# Semiconductor Lasers beyond the Fiber Optics Telecommunication Wavelength

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Abstract: Semiconductor lasers emitting at 1.55 microns are the cornerstone of the high bandwidth optical communications industry. Semiconductor lasers operating at this and other wavelengths are also used in the engineering, biology, chemistry and medical fields. The light emission in most semiconductor lasers is due to the optical transition between the valence and conduction bands of the semiconductor active material. This means that the intrinsic properties of the semiconductor active material i.e., the bandgap energy dictates the emission wavelength. This limits the efficient operation of these lasers at wavelengths above 3 microns. In the mid 1990s this limitation was overcome with the emergence of new laser architectures, such as the intersubband and interband Quantum Cascade (QC) lasers. The emission wavelength in these QC lasers is set by engineering the bandgap to extend the accessible spectral range well beyond 3 microns. Optical radiation from intersubband QC lasers is emitted by electrons undergoing an optical transition between the quantized energy levels in the conduction band rather than by direct transition from the conduction to the valence bands as in conventional semiconductor lasers. Quantum engineering of the electronic energy levels has enabled demonstration of intersubband QC lasers covering a very wide spectral range from 3.5 to 150 microns (except for a window for the Reststrahlen gap). Despite rapid and tremendous progress in the research and development of these QC laser sources, the technology is far from being sufficiently mature to be deployed for use in space instruments. We will discuss our efforts at the Jet Propulsion Laboratory to advance QC laser technology sufficiently to enable their use in new instruments for future NASA Earth and Solar System Exploration missions.

**Keywords:** Remote sensing, optical spectroscopy, mid-IR lasers, semiconductor lasers, Quantum Cascade Lasers

## Introduction

The mid-infrared spectral range (5 - 20 µm) is of particular interest for optical spectroscopy as many molecules have telltale absorption features in this wavelength range that are associated with molecular rotational-vibrational transitions.[1] These include molecules such as $N_2O$, $CH_4$, CO, $NH_3$, $NO_x$, HCl, and many other compounds whose absorption spectra are shown at Fig. 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. The deployment of active mid-IR optical spectrometers has been delayed by the lack of compact, reliable, high power Mid-IR optical sources. The invention of intersubband Quantum Cascade (QC) lasers in 1994[2,3] promises to change this.

