R2-B.4: Mid-Infrared Photonic Integrated Circuits for Stand-Off Detection of Trace Explosives

I. PARTICIPANTS

<table>
<thead>
<tr>
<th>Faculty/Staff</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Title</td>
</tr>
<tr>
<td>Anthony Hoffman</td>
<td>Co-PI</td>
</tr>
<tr>
<td>Michael Wanke</td>
<td>Co-PI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Graduate, Undergraduate and REU Students</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Title</td>
</tr>
<tr>
<td>Ahmet Cagri Aydinkarahaliloglu</td>
<td>Ph.D.</td>
</tr>
<tr>
<td>Owen Dominguez</td>
<td>Ph.D.</td>
</tr>
<tr>
<td>Kaijun Feng</td>
<td>Ph.D.</td>
</tr>
<tr>
<td>Galen Harden</td>
<td>Ph.D.</td>
</tr>
<tr>
<td>Irfan Khan</td>
<td>Ph.D.</td>
</tr>
<tr>
<td>Junchi Lu</td>
<td>Ph.D.</td>
</tr>
<tr>
<td>Bryce Beddard</td>
<td>B.S.</td>
</tr>
<tr>
<td>Zhaoyuan (Andy) Feng</td>
<td>B.S.E.E.</td>
</tr>
</tbody>
</table>

II. PROJECT DESCRIPTION

A. Project Overview

This project aims to develop a mid-infrared photonic integrated circuit (MIR-PIC) and to use the device for the stand-off detection of trace explosives in the solid phase. The proposed MIR-PIC is a mid-infrared (mid-IR) heterodyne receiver comprising a high-performance, mid-IR quantum cascade laser (QCL) with an integrated Schottky barrier diode. This research addresses the void of high-performance, compact technologies capable of measuring the phase and amplitude of mid-IR light that has interacted with a sample under test. This novel, compact semiconductor transceiver operates by mixing light scattered off the sample under test and coupled back into the QCL waveguide with the internal field of the waveguide. Changes in the phase and amplitude of the scattered light are detected by measuring the voltage over the integrated diode. Compared to existing optical stand-off detection technologies, there is no need for an external detector or optics, the entire sensor operates at room-temperature, and the sensitivity and detection limits are anticipated to improve by orders of magnitude. The proposed MIR-PIC is ultra-compact (~5 mm x 300 µm), low-cost, appropriate for commercial-scale production, and can be integrated into large format arrays for imaging. Single devices will enable rapid stand-off detection of explosives, and arrays of these devices will enable imaging with phase, amplitude, and spectral content for improved detection.

This project addresses a near-ubiquitous limitation of stand-off detection using mid-IR QCLs, including the relative intensity noise (RIN) of the lasers. The RIN of QCLs is most often the limiting factor in sensor performance and detection sensitivity. This project improves the sensitivity by orders of magnitude (approaching
the quantum limit) by shifting the signal into the radio frequency (RF) domain via nonlinear mixing in the integrated diode; in the RF domain, the RIN of the QCL is substantially lower. Additionally, the integrated diode allows the MIR-PIC to function as both source and detector, enabling the ultra-compact footprint while reducing complexity and cost.

The MIR-PIC represents a fundamentally new type of mid-IR semiconductor transceiver that will enable phase- and amplitude-sensitive imaging in the mid-IR via an ultra-compact device. This research will have significant impact on the Department of Homeland Security (DHS) enterprise due to the complementary sensing and imaging modalities the MIR-PICs enable, as well as the low-cost, small footprint, and improved sensitivity of these devices. Ultimately, the sensors can be used for detecting explosives residues on skin, clothing, personal items (travel bags, briefcases, etc.), containers, vehicles, and other substrates. Additionally, a myriad of other fields, including medicine, drug enforcement, and environmental monitoring, will also benefit.

B. State of the Art and Technical Approach

Optical spectroscopy has played an increasing role in materials characterization and sensing over the past two centuries. The growing role of light in characterization and detection applications has been enabled by our access to and control over different regions of the electromagnetic spectrum. By monitoring the interaction of light with matter, it is possible to gain qualitative and quantitative information about a sample under test [1]. Vibrational spectroscopy is concerned with interactions between light and vibrational and rotational modes of molecules. These modes can be excited via photons, resulting in absorption spectra that are dictated by the energies of the vibrational and rotational modes. These absorption spectra are unique to the molecule, meaning that molecules possess a spectral fingerprint that can be differentiated using optics. Mid-IR light interacts with the fundamental vibrational and rotational modes of many molecules, meaning that these light-matter interactions can be orders of magnitude larger than in neighboring spectral regions [2,3]. Prior to the demonstration of mid-IR semiconductor lasers, most mid-IR spectroscopy was performed using expensive and bulky Fourier transform infrared spectrometers (FTIRs) or dye lasers, drastically limiting access to this portion of the spectrum. The QCL unlocked the mid-IR to the broader scientific and engineering communities, and enabled countless new applications—including explosives detection—across a myriad of fields.

