors. Commercial interest and interactions at the upcoming Photonics West trade show will help us decide what type of hire will be most useful.

<u>Total Expenditures</u>

Personnel & Operations $18,305.35, total expenditures $18,305.35.

Subproject 8: Active waveguides and integrated optical circuits (Rufus Cone, cone@physics.montana.edu, 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.

Activities to date

- During this second reporting period, we achieved a major project milestone by demonstrating that rare-earth-activated optical waveguides can provide performance equivalent to bulk crystals, even in micron-scale integrated photonic circuits. Efforts at MSU continue on developing the scientific, technical, and computational tools required to successfully integrate this new avenue with the products and capabilities of the local Montana companies S2 Corp., FLIR / Scientific Materials Corp., Montana Instruments, and AdvR Inc. to enable the new Montana products and Montana technologies envisioned in our MREDI effort. This work involves broad interdisciplinary collaborations between six different research groups at MSU from several departments and centers, providing unique synergy that establishes a long-term program of sustainable collaboration in this field, with short-term development focused on immediate return for Montana businesses and current research programs at MSU.
- Our first project milestone was reached by obtaining rare-earth-activated optical waveguides and verifying the optical coherence properties of micron thick layers of Tm-indiffused ions in $LiNbO_3$ crystal wafers at MSU and as part of a scientific collaboration with researchers at the University of Calgary also in optical-fiber-integrated $LiNbO_3$ channel waveguides. All activities are on schedule to successfully meet our future project objectives and milestones. Several key steps and outcomes of these efforts have been accomplished during this quarter, including those outlined below.

Progress on Technical/Educational Objectives:

- We continue development of our new concept for optical waveguide structures based on micro- and nano-fabrication of dielectric structures or "strips" on the surface of existing bulk transparent optical crystals. This novel approach introduces a completely new option for the fabrication of active integrated photonic devices by enabling the use of existing materials that have been traditionally inaccessible due to a lack of specialized chemical (indiffusion) processing techniques. The simplest architecture envisioned for this technology is illustrated in *Figure 12*, where a thin crystal layer is bonded to an inert substrate (such as glass) and a "strip" of dielectric material (such as silica SiO_2 or sapphire Al_2O_3) is patterned on the surface using nanofabrication lithography techniques available at the Montana Microfabrication Facility. During this quarter, progress has been made on fabricating the crystal wafers, developing fundamental theoretical models to describe and design device structures, and sophisticated numerical modeling of actual light propagation through such a device. Successful development of these systems will provide new capabilities for research at MSU as well as new products for Montana industry, including S2 Corp. and AdvR Inc..

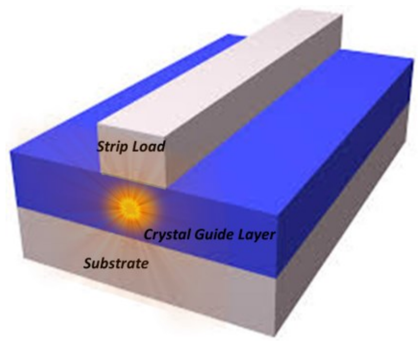

*Figure 12. Illustration of the novel "strip-loaded" photonic waveguide structure being developed***.**

- We have continued to make significant progress on developing and expanding our waveguide fabrication and characterization capabilities. In particular, a new vacuum thin-film deposition system was constructed; an optical ellipsometer and laser m-lines setup for measuring thin film thickness and index of refraction (speed of light in the crystal) was obtained and retro-fit for our work, with initial characterization of samples currently under way; the budgeted high-temperature furnace for waveguide fabrication was purchased and installed; a chemical crystal growth system was constructed and placed in operation to produce new optical materials; and work has progressed on implementing new telecommunications-compatible laser systems for characterization and operation of waveguide devices.
- The process of specifying, researching, and purchasing the Montana Instruments cryostat required for this effort was completed and the order was placed during this quarter, with delivery expected during the next quarter. Our collaborative effort with Montana Instruments also investigated new design options and custom product development that are of broader interest for other customers. In addition to enabling sustainable research in this area at MSU, this system will also greatly expand the access and training of undergraduate and graduate students with high-end commercial cryogenic systems, an area of specific importance for the local optics industry.
- During this quarter we have met one of our primary milestones of demonstrating rare-earth-activated waveguides suitable for photonic signal processing applications. We have obtained both Titanium-indiffused Thulium-activated Lithium Niobate ($LiNbO_3$) channel waveguides as well as a Helium-implanted Thulium-activated Yttrium Aluminum Garnet (YAG) planar waveguide. We have successfully demonstrated that suitable optical coherent transient signals can be produced by very thin layers (~6 microns) of indiffused Tm^{3+} ions in the $LiNbO_3$ waveguide wafers, as illustrated by the measurements shown in *Figure 13.* In collaboration with our partners at the University of Calgary, Canada, we have also demonstrated that the optical coherence properties needed for information processing devices are fully maintained in the channel waveguide structures, a key milestone required to elevate our effort to the next stage along the path to commercial development.