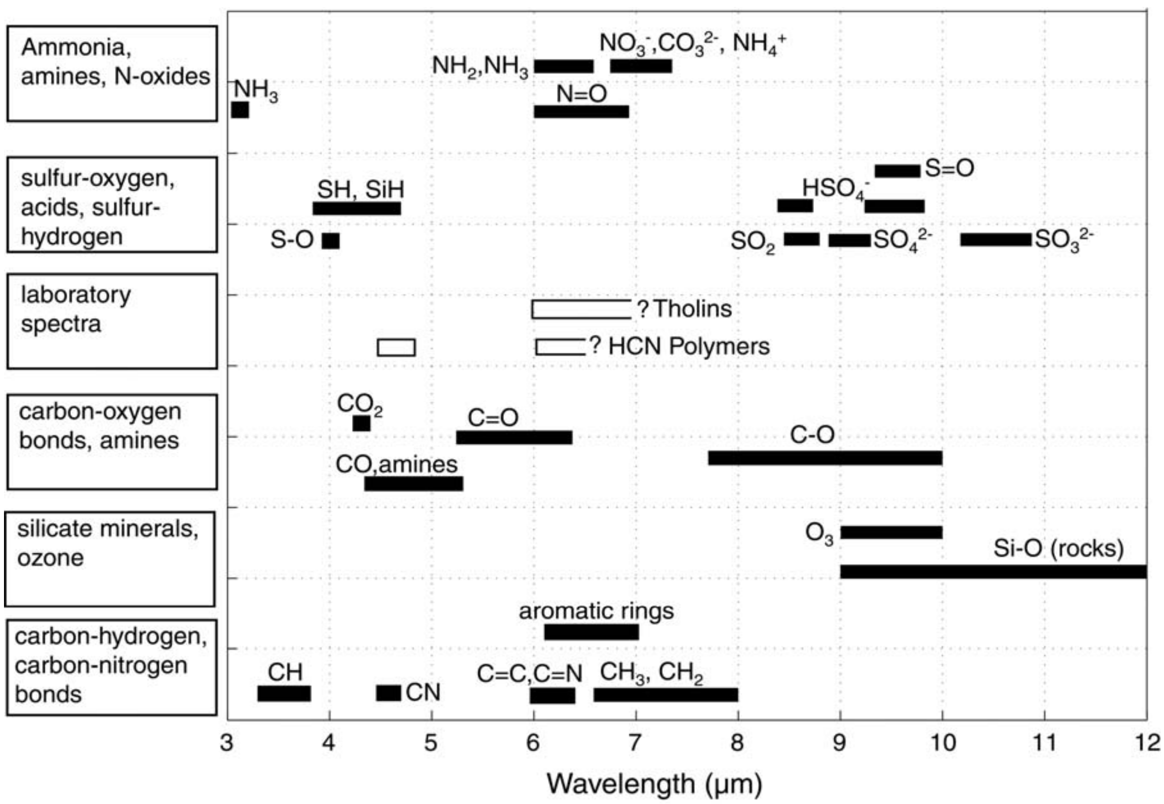


Fig. 1 Spectral ranges of optical absorption in mid-IR by various chemicals.

## 1. Quantum Cascade Lasers

QC lasers are new mid-IR semiconductor laser sources 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).

QC laser structure consists of multiple Quantum Wells grown by Molecular Beam Epitaxy (MBE) in GaInAs/AlInAs/InP[3] 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 (Fig. 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]

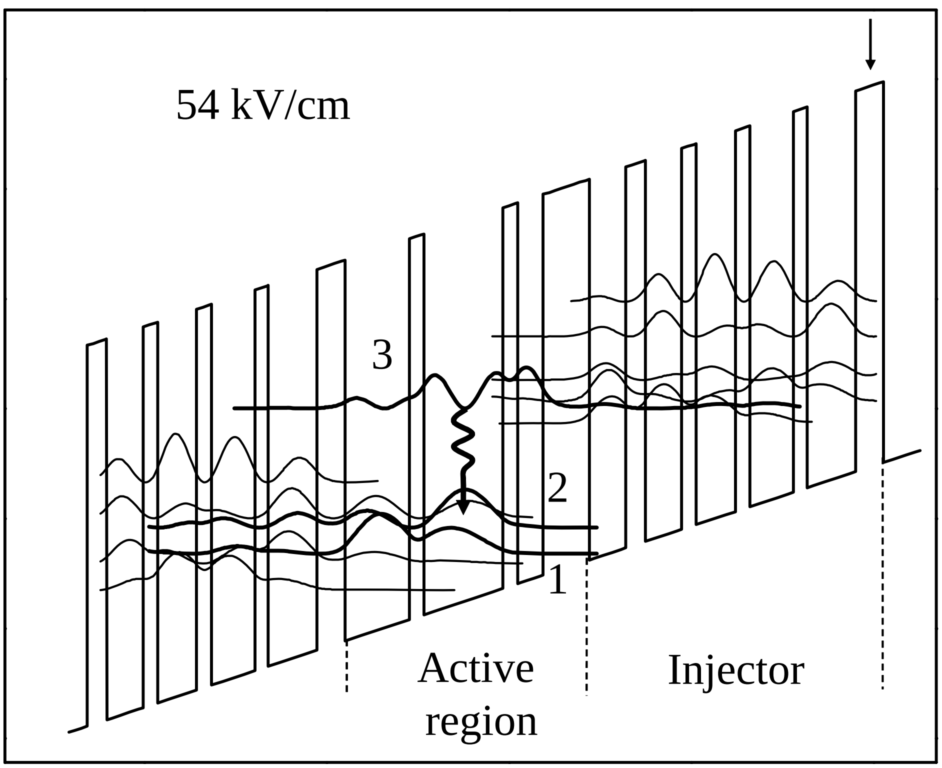


Fig. 4.2 Conduction band diagram and moduli squared of the wave functions of the Quantum Cascade laser active region designed for emission at $\lambda$ = 8.1 μm, sandwiched between two injectors. The layer thickness for one stage of injector and active region in nanometers from right to left starting 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.

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.