Mid-IR QCLs have matured tremendously since their first demonstration in 1994 [4]. These electrically-injected devices emit mid-IR radiation via engineered optical transitions for electrons in semiconductor heterostructures. QCLs are now capable of room-temperature operation in pulsed and continuous wave (CW) mode, with optical output powers greater than 1 W [5]. Much of this progress has been enabled by careful quantum engineering of the semiconductor heterostructure comprising hundreds of coupled quantum wells. The lasers are available commercially from several domestic and international companies including Thorlabs Inc. [6], Daylight Solutions [7], and Alpes Lasers [8].

Despite their maturity and commercial availability, large gains in performance were recently realized by more carefully considering the physics of electron transport in the quantum well superlattice and revisiting the design of the QCL active region (i.e. the portion of the QCL responsible for generating gain). In these so-called “ultra-strong coupling lasers,” the gain provided by the active regions is many times larger than more conventional QCL active region designs [9, 10]. These new designs with improved gain have resulted in lasers with record wall-plug efficiency (electrical-to-optical conversion efficiency) and optical powers [10]. In addition to improved wall-plug efficiency and high output powers, the improved gain can also be used to enable lasing in devices with novel waveguides, such as those employed by the MIR-PICs in this project that might have larger optical losses than conventional waveguides.

QCLs have already been employed in a number of sensing setups. The most straight-forward incorporation of QCLs into infrared absorption spectroscopy (IAS) uses the QCL as a mid-IR source and a conventional
detector, typically HgCdTe (mercury cadmium telluride (MCT)), for monitoring the intensity of the mid-IR light after interacting with a sample under test [11]. More sophisticated sensing systems that improve the sensitivity and selectivity of the system have also been employed. These more sophisticated approaches include photoacoustic spectroscopy [12], cavity ringdown spectroscopy [13, 14], and Faraday rotation spectroscopy [15, 16], among others. These schemes have been used by a number of groups to detect explosives and precursors to explosives in the solid and gas phases [11, 17-19]. The detection sensitivity limit in all of these approaches is determined in part by fluctuations of the intensity of the QCL, that being the RIN.

The RIN noise is determined by a number of factors, including the current source and the underlying physics of the laser. Even for extremely stable current sources, the RIN of a QCL is larger compared to more traditional interband diode lasers due to the cascading of electrons in the active core. It has been demonstrated for QCLs that non-radiative losses out of the upper laser states dominate the RIN [20]. Since the RIN of the QCL is a fundamental impediment to the lasing physics, new strategies are needed to circumvent this limitation and to further improve the detection limit.

The three primary strategies to reduce laser noise are: 1) heterodyne detection, 2) active laser intensity stabilization, and 3) balanced detection [21]. Active laser intensity stabilization requires custom equipment that increases the cost, complexity, and footprint of the sensor. Balanced detectors with differential amplifiers are only available in the mid-IR via custom design, and are therefore very costly. Heterodyne detection shifts the detection to the RF domain (about 14 GHz for the devices in the project), where the QCL RIN is much lower [21]. Heterodyne detection using QCLs has been demonstrated using discrete free-space optical components [21, 22]. For heterodyne-enhanced Faraday rotation spectroscopy, systems have been demonstrated at only 5.6 times the ultimate theoretical sensitivity, demonstrating the significant improvements that can be realized using heterodyne detection.

In addition to improving the sensitivity by reducing RIN, heterodyne detection also enables acquisition of both phase and amplitude information for detected scattered or transmitted light without the need for calibration [21-23]. Phase sensitive detection or imaging is often used to distinguish between similar materials. In the context of explosives detection, it may be possible to use phase sensitive detection to sort out decoys from true threats. Furthermore, combined phase and amplitude information can improve the sensitivity and selectivity of detection.

Unfortunately, with all the benefits of heterodyne detection, the size and complexity of the system is a significant drawback. Numerous free-space optical elements, such as lenses, mirrors, and acousto-optic modulators, are required to implement the technique. Our project advances the state of the art through the development and demonstration of PICs that combine a high-performance QCL active region with a diode engineered for heterodyne mixing of the internal modes of the QCL with back-scattered light that has interacted with a sample under test. Our MIR-PIC is a single semiconductor device that serves as both source and detector.