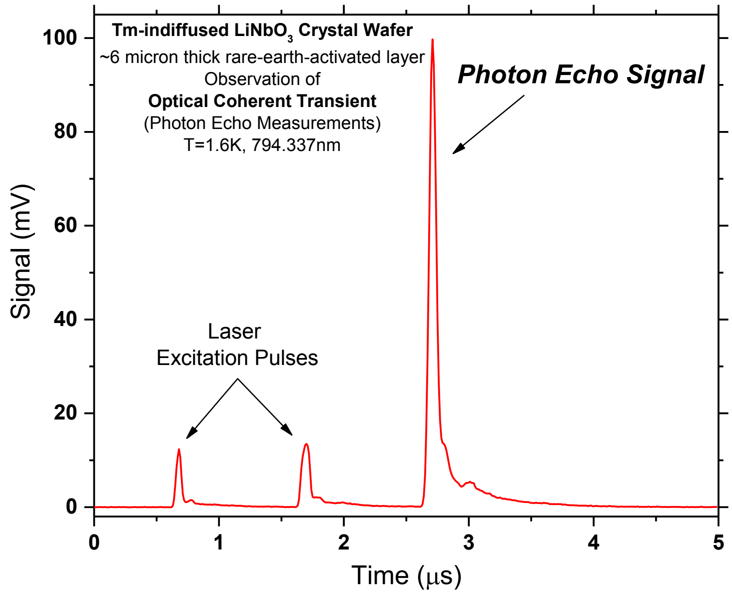

Figure 13. Successful demonstration of optical coherent transient signals required for photonic information processing technologies in several micron thick rare-earth-indiffused layers in the surface of optical crystals.

- The sophisticated commercial software package Comsol Multiphyics, including the Wave Optics Package, was purchased and installed at MSU during this quarter. This MREDI effort enables opportunities for student training, device design and engineering, and scientific research and development in Physics, Electrical and Computer Engineering, and Spectrum Lab. This computer tool is well-suited to the design and analysis of optical waveguide and integrated photonic devices for light guiding based on structural modifications or index modulation of materials, all of which are being explored and developed in this project. The broader computation abilities of this software (3-D finite-element solution of partial differential equations) also allow expanding design and modeling capabilities beyond electromagnetic interactions (propagation of light) to also include thermal effects (heat conduction), mechanical stress (physical strain and design), and more general nonlinear optical phenomena. Furthermore, the Comsol Multiphysics software is adaptable to solving a broad range of optics and electromagnetics problems, and could be used to support ongoing research in these areas in a number of departments. In particular, the Nano Optics group in Electrical and Computer Engineering will adapt this tool for the analysis and design of nanostructure-based optical devices in a number of research projects, including those funded by NASA, ARL, and others. Since the software is designed to support the analysis of more general multi-dimensional electromagnetic, thermal, and mechanical phenomena, it could be used to support current and new interdisciplinary research. Currently, two PhD students (one in ECE, one in Physics) are being trained to use this software, and this number is expected to grow over the course of the MREDI effort. This know-how and experience, in addition supporting their current research and progress towards the doctoral thesis, will be an important competitive skill after these students graduate and pursue a professional career.
- MSU Spectrum Lab has begun investigations incorporating optics into the cryogenic environment to provide more compact and robust spatial-spectral processing systems. One S2 optical system being investigated is based on optical fibers being collimated/focused using gradient index (GRIN) lenses

through a bulk spectral hole burning crystal and recollected into fiber with a second GRIN lens (see *Figure 14)*. Two effects must be evaluated: irreversible damage/misalignment due to thermal cycling of optics composed of dissimilar materials such as glass and optical epoxy/waxes; and reversible optical misalignment due temperature induced deformation. Simple thermal tests on standard commercial optics and fiber optics were performed using liquid nitrogen (77 K or -196° C) as a cryogen. Although liquid nitrogen is warmer than the 4 K liquid helium temperature used with spectral hole burning materials, most of the thermal contraction that can lead to damage or misalignment occurs over the temperature range from room temperature (300 K) to 77 K. None of the optical components tested showed irreversible damage. This includes a commercial fiber optic isolator containing GRIN lenses and several micro-optical components cycled to liquid nitrogen temperatures. Some misalignment of internal micro-optical components was observed when cooled, suggesting the need for additional steps to improve performance in some cases. Nevertheless, because no damage was observed, Spectrum Lab will move on to building and more detailed testing of the simple fiber → GRIN → bulk crystal → GRIN → fiber optical system.