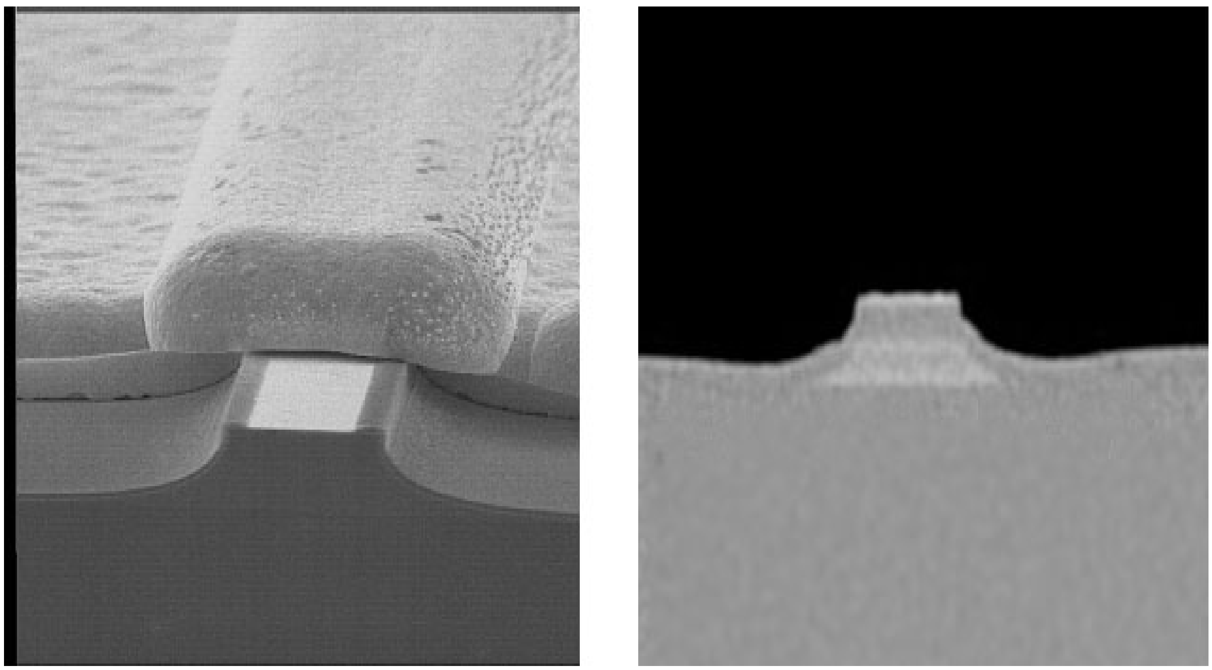

Fig. 3 Scanning electron image of QC laser waveguide ridge laser with gold electroplated coating (left) and an optical image of QC laser laser with InP regrowth (right).

There is an existing need in JPL and in NASA for development of mid-IR lasers for *in-situ* and remote laser spectrometers. Mid-IR, compact, low power consumption, *in-situ* 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.

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 current effort concentrated 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 and laser array fabrication process. 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. As a part of our optimization strategy for QC lasers, we have developed capabilities to design the QC lasers with different types of active sections for operation at different wavelength range (5-12 μm). We have designed QC lasers for both high power and single mode operation. The designed structures were grown by state-of-the-art MBE system. High quality growth of the QC lasers is essential for achieving good 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.