Figure 1 is a schematic of a MIR-PIC deployed as a sensor. The device comprises a mid-IR waveguide (blue, horizontal line) with a mid-IR QCL active core (the active core resides inside of the waveguide), and an integrated Schottky barrier diode (gold dot). The active core of the QCL generates mid-IR photons via electron transitions between the bound subbands of hundreds of coupled quantum wells, which are then guided in the waveguide. During operation, some of the generated photons are emitted from the facet of the waveguide, scatter off the sample under test, and re-enter the waveguide. These photons are then mixed by the Schottky diode with the internal field (photons) of the waveguide. This nonlinear mixing results in a voltage over the diode that oscillates at the difference frequency between the internal field and the light that re-entered the cavity, called the intermediate frequency (IF). For a multi-mode Fabry-Perot cavity, a mixing response in the diode is observed at the free spectral range (mode spacing) [24, 25]. For cavities ~ 3mm long, the IF is ~14 GHz, a frequency that is easily accessible using common microwave equipment available in our laboratories.
This project explores using the MIR-PICs in two configurations for stand-off detection: (1) with an external ZnSe lens, and (2) without an external lens. An external lens is useful for collimating the emitted beam and collecting more of the back-scattered light. Collimating the beam provides more power on target and collecting more light will improve the sensitivity of the MIR-PIC. We anticipate that including the external lens will improve the stand-off distance. While the external lens introduces an external optical component, this could be integrated into the final MIR-PIC package; this is not true for the optical components used in stand-off detection with discrete sources and emitters. An integrated lens can be incorporated into the device package via our collaboration Adtech Photonics Inc. Such lenses are already incorporated into industry-standard high-heat load (HHL) mounts offered by Adtech Photonics. This single, integrated lens is in contrast to multiple, free-space lenses, which would be needed when using discrete components. These free-space lenses are difficult to deploy in the field and ruggedize, as they require careful optical alignment. We anticipate that for small stand-off distances appropriate for scanning fingerprints, handled documents, baggage, etc., an external lens is not needed.

We will systematically study stand-off detection using the MIR-PICs, including how the following parameters affect the sensor: (1) incident angle on the sample, (2) sample substrate, (3) stand-off distance, (4) operation mode of the LO (pulsed versus continuous wave and fixed-frequency versus tuning), (5) operating temperature, (6) LO power, (7) design and fabrication variations (cavity length, ridge width, diode design, diode location, facet coatings, etc.), (8) heterodyne integration time and amplifier chain, (9) LO tuning rate, and more. We will determine the MIR-PIC sensitivity by measuring the heterodyne signal versus the amount of solid trace explosive for a fixed integration time (1 s). For all measurements, we will compare the results with those obtained using a custom vacuum FTIR with a cooled HgCdTe detector that is available in our lab to verify that the measured heterodyne signal is from the trace explosive.

C. Major Contributions

This is a new project that was launched in January 2017. This section details the major contributions that we have made in the past 1.5 years.

C.1. Study Preliminary Devices

We have fabricated and characterized MIR-PICs that exhibit a heterodyne signal from 14 GHz (3 mm cavity) to ~21 GHz (2 mm cavity). A top view of a fabricated device is shown in Figure 2(a), and an exemplary diode response is shown in Figure 2(b). These preliminary measurements indicate that mixing in the Schottky diode is possible at mid-IR frequencies. However, while these preliminary data indicate the heterodyne detec-
tion is possible, the IF amplitude should be increased to improve the signal-to-noise ratio (SNR) and detection limit of the MIR-PIC. The IF amplitude can be improved via several approaches, including increasing the internal field of the MIR-PIC, redesigning the waveguide, and engineering the Schottky diode. Additionally, the tested devices only operate in pulsed mode. This is problematic since there is frequency chirp (i.e. a shift in the lasing frequency) over the duration of the applied pulse (200 nm to 2 µs in duration) due to heating of the active core. Our analysis of these initial devices indicates that a new, high-performance QCL active region with improved gain is necessary. To this end, we have established a collaboration with Adtech Photonics, Inc. Adtech Photonics employs state-of-the-art metal organic chemical vapor deposition (MOCVD) to grow high-performance QCLs and quantum cascade gain materials, and together with Hoffman they have demonstrated world-record efficiency in QCLs [10]. MOCVD is a high throughput technology that is preferred for commercial products. Additionally, Adtech Photonics is able to grow high-quality InP which allows for superior thermal management and optical performance.

C.2. High-performance QCL Active Core

The IF amplitude and SNR are related to the internal field of the MIR-PIC waveguide. From our preliminary measurements, we believe that the IF amplitude is limited by the internal field of the waveguide at the Schottky diode. To increase the internal field, we designed a QCL active core that incorporates elements from state-of-the-art, high-performance mid-IR QCLs. The active region is designed for detecting RDX at 6.25 µm and is depicted in Figure 3. In addition to increasing the internal field, a high-performance design will also enable continuous wave operation, which is needed to avoid frequency chirp observed in pulsed mode.

