Development of mid-IR lasers for Laser Remote Sensing

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ABSTRACT

There is an existing need in JPL and in NASA for development of mid-IR lasers, such as Quantum Cascade (QC) lasers, for in-situ and remote laser spectrometers. Mid-IR, compact, low power consumption laser spectrometers have a great potential for detection and measurements of planetary gases and biological important biomarker molecules such as H_2O, H_2O_2, CH_4, and many additional chemical species on Mars and other Solar system planets. Another potential application of QC lasers for future NASA mission is in high power remote Laser Reflectance Spectrometers (LRS). In LSR instrument, mid-infrared lasers will act as the illumination source for conducting active mid-IR reflectance spectroscopy of solid-surfaced objects in the outer Solar System. These spectrometers have the potential to provide an incredible amount of information about the compositions of surfaces in the outer Solar System. In this work, we will discuss our current effort at JPL to advance QC lasers to a level that the laser performance, operational requirements and reliability be compatible with the instruments demands for space exploration applications.

INTRODUCTION

The mid-infrared spectral range (5 - 20 μm) is of particular interest for remote sensing of material composition as many chemical species have telltale absorption features in this wavelength range that are associated with molecular rotational-vibrational transitions.[1] These include molecules such as H_20, CO_2, N_2O, CH_4, CO, NH_3, NO_x, HCl, and many other compounds whose absorption spectra are shown in Figure 1. Detection of these molecules is essential for many applications in space research, atmospheric chemistry, pollution control and industrial processing. Space research applications include in-situ and remote sensing of the gases in planetary atmospheres, isotope detection and the identification of the surface composition of planetary and lunar bodies. For example, water (H_2O), that has a strong absorption lines in mid-IR spectral range, is a critical component in biological activity. Remote detection of the location of the water reservoirs on Mars will contribute to successful realization of the human explorations programs that were recently outlined in new NASA Vision for Space Exploration. Moreover, study of partitioning among vapor, liquid, and solid phases of water is a high–priority for future unmanned Mars mission that address the possibility of life on Mars.

In particular, spectroscopy in the 4.5 to 10-μm region has the potential to provide an incredible amount of information about the compositions of surfaces in the outer Solar System. At the outer Solar System, both solar illumination (<4% of the level at Earth) and thermal emission (10^{-2} to 10^{-4} the level at earth) are low in the mid-IR. Lack of sunlight and cold conditions, make reflected solar spectroscopy and thermal emission spectroscopy difficult to perform. Another source of light in mid-IR spectral region is needed. Spectral observations in mid-IR, made possible with active illumination, will better enable one to determine the silicate and oxide mineralogy, ice composition, and the composition of organic materials on outer solar system surfaces by being able to observe fundamental absorption bands.

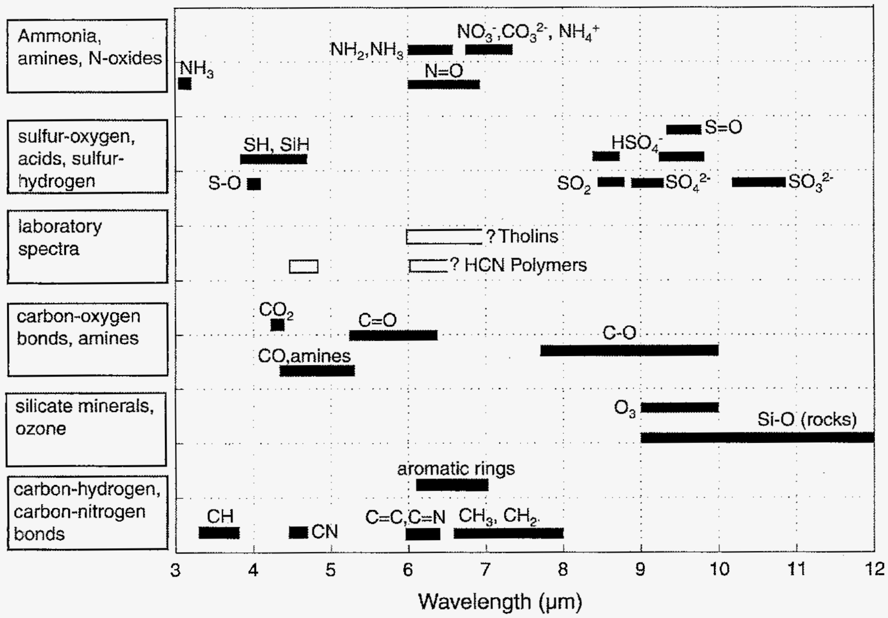

Figure 1. Spectral ranges of optical absorption in mid-IR by various chemicals.