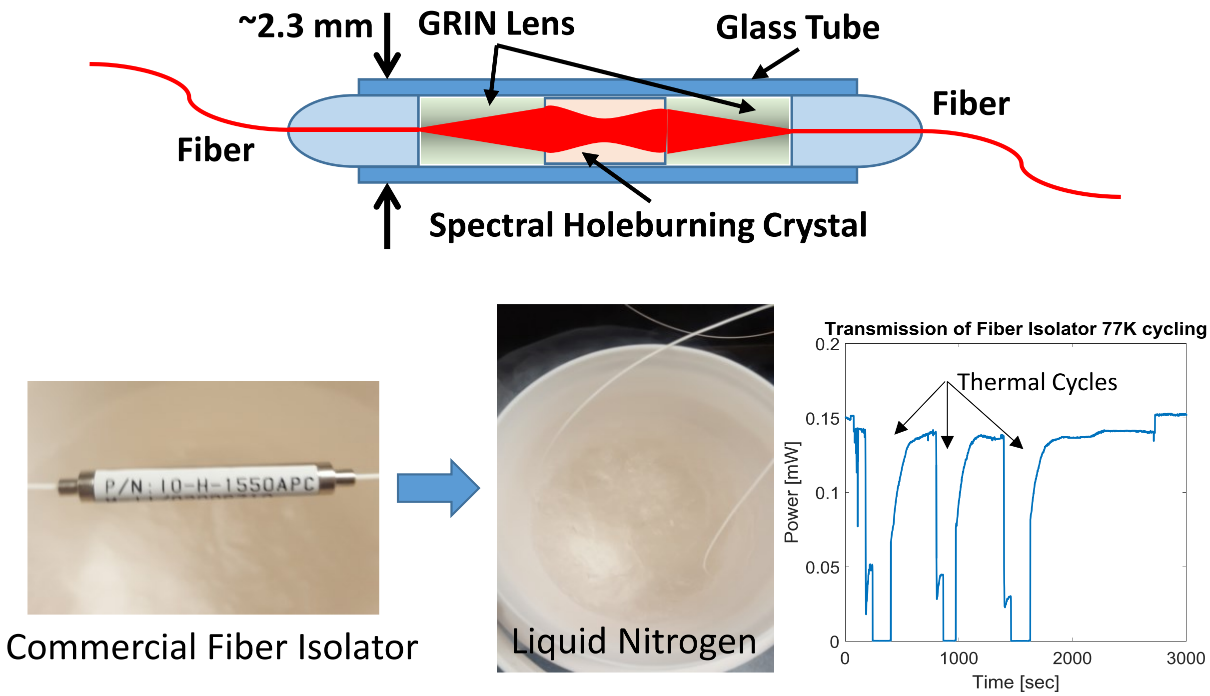

Figure 14. Commercial fiber optic component that was thermally tested for cryogenic applications by exposing to liquid nitrogen at -196 C (-321 ℉).

- A used wavelength-dispersed X-ray Fluorescence (XRF) system was identified, researched, and purchased by MSU Physics and the Imaging and Chemical Analysis Laboratory user facility in part to support the efforts on this MREDI project. This sophisticated instrument allows precise analysis of elemental composition of solids and liquids for all elements on the periodic table from Boron to Uranium at parts-per-million levels, providing an entirely new and much needed capability for both the MSU community as well as local industry. The XRF system will allow us to evaluate the effects of our device fabrication processes on the chemical composition of the optical crystals, an essential capability required to determine successful development avenues for commercially practical implementations of our technologies. Furthermore, this advanced instrument is expected to receive much use by local companies such as Scientific Materials Corp and others, improving the ability and reducing the cost for analyzing product runs and performing quality control.

- The new apparatus for fabricating very thin optical wafers (~10 microns or less) that was designed and under construction during the previous quarter was completed and tested during this quarter. Initial trials have demonstrated the capability to produce optical wafers of less than 100 micron thickness, improving to the ~10 micron level with continued refinement of the operation. These thin crystal wafers are required for our new strip-loaded optical waveguide technology as well as for a number of other potential commercial products being investigated by Scientific Materials Corp., AdvR Inc., and S2 Corp.
- Prof. Cone and Charles Thiel were invited to visit the Nanoscale and Quantum Optics group at California Institute of Technology to discuss the current optics and photonics work at MSU and to present an invited seminar at the university. This visit is a significant early outcome of the MREDI project since our work on developing integrated photonics at MSU is directly related to the prominent research and technology being developed at Caltech and we expect this visit to lead to greater exposure for the Montana optics community and to new high-profile collaborative research programs in partnership with Caltech. All travel expenses for this visit are being paid by Caltech, a further indication of their interest in our MSU work.
- A number of options for custom growth of rare-earth-doped $LiNbO_3$ crystals were investigated during this quarter. Given the current needs of the MREDI project as well as related projects at Spectrum Lab and S2 Corp., it was deemed important to identify all possible sources. Spectrum Lab has conducted an extensive search for potential crystals growers capable of growing these crystals to custom specifications. This study verified that Scientific Materials Corp. (FLIR) in Bozeman, MT can provide the highest quality materials at the lowest cost/volume. With our material characterization results on crystals produced by Scientific Materials in 1999 and 2004 demonstrating their outstanding optical properties, we have initiated discussion to produce new crystal growths for photonic signal processing applications. We expect this to lead to new products for Scientific Materials Corp. as well as additional positive exposure of their superior material quality compared to other commercial sources.
- Tia Sharpe (Research Engineer, MSU Spectrum Lab) has begun training efforts on integrating the lithography capabilities of the Montana Microfabrication Facility (MMF) with Spectrum Lab and S2 Corp technologies in order to fabricate complex channel waveguides in spectral hole burning materials.
- Four Physics graduate students (Aaron Marsh, Aislinn Daniels, Torrey McLoughlin, and Jacob Braunberger) working in the area of spectral hole burning and spatial-spectral holography in Prof. Cone's Lab, Prof. Babbitt's Lab, and Spectrum Lab completed their oral comprehensive exams for their Ph.D. degrees on work related to and supported by the MREDI effort.
- A seminar series for students involved in the MREDI project, as well as other students, was hosted by Spectrum Lab (offered as a class through the Physics Department). In the seminar, the students learned about the physics of optical coherent transient phenomena, including those used in the coherence testing of Montana Instrument's cryostat; the physics and chemistry of the spectral hole burning crystals produced by Scientific Materials; the physics and engineering involved in the spectral hole burning based spectrum analyzer produced by S2 Corporation; and the design and commercial technology of optical components and laser systems, including those produced by AdvR and Bridger Photonics.