Figure 2: (a) Top-down image of a 2mm long MIR-PIC; and (b) generated RF spectra from mixing internal cavity modes at various voltages over the laser. Inset: focused-ion-beam image of a cross-section of a 2µm diameter diode. Measured by Sandia National Laboratories (SNL).
For the design, we modified existing density matrix models in our laboratory to properly include coherent coupling and interface roughness scattering in the QCL. We have submitted a manuscript to the *Journal of Optics* related to these design efforts [26]. Compared to a conventional design at the same wavelength, our design is expected to exhibit gain more than five times larger. Figure 4 shows the results of a calculation of the QCL gain versus the coherent coupling between the upper-laser level and the electron injection level. By increasing coherent coupling between these levels, we improve electron injection into the optical transition and increase gain. Increasing the coupling too much would lead to spectral splitting of the optical transition and a reduction in the peak gain. Importantly, these models could be used for designing other high-performance QCLs for ALERT projects or for projects with our external collaborators.

For the design, we modified existing density matrix models in our laboratory to properly include coherent coupling and interface roughness scattering in the QCL. We have submitted a manuscript to the *Journal of Optics* related to these design efforts [26]. Compared to a conventional design at the same wavelength, our design is expected to exhibit gain more than five times larger. Figure 4 shows the results of a calculation of the QCL gain versus the coherent coupling between the upper-laser level and the electron injection level. By increasing coherent coupling between these levels, we improve electron injection into the optical transition and increase gain. Increasing the coupling too much would lead to spectral splitting of the optical transition and a reduction in the peak gain. Importantly, these models could be used for designing other high-performance QCLs for ALERT projects or for projects with our external collaborators.

![Figure 3](image1.png)

*Figure 3: Portion of the conduction band of a QCL active region for lattice matched InGaAs/AlInAs on InP. The grey and red curves are the calculated single electron wave functions. The curves in red are most closely related to the designed optical transition. The applied field is 46 kV/cm, and the optical transition is 6.25 µm.*

![Figure 4](image2.png)

*Figure 4: Calculated peak gain versus the coupling strength between the injector and upper-laser level. The gain is calculated using a three-level density matrix model that includes coherent coupling, photon scattering, and interface roughness scattering.*

C.3. *Increasing Nonlinear Mixing*

We also redesigned the waveguide of the MIR-PIC to increase the magnitude of the electrical field at the contact of the laser, which will ultimately increase the non-linear mixing on the diode. We did this because
our analysis shows that it should be possible to use the entire top contact of the laser as the Schottky diode, greatly simplifying the nanofabrication process. Since the waveguide we are employing is different than what is conventionally used for QCLs, we had to modify our custom design software. The redesigned waveguide and calculated field profile are shown in Figure 5.

![Figure 5: Waveguide design and the calculated mode intensity. At the Schottky diode/contact (shaded gold region), the mode intensity is about 30% of the peak mode intensity to increase nonlinear mixing on the diode.](image)

Samples with the active region and waveguide designs shown above were grown via molecular beam epitaxy (MBE) through an unfunded collaboration with Princeton University. The samples were processed into standard QCL ridge waveguide lasers and are in the process of being characterized in Professor Hoffman’s laboratory. The characterization includes spectral measurements to determine the lasing wavelength and light-current-voltage measurements, as a means of ascertaining the electrical and optical properties of the lasers, such as peak power, threshold current density, temperature performance, etc. After the standard QCL characterization is completed, we will fabricate MIR-PICs using the same semiconductor material and characterize the devices in the microwave domain. Dr. Wanke’s laboratory at Sandia National Laboratories (SNL) is already configured to measure these devices. Professor Hoffman will send the graduate student working on this project to Sandia to be trained on RF measurements of MIR-PICs. The setup will be duplicated at Notre Dame using equipment available in our laboratory.

**C.4. Improving Impedance Matching for Microwave IF Signal**

We developed new MIR-PIC designs that provide better impedance mismatch between the MIR-PIC top contact and the coaxial cable. This work was carried out because we identified a large impedance mismatch between the microwave coaxial cable and the top metal contact of the MIR-PIC that was responsible, in part, for the small IF signal. This impedance mismatch results in poor coupling of the microwave IF signal from the MIR-PIC to the external instrumentation, limiting the amplitude of the measured IF signal. To address this limitation, we first developed microwave models of the MIR-PIC based on the materials used. Using the materials model, we then simulated the impedance of the MIR-PIC using a commercial software package (ANSYS High Frequency: Electromagnetic Field Simulation). Our results indicated a strong impedance (c.a. 5MΩ) and a large attenuation of 10 GHz microwave radiation. Using these models, we developed a new device geometry where the MIR-PIC active region is embedded into a microwave coplanar waveguide.