During the last decade, several sources with mid-IR emission have been developed. One can site numerous examples including cryogenically cooled Lead-Salt diode lasers, sources based on Difference Frequency Generation (DFG), quantum cascade (QC) semiconductor lasers, and other solid-state sources based on chromium-doped crystals and CO and CO_2 gas lasers. CO and CO_2 lasing occurs from transitions between excited rotational-vibrational states of the gas medium and this limits their tunability to discrete steps at 5 µm (CO) and 9-10 µm (CO_2). This does not cover the spectral range required for this application. Among these technologies DFG and QC lasers have been pursued most intensively. Of these two, the DFG technique is the simpler method for the generation of mid-IR wavelength. However, the low level of generated output power (~ mW range) prevents the DFG to be used in this application. In contrast, recent technical advances in thin film epitaxial technologies fabricated using the Molecular Beam Epitaxial (MBE) technique, together with material bandgap engineering have resulted in QC lasers that exhibit several orders of magnitude higher power than DFG in the mid-IR range. Consequently, quantum cascade (QC) lasers [2,3] have been successfully demonstrated in the 4-150 µm wavelength range and have become the most promising optical sources in the mid to far infrared range.

EXPERIMENT,

Quantum Cascade Lasers

QC lasers are new mid-IR semiconductor laser sources [2,3] that are fundamentally different from Tunable Diode Lasers (TDL). Optical radiation in the intersubband QC lasers is emitted by electrons undergoing optical transition between the quantized levels of the coupled

Quantum Wells in the conduction band in contrast to the optical radiation emitted by direct transition from the conduction to the valence bands in the conventional semiconductor lasers. The emission wavelength is determined by quantum confinement, i.e., by the epitaxial layer thickness in the active region rather than by the bandgap energy of the active material. This fundamental difference enables QC lasers to be designed to emit over an extremely wide spectral range from about 4 to 150 μm (except for a window for the Reststrahlen gap).

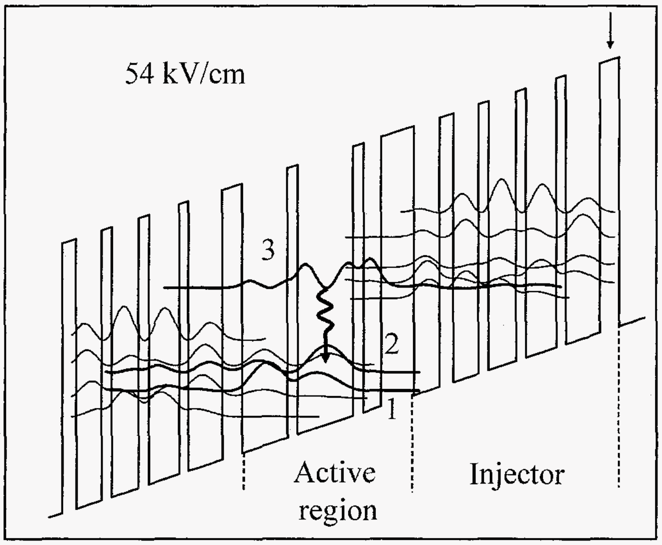

Figure 2. Conduction band diagram and moduli squared of the wave functions of the Quantum Cascade laser active region designed for emission at λ = 8.1 μm, sandwiched between two injectors. The layer thickness for one stage of injector and active region in nanometers from right to left starting from the barrier indicated by an arrow are: **2.3**/4.0/**1.1**/3.6/**1.2**/3.2/**1.2**/3.0/**1.6**/3.0/**3.8**/2.1/**1.2**/6.5/**1.2**/5.3 AlInAs layers are in bold. The moduli squared of the wavefunctions involved in the laser emission are indicated by thick lines and labeled 1, 2, 3.