<u>Progress on Economic Objectives</u>**:**

- A high-end Montana Instruments cryogenic system required for this effort was ordered from the Montana company during this quarter. It will enable development jointly with company of new technologies, expanded product options, student education and training, and scientific research programs.

- Charles Thiel (Senior Research Scientist, MSU Spectrum Lab and Physics) presented an invited lecture at the international conference on "Quantum Light-Matter Interactions in Solid State Systems" in Barcelona, Spain in which he presented research work occurring at MSU and also outlined and promoted the products and technologies of the local Montana optics industry. During the conference, discussions were carried out with representatives of the large international corporation Thales to highlight the specific capabilities and merits of S2 Corp., Scientific Materials, and Montana Instruments products and technologies. Travel expenses were partially covered by the conference organizers and the remaining amount was funded by the National Science Foundation.

- The new apparatus for fabricating very thin optical wafers (~10 microns or less) completed during this quarter is a key step toward developing several new commercial products that are being investigated by Scientific Materials Corp., AdvR Inc., and S2 Corp.

- Additional work was carried out with Scientific Materials Corp. to evaluate and improve new lines of optical laser crystals that will allow them to enter new markets and successfully compete with the current established suppliers. Additional characterization techniques beyond those employed in the previous quarter are being developed to improve product performance, with additional potential application to spectral hole burning technologies.

- Discussions and planning with Scientific Materials Corp were carried out to begin the process of expanding their capabilities to grow custom rare-earth-doped $LiNbO_3$ crystals for opto-electric and photonic applications. Cost estimates per growth run, size and specifications, potential to grow crystals with different dopants such as Tm and Er, as well as different hosts such as $LiTaO_3$ are being researched and developed.

- The advanced X-ray Fluorescence (XRF) system that will be installed in the MSU Imaging and Chemical Analysis Laboratory (discussed in detail earlier) will receive much use by local companies such as Scientific Materials Corp and others, improving their ability to analyze and develop materials as well as reducing the cost for performing quality control on new growth runs.

- Prof. Rufus Cone will attend the Photonics West 2016 technical conference in San Francisco during next quarter, a key forum for exposure and advertising of industry and technology. In his role as Deputy Director of the MSU Optical Technology Center – OpTeC, he will present a booth on optics and photonics at MSU and in Montana during the massive commercial trade show that is part of this conference, providing critical exposure and promotion for the Montana high-tech economy.

- Charles Thiel (Senior Research Scientist, MSU Spectrum Lab and Physics) was asked to give an invited keynote seminar at the 19th International Conference on Defects in Insulating Materials, hosted by the Institute of Light and Matter, a research institute of CNRS and University Lyon in France during July 2016. This high-profile invitation will provide an important avenue for promoting

MSU and the Montana optics and photonics industry. Travel expenses will be partially covered by the conference organizers and the remaining amount will be funded by the National Science Foundation.

- Charles Thiel (Senior Research Scientist, MSU Spectrum Lab and Physics) was asked to give an invited talk at the 2016 Fall meeting of the Materials Research Society in Boston Massachusetts. This invitation will provide another important avenue for promoting MSU and the Montana optics and photonics industry. Travel expenses will be partially covered by the conference organizers and the remaining amount will be funded by the National Science Foundation.

- A wide range of commercial sources for rare-earth-activated optical crystals were contacted to compare expense and capability for growth of photonic signal processing crystals relative to the local Scientific Materials Corp capabilities. Specific US and international sources contacted include United Crystals, Gooch & Housego, Del Mar Photonics, Greyhawk Optics, Deltronic Crystal, Altechna, and Castech Inc. We found that Scientific Materials Corp can provide superior products at lower cost/volume than all other sources.