The new MIR-PIC geometry is shown schematically in Figure 6. The top side is processed as a coplanar waveguide (CPW) with three terminals. The center contact pumps the active region and simultaneously serves as the center pin for the CPW. The side contacts, spaced approximately 10 µm from the center ridge, are the
ground plane for the CPW and serve as the current sink for the active region. The ratio of the center contact width to the bottom contact spacing is used to control the impedance. Here, we design an impedance mismatch of less than $5\,\Omega$ assuming typical variations in fabrication. The bottom of the device is also coated with gold to improve the thermal contact with the heat sink. In addition to improving the impedance matching, these devices have the advantage of all-top contacts and a planar geometry. This allows the use of standard microwave z-probes for contacting the device [27]. Professor Hoffman has extensive experience with the design, fabrication, and characterization of microwave coplanar waveguides from his previous work on superconducting circuits and qubits.

![Schematic of the new MIR-PIC design](image)

**Figure 6:** Schematic of the new MIR-PIC design that incorporates the active region into a CPW structure. Bottom contacts indicated by arrows extend beyond the bounds of the image. Typical dimensions are on the order of 500 µm.

### C.5. High Performance Active Regions for InP Substrates

We designed and fabricated active regions based on InGaAs/AlGaAs ternary materials grown on an InP substrate. There are two primary reasons for these new designs. First, due to complications with the MBE, our collaborator at Sandia National Laboratories, Dr. John Kelm, was not able to grow our most recent wafers. We therefore pursued a collaboration with Adtech Photonics, Inc. to grow the samples needed to implement the new MIR-PIC design. Adtech Photonics, a commercial supplier of QCLs, uses metal organic chemical vapor deposition (MOCVD) as their growth technology. The growth kinetics of MOCVD allows epitaxial layers to be grown much faster than MBE. While the quantum well interfaces in MOCVD can be inferior to MBE, some of the highest performance QCLs have been grown via this technology [5]. World-record QCLs were previously demonstrated by Professor Hoffman and several technical members of Adtech Optics (acquired by Adtech Photonics) [10]. Due to the change in the substrate and growth technologies, our samples had to be redesigned. We therefore designed samples for strain-compensated quantum wells and strain-balanced quantum wells. Those designs are shown in Figure 7.
In addition to new active region designs, we also designed new waveguides that incorporate InP. The high index of refraction of InP allows for better confinement of the optical mode and improved heat dissipation. The new waveguide designs are depicted in Figure 8.

![Figure 8: Schematic of the waveguide designed for the MIR-PICs grown on InP substrates.](image)

C.6. **Characterization of InP-based Active Regions**

We characterized the InP-based active regions using standard low-temperature and room temperature electroluminescence techniques. These measurements give information on electron transport through the device, the emission wavelength, and an indication of the optical gain provided by the active region. Figure 9(a) is an optical microscope image of a typical electroluminescence structure. The sample is electrically-pumped and light is emitted from the front, cleaved facet; there is no back facet to prevent optical feedback and thus lasing. The emission from the front facet is coupled into a FTIR, Figure 9(b), and the spectrum is measured as various experimental parameters are altered, including temperature and operating voltage. These structures emitted weakly at 80K. Emission levels are estimated at less than 1 µW, which is smaller than expected. We fabricated many devices to rule out the possibility of the fabrication limiting the emission, but all devices displayed similar behavior.
We also fabricated MIR-PIC devices and tested those devices for mid-infrared stimulated emission and sub-threshold amplified spontaneous emission. The experimental setup for both of the measurements is similar to Figure 9(b). Figure 10 shows voltage versus current density measurements performed at both 80K and ambient conditions. The measurements are for a device similar to that shown in Figure 9(a) and were taken using the setup shown in Figure 9(b). At both low-temperature and room-temperature, the device exhibits a non-linear current-voltage curve which is indicative of current flow through the device as the engineered quantized levels align and support electron transport.

![Microscope image of a tested electroluminescence structure and setup for temperature-dependent electroluminescence measurements.](image)

Figure 9: (a) Microscope image of a tested electroluminescence structure; and (b) setup for temperature-dependent electroluminescence measurements. The setup is similar for characterizing stimulated emission and amplified spontaneous emission.

![Graph showing voltage versus current density for processed mesas at 80K (blue) and room-temperature (red).](image)

Figure 10: Measured voltage versus current density for processed mesas at 80K (blue) and room-temperature (red). The measurements were taken using 100 ns pulses that were gated and averaged over 40 ns using the custom setup shown in Figure 9(b).

