NDnano Undergraduate Research Fellowship (NURF)  
2013 Project Summary

1) Student name: Arnaud Bacye  
2) Faculty mentor name: Prof. Anthony Hoffman  
3) Project title: External modulation of mid-IR quantum cascade lasers using a Mach-Zehnder interferometer.

4) Briefly describe any new skills you acquired during your summer research:
- Modeling optical waveguides and simulating electromagnetic field distribution using COMSOL  
- Tailoring and analyzing quantum cascade laser internal structure using ErwinJr  
- Designing a mask through L-edit and setting up experiment for optical loss measurements  
- Clean room training: mask making, photolithography, wet-etching, etc.

5) Please briefly share a practical application/end use of your research:
This research will hopefully see use in enhancing selectivity and sensitivity of QCL-integrated devices for photo-acoustic spectroscopy applications in environmental sensing, medical diagnostics, industrial process control, and homeland security.

Project summary:

Quantum cascade lasers have myriad applications in molecular species detection, free space data communication and homeland defense. Implementing QCL integrated devices for such application demands a careful external modulation of their optical properties including phase shift, amplitude and cavity losses. Here, we control the intersubband absorption of quantum wells via a change in applied electric field to adjust the phase difference between the arms of a Mach-Zehnder interferometer, thus modulating the output of the device.

My project consisted of designing an integrated device based on a Mach-Zehnder interferometer, engineered to be used for spectroscopic applications. An understanding of optical losses was required to implement a proper design. I spent the first half of my project modeling and interpreting optical losses in various mid-infrared waveguides. Using COMSOL, I first designed waveguide geometries and simulated the electric field distribution in these waveguides. Modal analysis characterized the main study I focused on in these simulations (Figure 1). By calculating the fundamental propagating mode, I could solve for other important parameters such as the overlap factor and the modal index of refraction in my device design. Once I acquired a sufficient understanding of optical losses, I incorporated this knowledge into modeling a new type of quantum cascade waveguide with a voltage-controlled phase shifter. The device structure consisted of two core regions: the gain region and a supper-lattice of asymmetric coupled quantum wells over which we could control the phase difference between the arms of the interferometer. Since the device was to be operating via an external modulation, I had to comprehend the QCL internal structure as well as its operating physical mechanisms. I studied
the intersubband transitions and absorption in quantum wells. After tailoring the asymmetric coupled quantum wells’ region to end up with a slight amount of overlap of the optical mode with the latter, we could then implement the external modulation. By applying an electric field to the ACQWs, the peak energy of the intersubband absorption shifts, as well as the accompanying phase shift, enabling control of the emitted radiation (Figure 2).

![Modal Analysis of a QCL facet](image1)

**Figure 1:** 2D simulations of the electric field: Modal analysis of a quantum cascade laser facet. We observe here that the optical mode is mainly concentrated at the center of the gain region.

![Intersubband Transition Energy](image2)

**Figure 2:** As the electric field is increased, the ground state decreases, while the higher energy states see a slightly attenuated average potential and are less affected. Hence, the applied field causes an increase in the transitional energy E21 and therefore an increase in the photon energy.