Expenditures to date

Salaries $48,393.00, Benefits $10,664.85, Operations $30,963.49, Capital $5,000.00 total expenditures $95,021.34.

Subproject 9: Optical Parametric Oscillator for Tunable Lasers (Kevin Repasky, repasky@ece.montana.edu, 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

Activities to date

The schematic of the optical parametric oscillator (OPO) based laser transmitter for carbon dioxide (CO_2) and methane (CH_4) detection is shown in *Figure 15*. This laser transmitter utilizes a pulsed Nd:YAG laser to pump a magnesium doped periodically poled lithium niobate (Mg:PPLN) crystal. During the previous quarter, the SNLO nonlinear optical modeling code created by Sandia National Laboratory was used to model the expected laser performance and inform the optical design. During this quarter, work has begun on developing the OPO laser prototype.

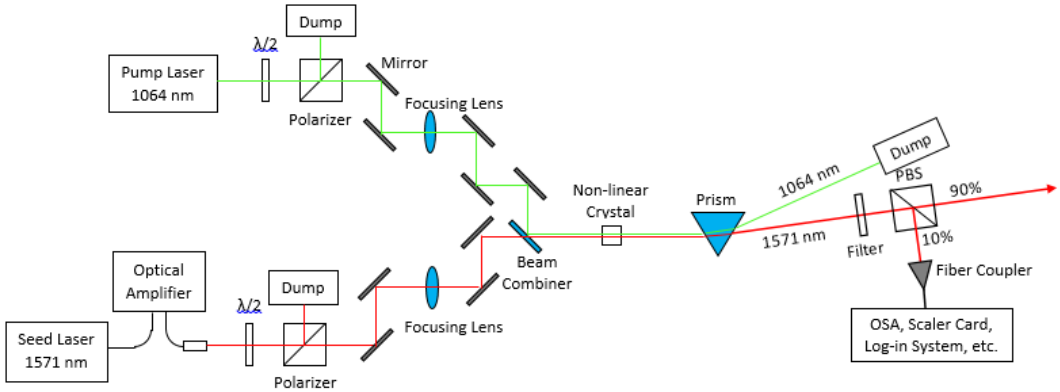

Figure 15. Schematic of the DIAL laser transmitter.

Initial characterization of the Nd:YAG pump laser was completed, including output beam power and transverse beam mode characteristics. A plot of the output laser pulse energy is shown in *Figure 16* as a function of the laser supply power setting. To achieve the needed 3 mJ pulse energy required for the DIAL instrument to achieve the needed measurement resolution, a conversion efficiency of approximately 10% will need to be achieved. SNLO modeling indicates this is possible with a singly resonant OPO (SR-OPO) design.

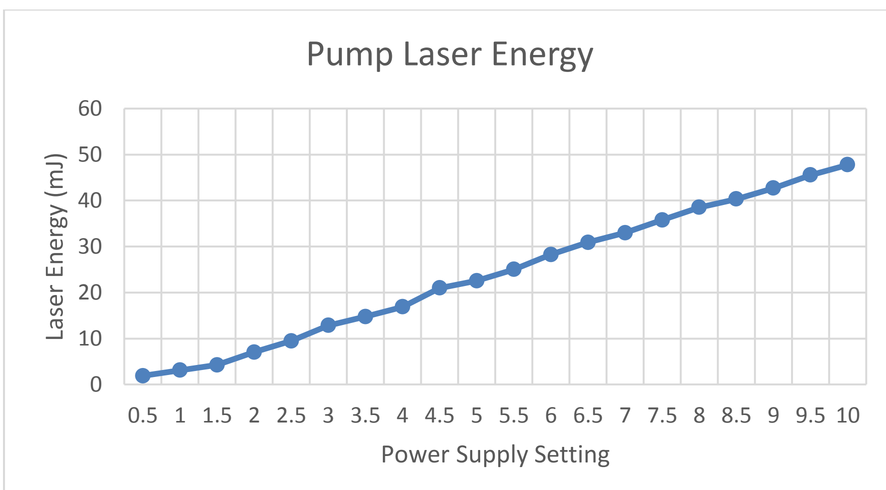

Figure 16. Output pulse energy achievable with the Nd:YAG laser.

The transverse mode structure for the pulse Nd:YAG laser is shown in *Figure 17*. While the Nd:YAG beam is not a signal spatial mode, the transverse mode structure does approach a Gaussian beam. Measurements of the 1/e beam waist as a function of distance is shown in *Figure 18* for various optical power settings. The black circles represent measurements made of the 1/e beam waist while the red lines indicate a least squares based on Gaussian beam propagation. This measurement provides the minimum beam waist or spot size, the beam divergence, and Rayleigh range and provides the information needed to finish the optical design of the laser transmitter.

