Cascaded Emission from Excited State Mid-Infrared Quantum Cascade Lasers

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Abstract—**We report simultaneous and dual-wavelength lasing from two "cascaded" energy transitions in a mid-infrared quantum cascade (QC) laser. The two "stacked" transitions share a common energy state, where an electron transitions from a high energy state to a center state, then from the center state to the lower state, while emitting two photons—the first at 9.6 µm and the second at 8.2 µm. The highest energy state is the second-excited state of an active region constituent quantum well, and we discuss advantages of making use of energy transitions composed of excited states for improving QC laser performance.**

I. Introduction

THE inherent flexibility in quantum cascade (QC) laser design has led to a multitude of unique and innovative laser concepts [1]. This "designer" nature of the QC laser has made possible devices that lase near 3.0 µm [2] on one extreme and 187 µm [3] on the other. In addition to such vast wavelength agility, the dynamic QC laser architecture has yielded such devices as multi-wavelength superlattice lasers [4] and lasers that make use of bulk nonlinearities to achieve frequency conversion [5, 6]. Another innovative design, while unsuccessful at achieving simultaneous multi-wavelength lasing, attempted stacked optical transitions for a so-called "cascaded" QC laser [7]. Here, we report on a QC laser that makes use of a constituent quantum well second-excited state to achieve simultaneous cascaded lasing from two energy transitions in each active region [8].

II. Excited State Transitions

Transitions composed of active region constituent quantum well excited states present a powerful approach to achieving greater gain and hence lower threshold currents in QC lasers. Since threshold current is inversely proportional to the laser gain coefficient g, an increase in g will decrease threshold. Gain g is directly proportional to the square of the optical dipole matrix element between the upper and lower states that comprise the optical transition z_{ul}^2, and g is inversely proportional to the width of the gain spectrum, often represented by the full-width at half-maximum (FWHM) of the device electroluminescence (EL) $2\gamma_{ul}$. Any design strategy that can simultaneously increase z_{ul} and decrease $2\gamma_{ul}$ can result in decreased laser threshold. Figure 1 illustrates how the optical dipole matrix element evolves for intersubband transitions between adjacent states for a single quantum well. Here, the optical dipole matrix element of a specific transition is calculated after adjusting the quantum well width to give a transition energy ε_{ul} of 125 meV. As can be seen, the optical dipole matrix element increases for higher-lying transitions. Thus an optical transition between the second- and first-excited states of a quantum well will have a greater gain coefficient than a first-excited to ground state transition of equal energy. To achieve energy transitions between higher-lying states while keeping the transition energy constant, one must increase the quantum well width, as illustrated in Fig. 1. For QC laser devices that use excited state transitions, this means interface roughness scattering will be less of a contribution to $2\gamma_{ul}$ because the energy states are affected relatively less by the interface roughness.

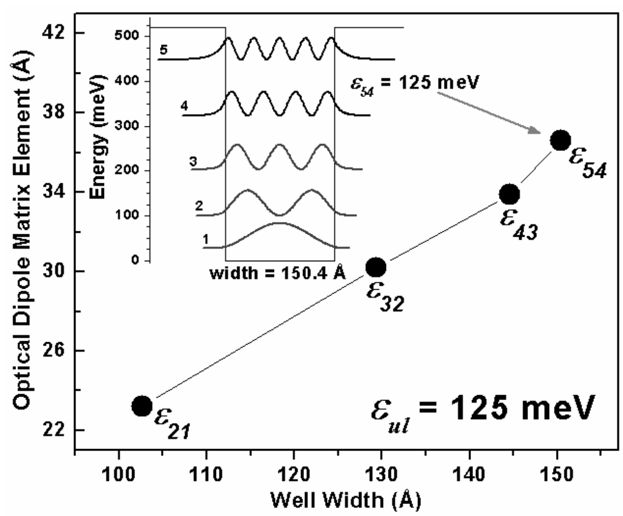

Fig. 1: The calculated optical dipole matrix element of the specified transition, where well width has been adjusted to give a transition energy ε_{ul} = 125 meV. For the constant transition energy, the optical dipole matrix element and quantum well width increase for transitions between higher-lying levels. Here we simulate optical transitions in the InGaAs/AlInAs:InP system, with a conduction band offset of 520 meV. The inset illustrates a quantum well with an energy difference of 125 meV between states 5 and 4.