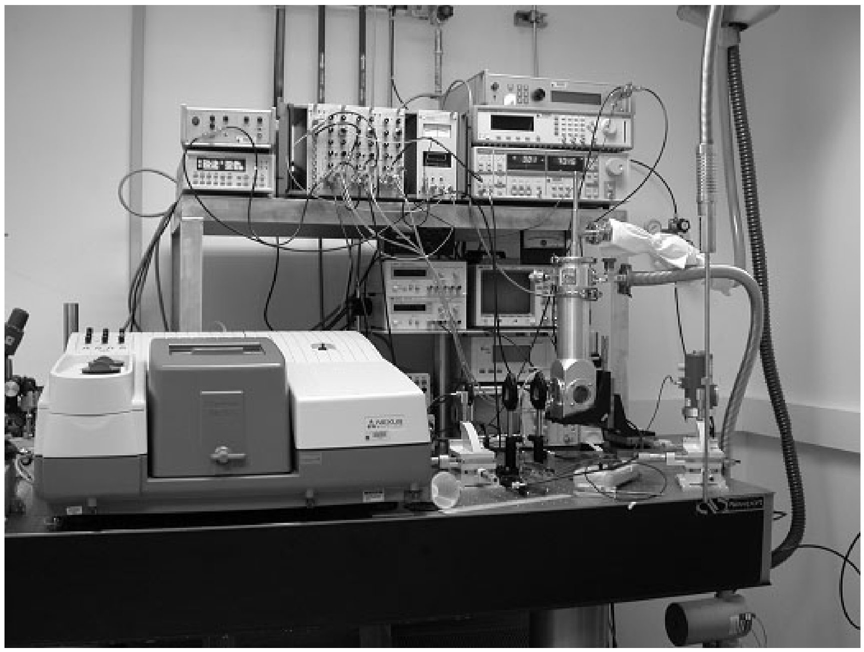

Fig 4. Photo of mid-IR lasers characterization set-up in JPL

At JPL the epitaxial wafers are fabricated into laser and arrays in the Microdevices Lab at JPL. This fabrication process involves etching, passivation, metallization, electroplating and lapping steps to make the laser and laser arrays. Laser cleaving, HR coating, mounting and packaging are also done in house. During this effort we have developed advanced processing and mounting procedures, such as thick Au electroplating of laser waveguide ridge and InP regrowth[18] (Fig. 3). These procedures improve the heat transfer from the lasers and increase the laser output power from 50 mW to more than 200 mW at $T$ = 77 K.

In our characterization and testing efforts we have set-up comprehensive test facility for evaluating and assessing of the QC laser performance (Fig 4). This computerized characterization facility allows us to test the laser parameters in both the pulsed and continuous wave operational modes over a temperature range of $T$ = 4-425 K. We have fabricated and tested different QC lasers emitting at various wavelengths and operating in both pulsed and continuous modes. Figures 5 shows optical spectra of three intersubband QC lasers emitting cw at different wavelengths at $T$ = 77 K. These lasers were designed with three-well-vertical and bound-to-continuum[19] designs of the active section to study and optimize the laser performance. Figure 6 shows LIV characteristics of 7.6 μm QC laser operating in pulsed and cw modes. An early decrease of the cw laser power at high currents indicated insufficient heat removal that had to be improved to enhance the laser operation.

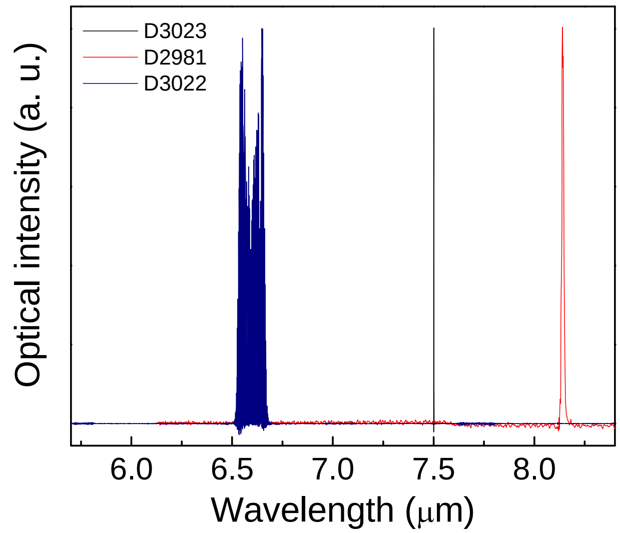


Fig 5. Optical spectra of three QC lasers operating cw at 77K

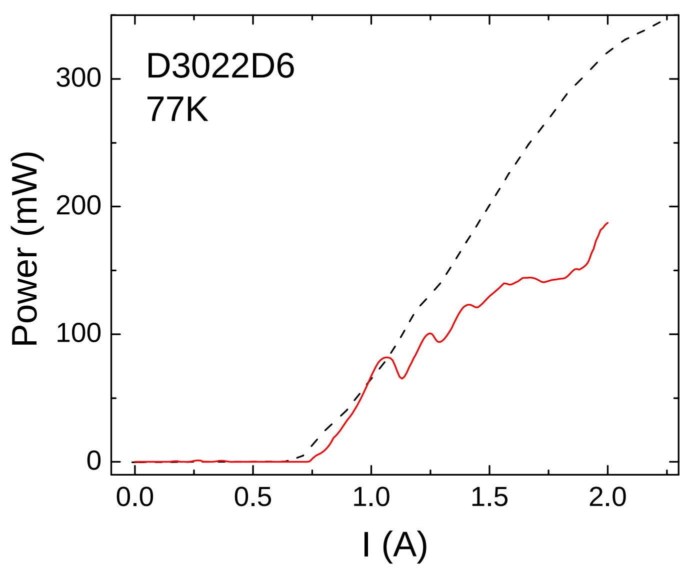


Fig. 6. LIV characteristics of 6.8 mm QC laser operating in pulsed (dash) and cw (solid) modes

As a part of our optimization strategy for QC lasers we have fabricated and evaluated QC lasers with different design parameters such as number of stages, applied field, doping level, ridge width and cavity length, in order to improve continuous wave optical power and operating temperature. Figures 7 shows 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 8 presents LI output characteristics of intersubband Quantum Cascade lasers with improved design of the active section. This design increased laser characteristic temperature to $T_0 \sim$ 150 K and enabled the pulsed operation up to $T$ = 350 K.