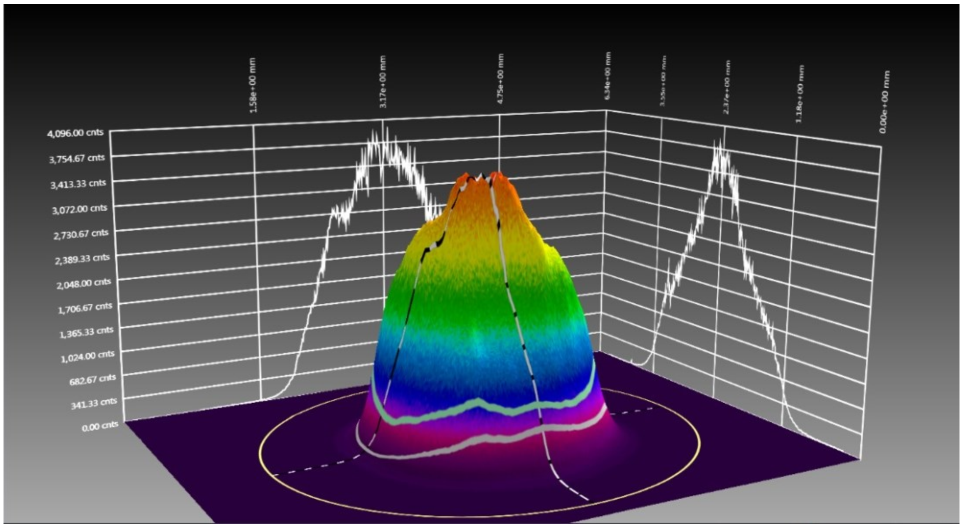

Figure 17. Transverse mode structure of the Nd:YAG laser.

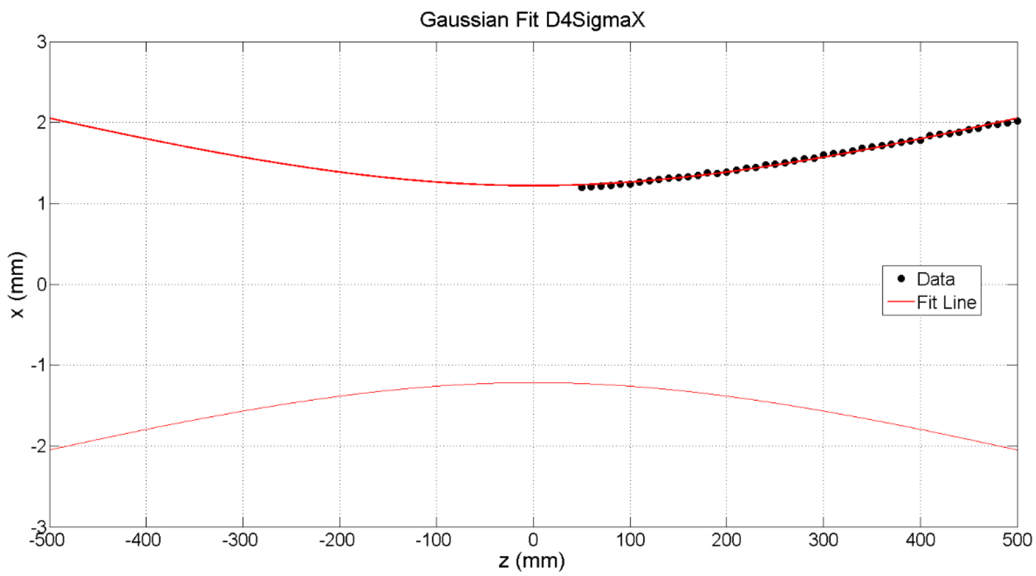

Figure 18. Measured 1/e beam waist as a function of distance is shown as the black circles while the 1/e beam waist modeled using Gaussian beam propagation is shown as the red lines.

The diode laser needed for injection seeding the SR-OPO laser was characterized. A table of the drive current, temperature, and output power is shown in *Table 2,* achievable while maintaining the operating wavelength of 1571 nm, the seed laser wavelength needed for CO_2 measurements. The diode laser operates with a single longitudinal mode and can produce over 8 mW of cw power. This is enough optical power to saturate the gain in the fiber amplifier allowing up to 1 W of cw power with the spectral characteristics of the seed laser. The ability to amplifier the injection seeding laser will be important as one question the remains unanswered at this point is what injection seed power is needed to control the spectral properties of the SR-OPO.

Table 2. Operating temperature, drive current and output power available from the injection seeding laser for operation at 1571 nm.