D. **Milestones**

- We have developed numerical code to model the quantum and optical properties of the MIR-PICs. Using these models, we have designed MIR-PIC devices that aim to address problems with the devices used for...
our preliminary study that prevented the devices from operating in continuous wave mode. **Specifically, we have developed a quantum cascade gain region capable of providing double the gain of our previous design.** These new active region designs employ ultra-strong coupling to improve the injection of electrons into the upper-laser level.

- We have used our optical models to design new optical waveguides, focusing on the optical loss, field strength at the metal contact, and confinement factor. **We have reduced the optical loss by approximately 60%** by modifying the field strength at the metal contact and the doping of the cladding layers. The field strength at the metal contact is now 20% of the peak field in the active region; we estimate that this will be sufficient for the MIR-PICs in this project. In order to improve gain, **we have also increased the optical confinement factor by ~30%** by adding additional active regions. We expect that these changes should enable continuous wave operation of the MIR-PIC.

- We have fabricated MIR-PIC devices and performed basic electrical and optical characterization. The devices have been operated in pulsed and continuous wave mode.

- We did not achieve an improvement of >10x in the IF amplitude SNR, but we identified a problem related to the design of the MIR-PIC. This delay in this milestone results from two challenges: (1) wafer growth; and (2) design of the Schottky diode. Each is described in more detail in the following bullet points.
  - High quality semiconductor crystal growth is needed to fabricate quantum cascade laser heterostructures. We have had difficulty obtaining such high-quality material due to issues with our collaborator’s molecular beam epitaxy growth chambers. These issues result in reactor downtimes that have limited somewhat our material supply. Since the device that we are creating is novel in design, iterations on the growth are important. We have not been able to iterate the growth as originally planned.
  - Through testing and modeling of our fabricated devices, we have determined the microwave output line is not properly impedance matched. This is resulting in strong attenuation of the IF signal. We are exploring other designs such as microstrip lines to recover the IF signal.

### E. Future Plans (Year 6)

In Year 5, we developed new design tools for engineering the active region of quantum cascade heterostructures using the so-called “ultra-strong coupling” paradigm. These design tools also include new models for waveguides that incorporate Schottky diodes. We also fabricated and characterized MIR-PIC devices. During our testing, we identified a problem related to coupling of the IF signal off the MIR-PIC. We therefore designed new devices to address this limitation.

In Year Six, we will achieve the following milestones:

- Demonstrating an improvement in the IF amplitude is an important metric and will continue to be a quantitative outcome in Year 6.
- Demonstrate stand-off detection of a trace explosive or mimic in the gas or solid phase using a MIR-PIC. We are targeting a detection limit of better than 1 µg/cm² of C4.
- Characterize stand-off detection on various substrates such as wood, cardboard, cloth, metals, painted/coated metals, etc.
- Explore the feasibility of using these devices for imaging. This has been a plan of ours from the onset of the project, but we received useful feedback in the review that it should be incorporated into this project. Therefore, we will explore several methods for imaging. The methods are described below.
  - MIR-PIC Arrays: Linear arrays of MIR-PICs will be studied for their feasibility in an imaging system. Here, we will explore different implementations for acquiring images. This is important due to the power consumption of QCL heterostructures, ca. 15 W. Therefore, we will investigate long duty
cycle pulses supplied to the MIR-PIC array simultaneously and sequentially. PI Hoffman has a patent pending for sequential activation of QCLs as a quasi-continuous wave source for improved system efficiency. In principle, the same strategy can be used with these arrays.

- MIR-PIC Scanning Imaging: Imaging using a single MIR-PIC will be explored by translating the sample or MIR-PIC or by scanning the output beam of the MIR-PIC. The advantage of this approach is a reduction in the imaging system complexity and cost. The disadvantage is that each pixel of the image is acquired serially.
- Continue to pursue externally-funded collaborations with our contacts at Thorlabs and Northrup Grumman.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

This project addresses the need for ultra-compact, sensitive sensors for the stand-off detection of trace explosives in the solid phase (ng/cm²). Such capabilities could be integrated into handheld devices, unmanned aerial vehicles, remote operated vehicles, and existing security-screening infrastructure as primary or confirming sensors.