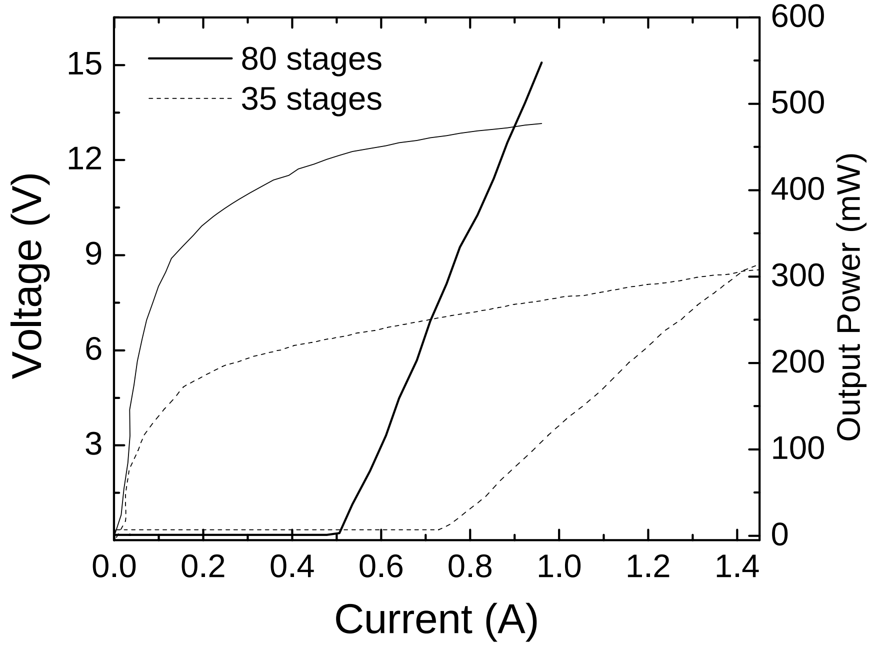


Fig. 7. LIV characteristics of two QC lasers with 35 (dash) and 80 (stages) operating in pulsed mode.

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 >200 mW as a consequence of improving our 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.

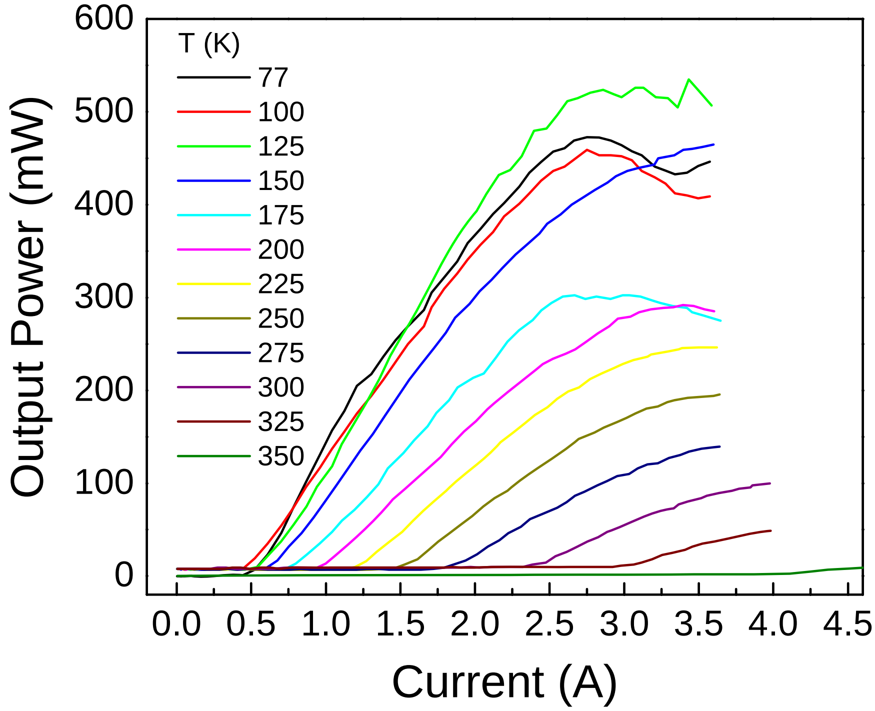


Fig 8. LI characteristics of QC laser operation at *T* = 77-350 K temperature range.

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