		Laser	Fiber
T (C)	I (mA)	P (mW)	P (mW)
30.3	104.6	9.16	8.36
31	102	8.96	8.24
32	98.4	8.69	8.04
33	94.7	8.44	7.79
34	90.9	8.07	7.44
35	87	7.77	7.23

With the characterization of the pump and injection seeding laser complete, work to build the SR-OPO continues. The Mg:PPLN crystal has been obtained from Advr, a Bozeman based optical company. This crystal is periodically poled with a pole spacing of 31.447 μm allowing phase matching at 1571 nm and 1645 nm by controlling the operating temperature of the crystal. A picture of the crystal, including the thermoelectric heater and enclosure for uniform heating, is shown in *Figure 19.*

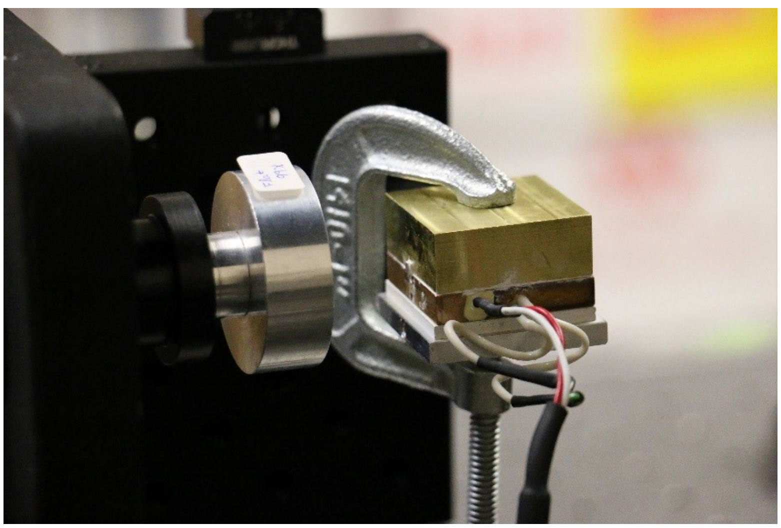

Figure 19. The Mg:PPLN crystal in the brass housing with the thermoelectric heating element. A cavity mirror housed in an aluminum mount that can be scanned using an embedded piezo-electric transducer is shown to the left of the crystal.

Some project highlights:

- Briana Jones, a graduate student who worked on this project is now employed by Advr. We are currently seeking funding to develop a DIAL instrument with Advr based on this work.
- An SBIR proposal is pending with Michigan Aerospace to develop a methane DIAL for agricultural monitoring.

<u>Expenditures to date</u>

Salaries $13,804.40, Benefits $977.15, Operations $10,384.10, total expenditures $25,165.65.

Subproject 10: Nonlinear Optical Detection of Surface Contaminants (Rob Walker, rawalker@chemistry.montana.edu, 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.

Activities to date

- This project's goal is to develop new surface-specific, optical methods capable of detecting adsorbed molecules. Specifically, our efforts are focused on exploiting the advantages of nonlinear optical spectroscopy to create a simple, sensitive technique that can identify the presence of organic contaminants at water/air and solid/liquid interfaces. Our ultimate objective is to use discoveries from our seminal studies to guide the development of portable devices capable of being used for field measurements.
- The final quarter of 2015 saw some advances and one substantive setback. Working with a local machine shop, Autopilot, we completed designs for the experimental detection assembly and had the assembly built. This rig (*Figure 20*) needed to house a small, 15 cm monochromator inline with a separate casing that housed the near-IR photomultiplier tube. These two pieces are separated by ~8 cm and require alignment precision of ~1mm along the path traveled by the incident signal. Furthermore, the assembly requires the ability for optics such as neutral density filters, band pass filters, irises, etc.) be included in the beam path. This project required that a graduate student, Grace Purnell, learn the basics of instrument drafting (using SolidWorks). Grace also was the liaison with Autopilot and consulted frequently with their machinists to discuss how her original design could be adapted to improve reproducibility of assembly and ease of use.