QC laser structure consists of multiple Quantum Wells grown by Molecular Beam Epitaxy (MBE) in GaInAs/AlInAs/InP[2] or GaAs/AlGaAs material systems.[4] Figure 2 shows a conduction-band diagram of an active region sandwiched between two injectors of QC laser designed for operation at 8.1 micron. Optical radiation in QC lasers is generated by electrons undergoing intersubband transitions between the energy levels 3 and 2 of coupled Quantum Wells (Figure 2). Important feature of QC lasers is a cascading, namely after photon emitting at one stage of the device, the electrons are injected into the next stage, where they may emit another photon and so on. Such cascading allows to improve significantly the efficiency of the intersubband QC lasers and to develop lasers emitting at multiple wavelengths simultaneously.[5] The advantages of the QC lasers are their narrowband and tunable emission, wavelength agility, well-established technology of III-V semiconductors materials and reliability.

Progress in QC laser development has been very rapid. Just one year after the laser development, continuous wave (cw) operation at the cryogenic temperatures[6] and pulsed operation at the room temperature have been demonstrated.[7] In 1997, Distributed Feedback

(DFB) QC laser has been realized to provide single-mode tunable radiation.[8] New designs of the lasers active region, such as superlattice design,[9] have been developed that allowed to extend the laser wavelength to far-IR, above 20 μm.[10] Until 1998, all QC lasers were demonstrated in InGaAs/AlInAs on InP material system, when GaAs/AlGaAs QC lasers were realized.[11] Research of QC lasers expanded into new areas and resulted in demonstration of QC microdiscs lasers,[12] mode-locked QC lasers,[13] and broadband QC lasers.[5] More recent progress included the cw room temperature operation[14] and optical emission at THz frequencies.[15]

Following the invention of the QC lasers, it has been realized that these lasers have a potential to become a favorable choice as the mid-IR optical source for spectroscopic applications. DFB QC lasers have been used for a first time for detection of NO and NH_3 in 1998.[16] Since that demonstration, QC lasers have been employed as mid-infrared optical sources in spectroscopic system for detection and monitoring of several gases and their isotopes in ambient air at part-per-million in volume (ppmv) and part-per billion in volume (ppbv) levels. Spectroscopic measurements were performed using several techniques such as direct absorption, wavelength modulation, and cavity enhanced and cavity ringdown absorption spectroscopy.[1] Cryogenically cooled cw DFB QC lasers were recently flown on high-altitude aircraft to measure CH_4 and N_2O in the Earth's stratospheres by JPL/NASA.[17] QC lasers significantly improved the measurement precision and spectral stability that enhanced a minimum detectable mixing ratio for methane to be 2 ppbv.

There is an existing need in JPL and in NASA for development of mid-IR lasers remote sensing. Our effort at JPL is to advance QC lasers to a level that the laser performance, operational requirements and reliability be compatible with the instruments demands for space exploration applications. The current technical problems that limit the implementation of the QC lasers into these instruments are: large power consumption, significant heating, cryogenic operational temperature requirement in cw mode, and limited output power. We are currently working to resolve these technical issues to improve the laser operation beyond the current state-of–the art. Our effort concentrate on several aspects of QC laser technology development: (1) Optimization of the QC laser and of the waveguide designs; (2) Improvement of the QC laser growth process; (3) Development of a reliable laser fabrication process; (4) Realization of QC laser arras. Advances in these developments will improve the laser operational characteristics such as optical power, electrical power consumption, threshold current, thermal heating and maximum operational temperature. More specifically, in our work on QC lasers for remote sensing, we focus on the increase the net output power of the devices. We are working on the optimizing the QC lasers for high power operation and on realization of QC laser arrays that have potential to provide a much higher output power than a single laser.

Development of Quantum Cascade Lasers

In our work, we focused on the development of QC lasers designed to emit at several distinct wavelengths in the mid-IR spectral range (5-12 μm) that are of interest for sensing applications. These lasers were designed with different types of active regions such as three-well-vertical and bound-to-continuum designs.[18] Each of these designs has individual characteristics that set the operational parameters of the QC lasers, such as a maximal output power, threshold current, etc. A choice of the specific active region makes possible to determine the optimal design for the application of interest. As a part of our optimization strategy for QC lasers, we have fabricated and tested QC lasers with different designs in order to improve optical power and operating temperature in cw mode. Figures 3 shows optical spectra of three intersubband QC lasers with different designs, all fabricated in JPL, that operate cw at at $T = 77$ K. Furthermore, we have evaluated the QC lasers with various design parameters such as number of stages, applied field, and doping level, to enhance laser performance. Figures 4 shows Light-Current and Voltage-Current (LIV) characteristics of two intersubband Quantum Cascade lasers with different number of stages. Increasing the number of stages led to a decrease in the threshold current and increase in output power, but these lasers experienced stronger laser heating. This heating prevented laser operation at high current levels.