- Stand-off detection of explosives is critical for the safety of Homeland Security personnel. We will demonstrate stand-off detection at distances greater than 3 feet. Longer stand-off distances should be possible and can be investigated if additional time is allotted for this project.
- Compact sensors with high detection sensitivity are needed for the detection of trace explosives. We will demonstrate detection of an explosive in the solid phase. Our sensitivity targets are sub-ng/cm²; however, since this sensor is entirely new, these detection limits may not be achievable immediately or within the time frame of this project. A goal of this project is to study the relationship between the design and performance of the MIR-PIC and the detection limits when the MIR-PIC is used as a sensor.
- Sensitive, stand-off detection could have a transformative impact on the detection of explosives by enabling widespread screening of individuals, vehicles, and objects. The high sensitivity could enable the use of these devices as a primary or confirming sensor, and the ultra-compact footprint could enable handheld deployment.

B. Potential for Transition

Our vision for this technology within the DHS enterprise is to develop a linear array of MIR-PICs for rapidly scanning and imaging letters and packages in sorting facilities or baggage and personal items in screening stations at airports. The array of MIR-PICs would comprise devices that target different spectral regions, enabling preliminary detection of many different solid phase trace explosives or contaminants. We are now collaborating with Adtech Photonics, Inc., a leader in QCL technologies. Adtech Photonics employs state-of-the-art growth using MOCVD. Prof. Hoffman has collaborated with several members of the technical staff and together they have demonstrated world-record QCLs. Mary Fong, the CEO of Adtech Photonics, has directly expressed interest in commercializing the technology in this project.

Outside of the DHS enterprise, we envision that this technology will be used for imaging the margins of tumors during breast cancer surgery. For such an application, rapid imaging is needed to determine if the entire tumor has been removed from the breast tissue. We are collaborating on this application with Dr. Jennifer Tseng M.D., Fellow of Surgical Oncology at the University of Chicago. We are continuing to seek seed funding for this application and will apply for funding from the National Institute of Health once we have preliminary data.
C. Data and/or IP Acquisition Strategy

Possible IP and disclosures are in the area of device and use patents. We are working with Tim Joyce in the Technology Transfer Office at Notre Dame to disclose potential IP and to submit patent disclosures and applications as necessary.

D. Transition Pathway

Ultimately, we aim to develop a MIR-PIC that can be transitioned for wide-scale deployment. To this end, we are pursuing a collaboration with Dr. Loan Li, Ph.D. of Northrup Grumman, who has expressed interest in the MIR-PICs being developed through this research. Dr. Li is interested in the possibility of developing mid-IR ultra-compact sensors based on our MIR-PICs and ancillary technologies. Dr. Li would help support our project via epitaxial growth and device processing. Funding for graduate students might also be possible.

We also have a collaborative relationship with Dr. Yamac Dikmelik, Ph.D., at Thorlabs Inc., a leading company in mid-IR optoelectronics. Dr. Dikmelik is interested in the impact our photonic integration could have on their existing line of QCL products. We published a manuscript with Dr. Dikmelik in 2017 related to the design of high performance quantum well active regions—a key component of our MIR-PICs and the mid-IR QCLs produced and sold by Thorlabs. We are also actively discussing new collaborations related to this project. Funding for this collaboration would come from joint proposals. The ultimate transition products also include students trained in technical areas relevant to the Homeland Security Enterprise (HSE), in addition to the MIR-PICs and derivative technologies developed in this program.

Finally, we recently established a collaboration with Adtech Photonics, Inc. Adtech Photonics is a leader in QCL technologies and is supporting this project through material growth using their state-of-the-art MOCVD reactors. Mary Fong, CEO of Adtech Photonics, has indicated that she is interested in commercializing the technologies we are developing in this project.

E. Customer Connections

- Dr. Yamach Dikmelik, Ph.D., Thorlabs Inc.; Frequency of contact: Every other month; Level of involvement: We published a manuscript with Dr. Dikmelik as a coauthor and collaborate with him on QCL design.
- Dr. Loan Li, Ph.D., Northrup Grumman; Frequency of contact: infrequent; Level of involvement: Has expressed interest in our work and a possible project with funding. Funding is not available at the moment due to budgetary priority issues within Northrup Grumman.
- Mary Fong, CEO of Adtech Photonics, Inc.; Frequency of contact: Currently, weekly; Level of involvement: Adtech Photonics, Inc. is now growing the MIR-PICs for our project and has directly indicated that they are interested in commercializing our technology.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Course, Seminar, and/or Workshop Development: Professor Hoffman developed and taught a new course for upper-level graduate students on quantum optics and nanophotonics. The course, EE87039 “Quantum Optics and Nanophotonics,” focused on current research in these fields, including potential applications that are relevant to the Homeland Security Enterprise. The course was first offered in Fall 2017 and will be offered again in Fall 2018. The first offering of the course had 14 enrolled graduate students and 8 students auditing or sitting in on the lectures for a total of 22 students. Professor Hoffman also invited speakers performing research in these areas to give seminars
2. **Student Internship, Job, and/or Research Opportunities:** During the summer of 2017, Professor Hoffman hosted Zhaoyuan (Andy) Fang in his research group. At the time, Andy was a rising sophomore at the University of Notre Dame. Andy’s participation in the summer research was funded through the NDnano Undergraduate Research Fellowship (NURF). Andy’s research focused on engineering and characterizing optical modes on ultra-thin epsilon-near-zero materials. This work is part of a larger effort in the Hoffman group that aims at developing far-infrared optoelectronic devices for applications in spectroscopy and sensing. Currently, the state-of-the-art for this portion of the spectrum is a globar (essentially a glowing wire) or a bulky discharge lamp. If these so-called optophonic devices are successful, they could be used for a new generation of ultra-compact sources with applications in sensitive detection and sensing of explosives and other illicit materials. In addition to his research, Andy also worked closely with the other students in Hoffman's group. He interacted with the students involved in this research project in the laboratory and in group meetings.

