REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Dec 04	Final Progress Report 6/1/00 – 8/31/04

4. TITLE AND SUBTITLE
Compact Broad-band Wavelength-Agile Mid-infrared Semiconductor Lasers for Spectroscopic Sensing

5. FUNDING NUMBERS
DAAD19-00-1-0361

6. AUTHOR(S)
H. Q. Le

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Houston*
Photonic Device and System Lab.
Dept. of Elec. and Comp. Engineering
308N Engineering Building 1
4800 Calhoun Street, Houston, Texas 77204-4005
**Prime contractor*

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
41410.1- PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
Advances on mid-IR lasers, photonics, and system applications are reported. Compact mid-infrared broadly tunable lasers have been developed and demonstrated for wavelength from 3 to 9.6 μm. Both material systems, Sb and InP quantum cascade have been used. Advanced concepts of tunable two-segment lasers and off-band surface-emitting Bragg-grating-coupled lasers were demonstrated with broad, continuous tunability, and fast wavelength modulation. Other advanced mid-IR photonics include optical preamplifiers with tunable Bragg for advanced receiver in remote sensing such as lidars. This program has verified key basic scientific aspects of the proposed tunable laser concept and design, which can eventually be transferred to manufacturing development. This mid-IR tunable laser technology is essential for spectroscopic chemical warfare agent detection. The advanced laser technology allows applications such as wavelength modulation spectroscopy (WMS), which was demonstrated with gas absorption spectroscopy. For advanced system applications, novel spectral imaging based on WMS has been developed and demonstrated to map spatial distribution of a gas with background-clutter rejection. More general multi-spectral mid-IR spectral imaging techniques based on these lasers have shown potential applications in chemical and biological target recognition based on spectral signatures.

14. SUBJECT TERMS
Mid-infrared laser, semiconductor laser, broadly tunable laser, external cavity laser, Bragg-grating coupled laser, optical preamplifier, spectroscopic sensing/sensor, lidar

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	UL

Final Progress Report

Compact Broad-band Wavelength-Agile Mid-infrared Semiconductor Lasers for Spectroscopic Sensing

Foreword

The infrared (IR) spectral range 3-10 μm contains the fundamental vibration band signatures of virtually all relevant molecules, and is most important for spectroscopic sensing. Photonics in this spectral region is the key enabling technology for applications such as spectroscopic detection of chemical and biological agents. A significant development in the late 1990’s was the emergence of IR semiconductor photonics that include the Sb-based laser and the InP-based quantum cascade laser. In order for these technologies to be useful for system applications, they must be further developed into advanced components that are capable of broad wavelength tunability and agility. Practical applications also demand desirable operational characteristics regarding to size, weight, and power consumption.

This program aims to develop advanced IR lasers based on these semiconductors to be used for system applications. The objective is a technology for advanced laser modules capable of broad wavelength tunability and agility. The program requires both fundamental study of wavelength tuning characteristics of these materials as well as advanced laser designs. An equally important aspect besides scientific/technological consideration is the viability of the technology for product development. A long-term anticipated impact is the ultimate widespread deployment and commercialization of this technology.

The program has achieved its objective of developing compact, broadly tunable and wavelength agile IR lasers as well as associated photonics including optical preamplifiers and Bragg grating devices. The technical essence is a fundamental understanding of these laser material properties and the development of advanced wavelength-tunable laser architecture. Equally important is the development of novel spectroscopic system applications as test-beds for these advanced lasers. Chemical and biological spectroscopic imaging was demonstrated. The program has also influenced directly and indirectly the emergence of some commercial laser products. It is anticipated that these laser products will ultimately enable widespread applications of IR spectroscopic sensing.

Table of Contents

List of Appendices

Appendix: Publication reprints and preprints.

Statement of the problem studied

1. The importance of mid-IR spectroscopic sensor

Infrared spectroscopy (3-10 μm) is a backbone of the analytical instrument and sensor technology. It is increasingly used in defense and commercial market, from environmental, industrial process & control, chemical, pharmaceutical, bio-medical, and health industries. For chemical and biological warfare agents, extensive work has indicate that FTIR spectroscopy and microspectroscopy are quite capable of detecting and identifying highly complex chemical agents and even microbes in the laboratory environment.

2. The need for advanced mid-IR enabling photonic technology

In spite of the known scientific potential mentioned above, IR spectroscopic sensing systems are scarce if not conspicuously absence in the field. The problem is that conventional IR instruments have evolved very slowly from what they were more than 40 years ago, limited by the lack of high performance components. Most still employ low-brightness incoherent sources that limit the measurement speed, reliability, and quality of output spectra.