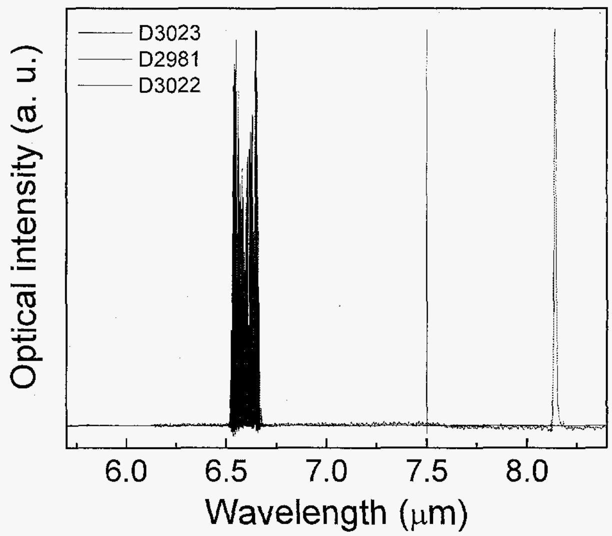

Figure 3. Optical spectra of three QC lasers operating cw at $T = 77$K

The designed structures were grown by state-of-the-art MBE system. High quality growth of the QC lasers is essential for achieving the superior laser performance. Growth of the QC lasers is challenging, requires high accuracy and precise calibration of material composition, doping levels and thicknesses. Epitaxial growth of our QC laser wafers were done at Bell Labs, Lucent Technologies that pioneered QC lasers. We continue to work on the improvement of MBE growth and to expand our growth capabilities. We are currently developing a growth of the QC lasers with top InP cladding. InP top cladding provides much better heat removal from the active section of the QC lasers than a typical InGaAs/InAlAs cladding that results in higher output power and operational temperature at cw mode. We also continue to optimize the QC laser growth process to achieve better layers uniformity, control of the layer thickness and of the doping concentrations.

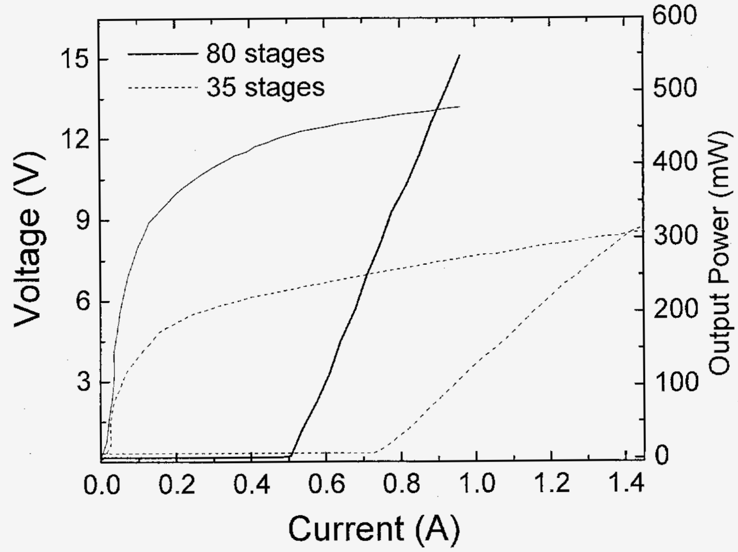

Figure 4. LIV characteristics of two QC lasers with 35 (dash) and 80 (stages) operating in pulsed mode.

At JPL the epitaxial wafers are fabricated into laser and packaged in the Microdevices Lab at JPL. Our developing of the fabrication processes concentrated on improvement of the heat transfer from the active section of the lasers and on realization of the high reflectivity (HR) coating of the laser facets. A heating of the QC laser active section is the major obstacles for high power and high temperature operations of these devices in cw mode. During our work we have developed thick Au electroplating of laser waveguide ridge and InP regrowth[19] on the waveguide ridge sides and top. Figure 5 shows images of the QC lasers with the deposited electroplated Au and with the InP regrowth. Both of these methods allowed to enhance the heat removal, such that a thermal resistivity of the devices dropped below 10 K/W, and to improve significantly cw power operation. HR coating of the laser facet decrease the mirror losses that reduces the threshold current and increases output power. We have realized the QC lasers with a metallic high-reflective coating of the back facet that consists of SiO_2/Ti/Au thin film layers. Figure 6 shows cw operation of two identical QC laser with and without HR coatings. Threshold current of the QC laser with HR coating is almost two times less than threshold current of the laser without HR coating as well as the output power of the HR coated laser is more than three times higher than of the other laser.

