Final Report

Project Title: IR Laser Based Chemical Sensor for the Cooperative Monitoring Program
DoE Grant Number: DE-FG08-99NV13656
Grantee Name: Stevens Institute of Technology
Grantee Project Number: 5-27545
Principal Investigator: Professor Edward A. Whittaker, Department of Physics
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Published Results

The purpose of this project was to investigate the device properties of the quantum cascade laser (QCL), a type of laser invented at Bell Laboratories, Lucent Technologies in the device physics research lab of Dr. Federico Capasso and more specifically to determine the remote sensing capability of this device. The PI and Stevens Institute of Technology collaborated with Dr. Capasso and Bell Laboratories to carry out this research project.

The QCL is a unique laser source capable of generating laser radiation in the middle-infrared spectral region that overlaps the most important molecular absorption bands. With appropriate modulation techniques it is possible to use the laser to measure the concentration of many molecules of interest to the remote sensing community. In addition, the mid-IR emission wavelength is well suited to atmospheric transmission as mid-IR experiences much less scattering due to dust and fog. At the onset of this project little was known about several key device performance parameters of this family of lasers and the NNSA supported research enabled us to determine values several of these characteristics.

The results of the research have been presented in publications in refereed journals. The following is a citation and brief summery of publication. Copies of the articles are included as an attachment to this report. Here we list each of the publications and provide a brief summary of their results.

- "High average power quantum cascade lasers with graded superlattice active regions operated at high duty-cycles", R. Martini, F. Capasso, C. Gmachl, A. Tredicucci, E. A. Whittaker, A. L. Hutchinson, D. L. Sivco, A. Y. Cho, *Journal of Applied Physics* **89**, 7735-7738 (2001).

The QC laser is capable of generating high powered beams of infra-red laser radiation but normally requires external cooling and must be operated with less than 100% duty cycle. In this paper we conducted a series of measurements to determine the laser power output as a function of duty cycle for several prototypical devices fabricated at Bell Labs.

- "High-frequency modulation without the relaxation oscillation resonance in quantum cascade lasers" R. Paiella, R. Martini, F. Capasso, C. Gmachl, H.Y. Hwang, J.N. Baillargeon, D.L. Sivco, A.Y. Cho, E.A. Whittaker, and H.C. Liu, Applied Physics Letters, 79, 2526-2528 (2001).

In order to use the laser for sensitive absorption measurements, it is necessary to modulate the laser at high frequency. In this paper we conducted measurements to determine the high

frequency modulation cut-off frequency for prototypical devices. In doing so we were able to demonstrate that the unipolar QC laser structure is inherently capable of very high frequency modulation due to the lack of a relaxation oscillation resonance commonly found in bipolar semiconductor lasers. This behavior, predicted by theory, makes the QC laser an attractive device for use in optical communications applications as well as in remote sensing.

We pursued demonstration of these capabilities in the next set of papers as the communications capability could be potentially useful in remote sensing applications as well. These results are discussed in the next three papers published in the journal Electronics Letters. The main point is that the QC laser is able to transmit high data density information through the atmosphere under weather conditions that would block transmission using shorter wavelength lasers.

- "Free-space optical transmission of multimedia satellite data streams using mid-infrared quantum cascade lasers", Rainer Martini, Roberto Paiella, Claire Gmachl, Federico Capasso, Edward A. Whittaker, H. C. Liu, Harold Y. Hwang, Deborah L. Sivco, James N. Baillargeon, and Alfred Y. Cho, Electronics Letters 38, 181-183 (2002).
- "High-speed digital data transmission using mid-infrared quantum cascade lasers", R. Martini, R. Paiella, C. Gmachl, F. Capasso, E. A. Whittaker, H. C. Liu, H. Y. Hwang, D. L. Sivco, J. N. Baillargeon, and A. Y. Cho, Electronics Letters 37, 1290-1291 (2001).
- "High-speed modulation and free-space optical audio/video transmission using quantum cascade lasers", R. Martini, C.J. Falciglia, F. G. Curti, C. G. Bethea, F. Capasso, E. A. Whittaker, R. Paiella, A. Tredicucci, A. L Hutchinson, D. L. Sivco and A. Y. Cho, Electronics Letters 37, 191-193 (2001).

Finally we also carried out a series of measurements to determine the ratio of amplitude to frequency modulation. This is a critical parameter for application of the QC laser for spectroscopic detection. Ideally, to have the most sensitive capability the laser should show a large ratio of frequency to amplitude modulation. Unfortunately in the case of the QC laser frequency modulation is accompanied by a substantial amount of amplitude modulation which ultimately limits its utility for spectroscopic applications. A manuscript is in preparation with this result but has been held up due to a delay with a PhD dissertation.

Human Resource Development

NNSA support has played an important role in the development of the scientific careers of several individuals. Two post-doctoral researchers received partial support during the course of the project. Dr. Frank Curti spent approximately three years as a post-doctoral researcher and visiting faculty member at the Department of Physics. Following is stay at Stevens, Dr. Curti obtained a tenure track faculty position at the physics department of Seton Hall University in South Orange, New Jersey where he has developed his own research program in surface science and sensitive optical measurements.

Dr. Rainer Martini also worked at Stevens as a post-doctoral scientist, supported in part by NNSA and partially by Lucent Technologies. Dr. Martini is now in his own tenure track faculty position here at Stevens. In addition to a continuing collaboration with the Principal Investigator of this project, he is developing an independent research program in ultra-fast laser science and technology.

Several graduate students received varying levels of support during the course of this project. Ms. Jennifer Falciglia worked as a research assistant on the high speed modulations experiments and appeared as a co-author on one of the publications. Jennifer completed her Masters degree at Stevens and has since taken a full time research position with Kodak Corporation in Rochester, NY.

Mr. Ke Wang worked as a full time graduate research assistant for one summer and while he ultimately pursued his doctoral research in another area, contributed to the FM/AM modulation experiments.

Mr. Jian Lin was supported as a full time graduate research assistant for two years of the project. His is currently completing requirements for his doctoral dissertation in sensitive laser spectroscopy and expects to receive his Ph.D. degree in the fall of 2005.

Mr. Nikolai Kirsinov received partial summer support as a graduate research assistant for work done on the FM/AM modulation experiments. Mr. Kirsinov went on to complete his PhD in another area of optical remote sensing.

Finally, three undergraduates were supported as summer research assistants. Ms. Jaweeria Ashraf worked on computer modeling of sensitive laser spectroscopy. Mr. Dan Copozzi and Mr. Camilo Lopez worked on developing calibration tools for laser spectroscopy measurements. All three have completed their BS degrees at Stevens Institute of Technology.

Continuing Research

Following completion of the NNSA supported project, research in the area of quantum cascade laser remote sensing and free space optical communications has continued at Stevens including a collaborative research project with researchers at DoE's Pacific Northwest National Laboratory.