There is need for high performance IR sensors with novel components and system engineering. A crucial element is broad wavelength tunable and agile lasers and associated photonics. Lasers offer spectral irradiance, brightness, modulation bandwidth, and noise figure that result in orders-of-magnitude improvement in speed, reliability, and quality of spectral data compared with incoherent sources. But a challenge for laser is also to achieve usage simplicity, robustness, and affordability. This program aims to achieve such a laser technology.

3. Key program features

3.1 To develop mid-infrared semiconductor laser technology that can be used in compact, portable, infrared spectroscopic sensors. Expected performance of the laser is given in the table below:

Broad wavelength tunable and agile laser

Average power, quasi-cw modulation	> -3 dBm
Relative intensity noise (RIN)	< -80 dB/Hz
Peak cooling power consumption	< 20 W
Electrical-to-optical power efficiency	> 0.5 %
Wafer-selectable wavelength range	3 to 10 μm
Device tunable wavelength range	> 5% of central wavelength
Wavelength accuracy	$< 10^{-3}$ of specified value
Programmable wavelength tunability	From 0.1% to > 2% of specified λ
Wavelength modulation bandwidth	> 1 kHz for 1% λ change
Linewidth	$< 5 \times 10^{-4}$ of central frequency
Direct modulation bandwidth	> 10 MHz
Beam quality	< 5 times diffraction limited

3.2 Specific attention will be given on approaches for wavelength tuning and control that allows miniaturization while meeting the accuracy and reliability requirement. Bragg-grating-based techniques will be studied.

3.3 As the ultimate application of this laser technology is IR spectroscopic sensors that can perform real-time detection and/or identification of chemical or biological agents, a sensor test-bed will be demonstrated as an embodiment of this technology.

Summary of key results

Technical details of all the following key results can be found in the reprints/preprints given in the Appendix.

- All critical features of a design for compact, broadly tunable, wavelength-agile spectroscopic grade mid-IR lasers have been developed and demonstrated experimentally. A blue print to implement this design for possible product has also been achieved.

  This achievement was the culminating result of both extensive studies of the laser material fundamental properties as well as development of advanced design and fabrication.

- Besides lasers, other advanced photonic devices including optical pre-amplifiers were also developed to be used in advanced receivers. Optical pre-amplification can boost an optical signal above the detector and electronic noise levels and enhance the receiver sensitivity. These devices have applications in both sensors and optical wireless communications.

- For test-bed and system development, the lasers have been used to demonstrate the advantages of laser-based spectral imaging, including:

  - Laser-based microscopic spectral imaging system with focal plane array detectors demonstrated a high signal-to-noise ratio (>20 dB) at video frame rate for a large illuminated area. Microscopic spectral imaging with fixed-wavelength and tunable lasers of 4.6, 6, and 9.3-μm wavelength was applied to a number of representative samples that consist of biological tissues (plant and animal) and solid material (a stack of laminated polymers). Transmission spectral images with ~30-dB dynamic range were obtained with clear evidence of spectral features for different samples.
  - Wavelength modulation spectroscopy (WMS) was applied to image the spatial distribution of a gas with an excellent background clutter rejection capability. A novel concept of multi-modal image fusion of passive and active techniques has been demonstrated.
  - A novel concept of multi-spectral laser sensing system using wavelength-division-multiplexing and code-division multiplexing have been demonstrated.

List of publications

1. <u>Refereed journal papers</u>

H.-L. Zhang, C. Peng, A. Seetharaman, G. P. Luo, and Han Q. Le, "*External Cavity Tunable Mid-IR Laser Using Off-Band Surface-Emitting Bragg Grating Coupler*," (to appear, Appl. Phys. Lett., 2005)

Huanlin Zhang, A. Seetharaman, Pradeep Johnson, Guipeng Luo, and Han Q. Le, "*High-gain, low-noise mid infrared quantum cascade optical pre-amplifier for receiver*," (to appear, IEEE Photon. Technol. Lett. Jan 2005).

Yi Wang, Chuan Peng, HuanLin Zhang, and Han Q. Le, "*Wavelength modulation imaging with tunable mid-infrared semiconductor laser: spectroscopic and geometrical effects*," Opt. Express, Vol. **12**, pp. 5243-5257 (2004).

Bujin Guo, Y. Wang, C. Peng, H. L. Zhang, G. P. Luo, **H. Q. Le**, C. Gmachl, D. L. Sivco, M. L. Peabody, and A.Y. Cho "*Laser-based mid-infrared reflectance imaging of biological tissues*", Opt. Express, Vol. **12**, pp. 208-219 (2004).