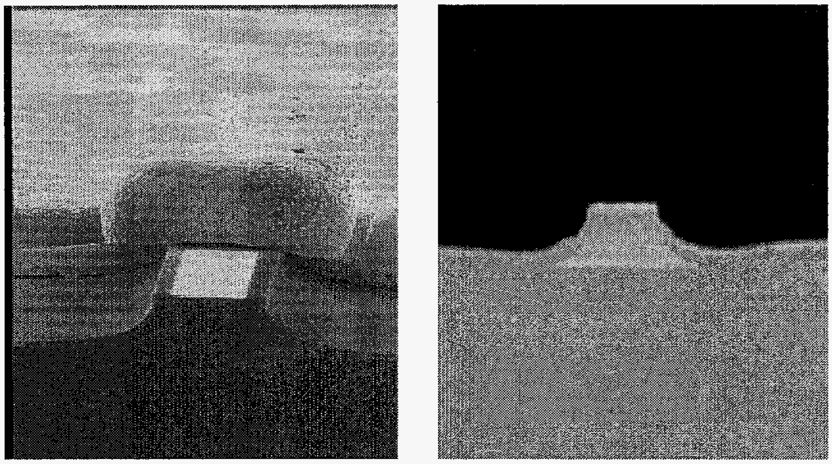

Figure. 5. Scanning electron image of QC laser waveguide ridge laser with gold electroplated coating (left) and an optical image of QC laser laser with InP regrowth (right).

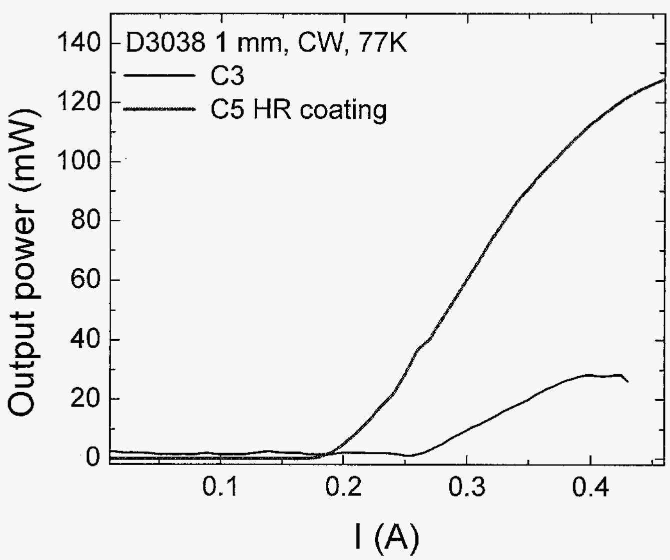

Figure 6. CW Operation of two identical 1 mm QC lasers with (C5) and without HR coating (C3)

In our work we succeeded to improve cw and pulsed operation of the QC lasers and bring it close to the state of the art. Optimization of the active design section increased the laser characteristic temperature to $T_0 \sim 150$ K and enabled the pulsed operation up to $T = 350$ K (Figure 7). We also increased the output peak power of the QC laser in the pulsed regime to $P =$ 800 mW (Figure 8). An enhancement of heat transfer from active section with Au electroplating and HR coating of the laser facets increased the laser cw output power from $P = 50$ mW (green dashed line, Figure 9) to about $P = 300$ mW (red line) at $T = 77$ K. Moreover, we reduced the electrical power consumption and the heat management requirement of the QC lasers in cw mode. As shown in Figure 9, at output power P = 100mW, the electrical power consumption was reduced from P_{el} = 10 Watt to P_{el} = 4 Watt.