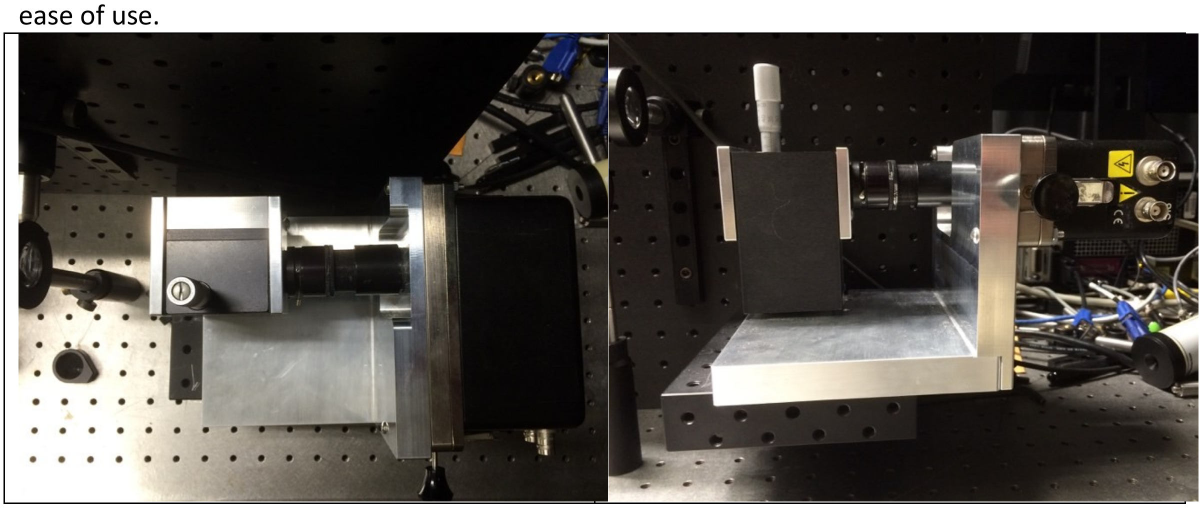

Figure 20. Photographs of the experimental detection assembly.

- The assembly was tested in early December. Of particular importance was that the assembly measured second harmonic signal (SHG) from surfaces accurately and with high sensitivity. Because SHG depends quadratically on the incident power, we tested the detection assembly's response to SHG generated from a gold surface using P-polarized incident light at 630 nm and detecting P-polarized signal at 315 nm.

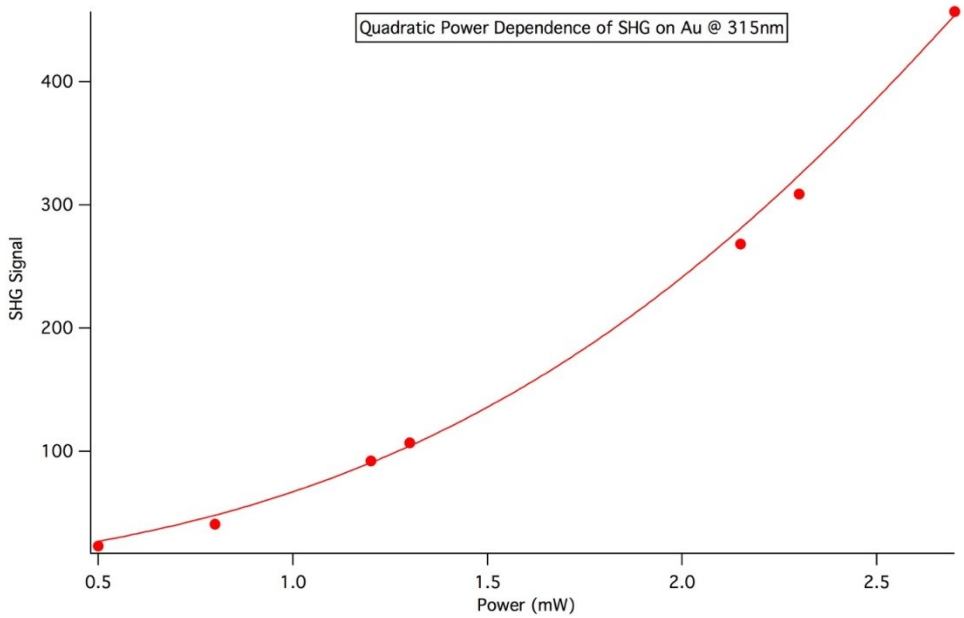

Figure 21. Detection assembly response to SHG generated from a gold surface using P-polarized incident light at 630 nm and detecting P-polarized signal at 315 nm.

- The data were fit to a 2nd-order polynomial and, as *Figure 21* illustrates, quadratic behavior was apparent. This result (and other supporting data) is important, because it illustrates the ability of the new assembly to measure an SHG response quickly and accurately with a minimum of uncertainty introduced by day to day variability in experimental setup and conditions.
- Shortly before the Christmas holiday the Chemistry and Biochemistry building experienced an unanticipated loss of chilled water. As a result, the chillers stabilizing our lab's Ti:sapphire regenerative amplifier were unable to keep up with the load and the system's temperature interlock tripped. After all of the cooling issues were resolved and the system turned back on, output power from the Ti:sapphire regen had diminished by ~15% and was below the threshold where our OPA can operate stably. The mode quality had also suffered. We have been working diligently to try and bring the Ti:sapphire regen back to operating at full power and with a TEM-00 beam profile. We have rotated and cleaned optics and continue to work on aligning the regen cavity. We remain in close contact with our region's service engineer and we get closer to having a functioning instrument every week.
- Once the lasers are functioning again at a level that allows us to do experiments, we will first measure an SHG response from an Au surface using the signal and idler outputs from the OPA. We then will work to measure a response from an Au surface functionalized with a highly ordered, covalently bound, alkyl thiol monolayer. The large no resonant response from the Au will serve as a local oscillator that amplifies the vibrational contribution from the thiol film.

Expenditures to date

Salaries $5,464.00, Benefits $646.88, Operations $6,330.42, total expenditures $12,399.23