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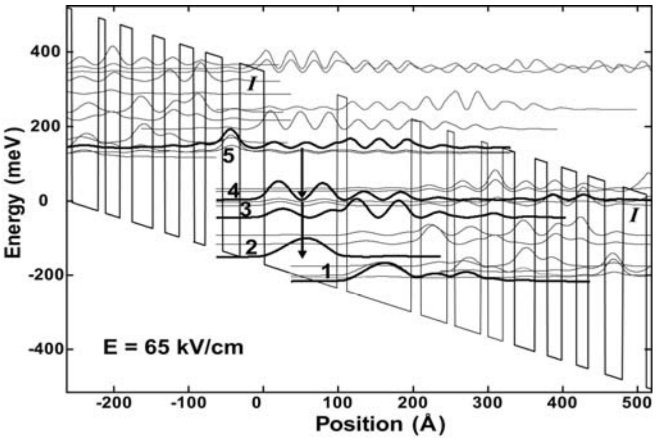

Fig. 2. Conduction band diagram for the post-calibrated layer sequence. Cascaded optical transitions are between levels 5→4 and 4→2. The single stage layer sequence is (in angstroms starting from the injection barrier) **32**/98/**13**/86/**13**/35/**10**/35/**10**/20/**16**/27/**16**/20/**19**/16/**23**/23, where $In_{0.52}Al_{0.48}As$ barrier layers are in bold, $In_{0.53}Ga_{0.47}As$ well layers are in normal font, and Si-doped (2×10^{17} cm^{-3}) layers are underlined. The injection barrier is labeled as ***I***.

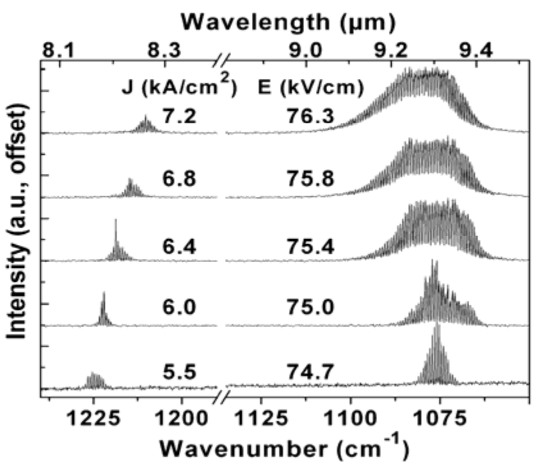

Fig. 3. Emission spectra of a 2.5 mm long and 10 μm wide laser at a heatsink temperature of 80 K operated with a 47 ns current pulse width. The electric field across the active laser core is calculated from current-voltage measurements.

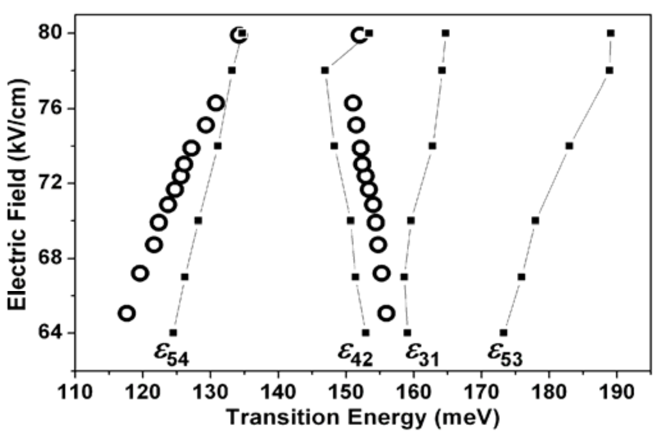

Fig. 4. Measured and calculated values of the optical transition energies in electroluminescence (EL) as a function of the electric field. Hollow circles represent the center points of multi-Lorentzian fits to the EL data. Solid squares show the calculated transition energies.

In the two-well active region design of our cascaded QC laser, we take the approach of using a second-excited state from one of the active region constituent quantum wells as the upper energy state of the first optical transition (state 5 in Fig. 2). The lower energy state of the first optical transition (state 4) is a first-excited state, and this same state is also the upper state of the lower optical transition (from 4 to 2), making the two optical transitions cascaded.

III. Cascaded Laser Fabrication and Results

The QC active region design shown in Fig. 2 was grown and processed as in [8]. Simulation for the post-calibrated structure with a 65 kV/cm applied electric field results in an energy of 128.0 meV (λ = 9.68 μm) for the upper optical transition (levels 5→4) and an optical dipole matrix element of z_{54} = 31.0 Å; we calculate an energy of 151.5 meV (λ = 8.18 μm) for the lower optical transition (4→2) and an optical dipole matrix element of z_{42} = 14.4 Å. Laser spectra for different applied fields are shown in Fig. 3, with two distinct lasing peaks at ~9.3 and ~8.2 μm.

Electroluminescence (EL) was studied with varying electric field. Two primary EL peaks were extracted from Lorentizian fits and are displayed as open circles in Fig. 4. Overlaid on Fig. 4 are simulated values for possible energy transitions, also displayed as a function of electric field. By comparing EL and calculated transition energies, we confirm that the ~9.5 μm light originates from the excited-state 5→4 transition, as expected. Because both the field behavior and energies of the 5→3 and 3→1 transitions differ from the EL and laser spectra, we rule out these two transitions as the source of the ~8.2 μm light, and determine that the ~8.2 μm light originates from the transition 4→2.

IV. Conclusions

Using an excited state transition of a QC active region constituent quantum well, we have demonstrated simultaneous laser action from cascaded optical transitions in each QC active region. Using such excited state transitions in QC laser design may be an effective approach to reducing laser threshold.

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