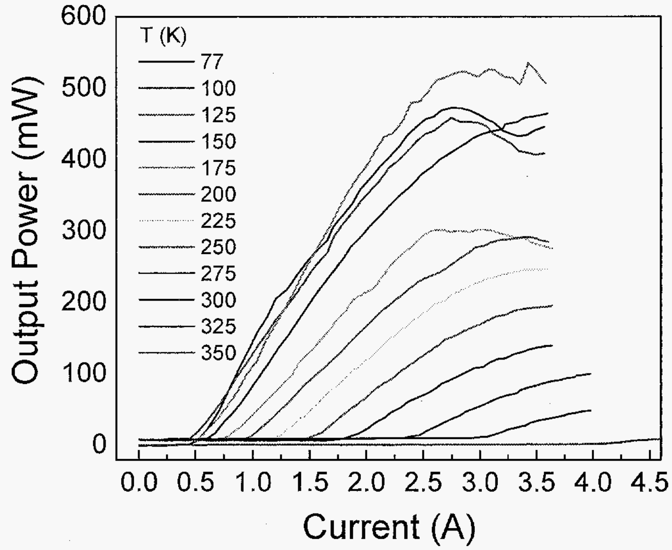

Figure 7. LI characteristics of QC laser operation at T = 77-350 K temperature range.

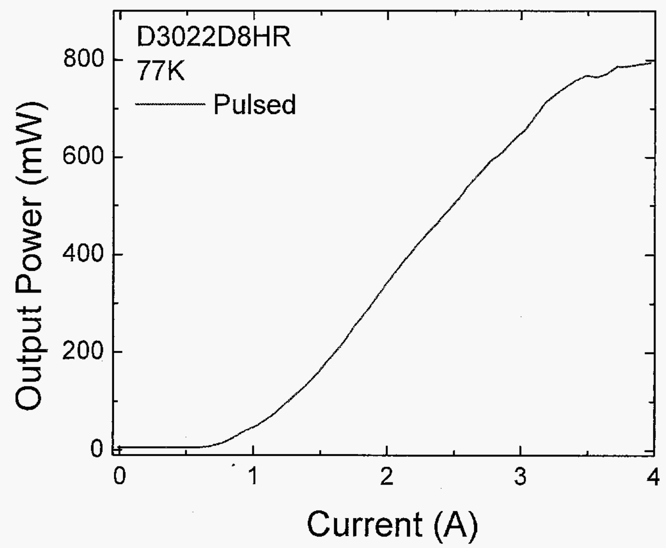

Figure 8. LI characteristics of QC laser operation in pulsed mode at T = 77 K.

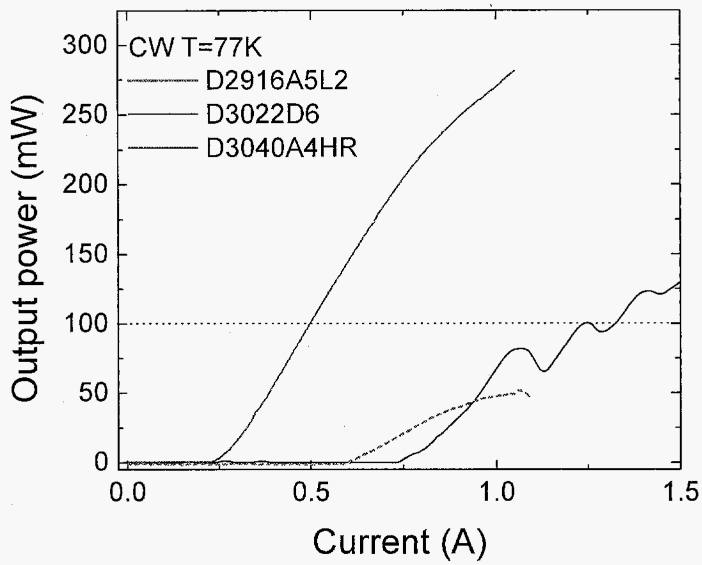

Figure 9. LI characteristics of several QC laser operating in cw at $T = 77$ K.

CONCLUSIONS, In summary, we have developed the capability to design, fabricate and test quantum cascade lasers in the 4.5-12 micron wavelength range. We have demonstrated pulsed and continuous operation of devices at a number of wavelengths. We have increased laser output power from <50 mW to ~300 mW as a consequence of improving our design, growth and fabrication processes. Future work will concentrate in the following areas: reduction of the laser threshold current, increase of the output power and heat removal improvement.

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