C. Peng, G. P. Luo, and H. Q. Le *"Broadband, continuous, and fine-tuning properties of external-cavity TE-stabilized mid-IR quantum cascade laser"*, Appl. Optics **42**, 4877-4882 (2003).

B. Guo, Y. Wang, C. Peng, G.-P. Luo, and H. Q. Le , "*Multi-wavelength mid-infrared micro-spectral imaging using semiconductor lasers*", Appl. Spectrosc. **57**, 811-822 (2003).

C. Peng, H. L. Zhang, and H. Q. Le *"Mid-infrared External-Cavity Two-Segment Quantum Cascade Laser"*, Appl. Phys. Lett. **83**, pp. 4098-4100 (2003).

Z. Morbi, D. B. Ho, H.-W. Ren, H. Q. Le, and S. S. Pei "*Short-Range Spectral remote sensor using Mid-Infrared Semiconductor Lasers with Code-Division Multiplexing Technique*", Opt. Engineer., Vol. **41**, pp. 2321-2337 (2002).

G. P. Luo, C. Peng, H. Q. Le, S. S. Pei, H. Lee, W.-Y. Hwang, B. Ishaug, and J. Zheng, "*Broadly λ-tunable external cavity mid-infrared lasers*" IEEE J. Quant. Electron. **QE-38**, 486 (2002).

G. P. Luo, C. Peng, H. Q. Le, S. S. Pei, W.-Y. Hwang, B. Ishaug, J. Um, James N. Baillargeon, and C.-H. Lin, "*Grating-tuned external-cavity quantum cascade semiconductor lasers*", Appl. Phys. Lett. **78**, 2834-2836 (2001).

Brian Ishaug, Wen-Yen Hwang, Jae Um, Bujin Guo, Hao Lee, and Chih-Hsiang Lin, "*Continuous-wave operation of a 5.2 μm quantum-cascade laser up to 210 K*", Appl. Phys. Lett. **79**, 1745-1747, (2001).

2. Proceedings

Yi Wang, Yang Wang, Chuan Peng, HuanLin Zhang, Anush Seetheraman, and Han Q. Le, "*Concepts for Scalable, CDMA-Networked, M/LWIR Semiconductor Laser Standoff Chemical Detection System*", Proceeding SPIE, Vol. 5617, Paper 33 (London, 2004).

H. L. Zhang, G. P. Luo, A. Seetharaman, P. Johnson, H. Q. Le, "*Grating-coupled surface emitting quantum cascade semiconductor optical pre-amplifier*," Conference on Laser and Electro-Optics, San Francisco, CA (May 2004).

Yi Wang, Chuan Peng, HuanLin Zhang, and H. Q. Le, "*Remote spectral imaging with Multi-wavelength and tunable, wavelength-modulation lasers*," Conference on Laser and Electro-Optics, San Francisco, CA (May 2004).

B. Guo, Y. Wang, C. Peng, G.-P. Luo, and H. Q. Le , "*Multi-wavelength mid-infrared micro-spectral imaging using semiconductor lasers*", Proc SPIE, Vol. 4959 pp. 1-11 (2003)

H. L. Zhang, G. P. Luo, A. Seetharaman, P. Johnson, H. Q. Le "*Mid-infrared quantum cascade optical pre-amplifier with Bragg-grating ASE-filter and output coupler*" Proceeding of OSA Annual Meeting, Arizona, October 2003.

G. P. Luo, H.-L. Zhang, and H. Q. Le "*Mid-IR receiver with quantum cascade optical pre-amplifier*" Proceeding of Conference on Laser and Electro-Optics, Baltimore, Maryland, Abstract and Summary, June 2003.

C. Peng, G. P. Luo, and H. Q. Le "*Fine wavelength tuning properties of external-cavity TE-stabilized mid-IR quantum cascade laser*" Proceeding of Conference on Laser and Electro-Optics, Baltimore, Maryland, Abstract and Summary, June 2003.

(invited) Han Q. Le, P. Chuan, B. J. Guo, P. Johnson, G. P. Luo, Y. Wang, and H. L. Zhang "*Mid-IR Semiconductor Lasers and Amplifiers for Optical Sensing Applications*", Proceeding of Solid State and Diode Laser Technology Review, Albuquerque, NM, (2003).

B. Guo, Y. Wang, C. Peng, G.-P. Luo, and H. Q. Le, "*Laser-based Mid-infrared micro-spectral imaging* ", PittCon, Orlando, FL, March (2003).