3. **Interactions and Outreach to K-12, Community College, and/or Minority Serving Institution Students or Faculty:** Professor Hoffman was invited to speak to ~30 5th graders participating in the Department of Defense STARBASE Indiana educational program. The educational program focuses on “hands-on, minds-on” activities in science, technology, engineering, and mathematics. Hoffman’s interactive presentation focused on light and nanophotonics. He taught the students about the differences between visible and infrared light and how mid-infrared imaging can be used in the “real world.” The demonstrations included imaging hot objects in classroom and imaging in a completely dark room. All of the students had the opportunity to take images and video using a mid-infrared camera, giving the students hands-on experience with infrared imaging.

4. **As the advisor of the Notre Dame SPIE Student Chapter, Prof. Hoffman helped organize a day-long outreach activity to Clay Middle School.** Here, 8 graduate students (5 from Professor Hoffman’s group) visited Clay Middle School to introduce the students to basic concepts in optics and photonics. As part of the visit, the students were taught about topics in optics relevant to this program, mainly mid-infrared spectroscopy and imaging. Each of the students was given a mid-infrared picture as a souvenir of the event. Figure 10 is an example of one of the pictures that was given to the students.

![Figure 11: Scaled image of the 4x6 inch “mid-IR selfie” souvenir that was given to students who participated in the outreach event. The image was captured using a mid-infrared camera and printed.](image-url)
B. **Peer Reviewed Journal Articles**


C. **Conference Proceedings**


D. **Other Presentations**

1. Briefings:
   a. Briefing to Army Research Office (Dr. James Harvey)

E. **New and Existing Courses Developed and Student Enrollment**

Professor Hoffman developed and taught a new course for upper-level graduate students on quantum optics and nanophotonics. The course, EE87039 “Quantum Optics and Nanophotonics,” focused on current research in these fields, including potential applications that are relevant to the Homeland Security Enterprise. The course was first offered in Fall 2017 and will be offered again in Fall 2018. The first offering of the course had 14 enrolled graduate students and 8 students auditing or sitting in on the lectures for a total of 22 students. Professor Hoffman also invited speakers performing research in these areas to give seminars in the Solid State Seminar Series at Notre Dame.

<table>
<thead>
<tr>
<th>New or Existing</th>
<th>Course/Module/ Degree/Cert.</th>
<th>Title</th>
<th>Description</th>
<th>Student Enrollment</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>Course</td>
<td>EE87039: Quantum optics and Nanophotonics</td>
<td>This course will introduce quantum optics and nanophotonics, emphasizing the foundation of these two fields. The material will include quantization of the electromagnetic field, quantum states of light, light-matter interactions, plasmonics, metamaterials, recent advances that merge the fields of quantum optics and nanophotonics, and the applications that are driving research in these areas.</td>
<td>14</td>
</tr>
</tbody>
</table>

F. **Technology Transfer/Patents**

1. Other:
   a. We published a manuscript with Dr. Yamac Dikmelik at Thorlabs Inc. We are using this unfunded collaboration to pursue a collaboration that will (1) provide funding and/or resources for this
research beyond that provided by the DHS, and (2) to transition out technology to a leading company in mid-infrared optics, optoelectronics, and photonics.

G. Software Developed

1. Models
   a. We developed new models for calculating the optical field inside of our MIR-PIC devices. While the models are appropriate for our research, they are not ready to be released to the public due to the nuances involved with running the code. We are working on a graphical user interface that will significantly ease the user burden while running the code; however, this is a lower priority than our experimental work. We plan to release the code on our group webpage (www.photon.nd.edu) and Github.

V. REFERENCES

[27] https://www.cascademicrotech.com/products/probes/rf-microwave/z-probe