"*Broadly λ-tunable external cavity mid-infrared quantum cascade (QC) lasers at high temperatures*", G. P. Luo, C. Peng, H. Q. Le, and S. S. Pei, H. Lee, W.-Y. Hwang, B. Ishaug, and J. Zheng, Conference on Laser and Electro-Optics, Long Beach, CA (2002)

Yi Wang, Z. Morbi, D. Ho, Han Q. Le, Bujin Guo, and S. S. Pei "*Scalable Multi-spectral Semiconductor-Laser Sensing System*", Proc. of the Joint Meeting of IEEE(EBM)/BMES Oct. 23-26, Houston, 2002.

Z. Morbi, Y. Wang, D. B. Ho, H. Krishnan, H. Q. Le, and S. S. Pei "*Scalable Multi-spectral Semiconductor-Laser Sensing System Using Orthogonal Code Division Multiplexing*", Post-deadline paper, OSA annual meeting, Long Beach, California (2001)

Z. Morbi, D. B. Ho, H-L. Zhang, H.-W. Ren, H. Q. Le, and S. S. Pei "*Short range spectral lidar using mid-infrared semiconductor laser with code-division multiplexing technique*", Conference on Laser and Electro-Optics, Baltimore, Maryland, Abstract and Summary (2001).

G. P. Luo, C. Peng, H. Q. Le, W.-Y. Hwang, B. Ishaug, J. Um, and James N. Baillargeon "*Grating-coupled external cavity quantum cascade semiconductor lasers*", Conference on Laser and Electro-Optics, Baltimore, Maryland, Abstract and Summary (2001).

Y.-M. Mu, H. Q. Le, and S. S. Pei, "*Modeling of optically-pumped type-II lasers*", SPIE Proceeding (2001).

3. Meeting papers (no proceeding)

2003 (*invitational meeting*) H. Q. Le (speaker) et al. DARPA/MTO review, Chicago, IL

2003 (*invitational meeting*) H. Q. Le (speaker) et al. AFRL/DARPA/SPO review, Arlington, VA

2002 (*invitational meeting*) H. Q. Le (speaker) et al. DARPA/MTO review, Alexandria, VA

2002 (*invitational meeting*) H. Q. Le (speaker) et al. AFRL/DARPA/SPO review, Arlington, VA

2002 (*invited talk*) H. Q. Le (speaker) *et al.* Environment Sentinel 2002, NASA, Houston, TX

2001 (*invitational meeting*) H. Q. Le (speaker) et al. , Air Force Research Laboratory, Diode Laser Technology Review, Albuquerque, NM.

2001 (*invitational meeting*) H. Q. Le (speaker) et al. DARPA/MTO review Los Angeles, CA

2001 (*invited talk*) H. Q. Le (speaker) *et al.* "*Tunable mid-infrared lasers*"
Mid-infrared Lasers Workshop, Army Research Office/DARPA Arlington, VA

2000 H. Q. Le "*Photonics Technology for Optical Networks*" (industry private meeting, December 2000, Santa Clara, CA)

2000 (*invitational meeting*) H. Q. Le (speaker) et al. at Annual DARPA/MTO review, Cincinati, OH

2000 (*invitational meeting*) H. Q. Le (speaker) et al. at Photonics for Wavelength and Spatial Signal Processing Workshop, DARPA Norfolk, VA,

2000 (*invitational meeting*) H. Q. Le (speaker) et al. , Air Force Research Laboratory, Diode Laser Technology Review, Albuquerque, NM

Scientific personnel

1. University of Houston:
   - Stefan Murry, Ph. D (2001).
   - Jun Zheng, Ph. D. (2001).
   - HuanLin Zhang, Ph. D. (2004).
   - Chuan Peng, Ph. D. (2004).
   - Yida Tan, M. S. (2002).
   - Don DB Ho, B. S. (2002).
   - Joe Therrier
   - Nathan Howard
   - G. P. Luo
   - B. J. Guo
   - Z. Morbi
   - D. P. Xu
   - Yi Wang
   - Brad Koch
   - Anush Seetharaman
   - Pradeep Johnson
   - Yang Wang
   - H. Q. Le
   - S. S. Pei.

2. Applied Optoelectronics Inc.
   - H. Lee
   - W. Y. Hwang
   - H. W-Ren
   - J. N. Baillargeon,
   - Brian Ishaug
   - C. H. Lin

3. University of Connecticut
   - Chandrasekhar Roychoudhuri
   - Oleg Smolski
   - Mr. Jun Jiang

4. Honeywell
   - Alan Cox

Report of Inventions

CDMA techniques in optical sensing (patent pending).