Design and Modeling of Mid-Infrared Transistor-Injected Quantum Cascade Lasers

Kanuo Chen, John Dallesasse

***Abstract*—A novel photonic device, the transistor-injected quantum cascade laser, is designed and modeled. Quantum cascade lasers are promising coherent light sources for infrared and terahertz range radiation, and much progress has been made on the band engineering of the active region, as well as the design of the waveguide, both of which are extremely important due to the long lasing wavelength. The transistor laser, on the other hand, is a promising three-terminal laser based upon the bipolar transistor, allowing for an ultrafast electron-hole radiative recombination lifetime in the base region and separate control of injection current and bias over the lasing medium. In our design, we combine the merits of these two kinds of lasers and propose a transistor-injected quantum cascade laser. Simulations have been conducted to optimize the design of the active region and waveguide and demonstrate its validity and advantages over traditional quantum cascade lasers.**

***Index Terms*—Quantum Cascade Laser, Transistor Laser**

I. Motivation and Background

QUANTUM cascade lasers [1-4] are unipolar devices with stimulated emission based on electron intersubband transitions rather than interband transitions. The quantum cascade laser (QCL) has become an important coherent light source in the infrared regime. However, the output power of the QCL is limited by the coupled control of current and field over the lasing active region. At certain current injection levels, the applied bias across the device can largely limit the laser performance due to the misalignment of quantized electron states.

The transistor laser was invented in 2004 [5-8]. By employing electron-hole recombination in the base region of a bipolar transistor, stimulated emission radiation can be realized in a three-terminal device.

In order to address the inherent issues of quantum cascade lasers, we propose a design that combines these two different lasing systems: a transistor-injected quantum cascade laser [9-11]. By incorporating the quantum cascade active region in the base-collector junction of an n-p-n bipolar transistor, the applied bias is controlled by the transistor base-collector voltage, while the injection current comes from the emitter region. Therefore, the current and bias in the quantum cascade lasing region is decoupled and higher optical output power is expected. Another important feature in the transistor-injected quantum cascade laser is the low doping level of the p-type base region which decreases free carrier absorption in the active region compared to n-doped QCLs, further improving performance.

Based upon these ideas, we provide simulation results for the transistor-injected quantum cascade laser. Band engineering is optimized with a Schrödinger-Poisson solver. We also simulate the optical field distribution in a transistor-injected quantum cascade laser device-level waveguide. The electrical merit of the transistor is modeled as well.

II. Design and Modeling of Transistor-Injected Quantum Cascade Laser

As is mentioned above, our design of a transistor-injected quantum cascade laser (TI-QCL) employs an n-p-n heterojunction bipolar transistor structure. The electrons injected from emitter through the forward biased emitter-base junction diffuse through the base. As minority carriers in the base region, once the electrons enter the fully depleted base-collector junction they are swept through the quantum cascade lasing region where an intersubband transition occurs for radiative emission. The base-collector voltage controls the bias over the lasing core while the injection current is supplied by the emitter.

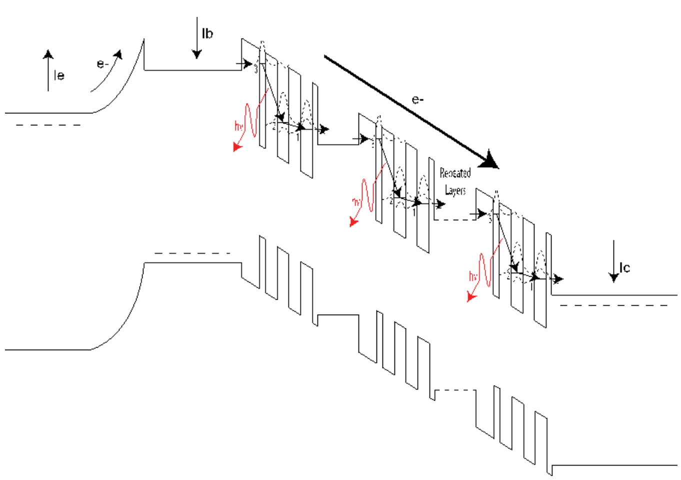

Figure 1. Band diagram illustration in a TI-QCL.

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A. Band diagram illustration

In our design, the quantum cascade lasing region is embedded in the base-collector junction. An illustration of band diagram is shown in Fig. 1. The electrons are injected from the emitter, after which they transit through the base-collector junction while emitting photons within the intrinsic quantum cascade region. Finally, they reach the collector and are swept away.

B. Lasing active region design and optimization with a self-consistent Schrödinger-Poisson solver

In order to obtain the desired lasing transition energy between electron subbands in a group of quantum wells and barriers, an iterative Schrödinger-Poisson solver is developed. In the one-dimensional case, the electron wavefunctions and eigenenergies can be obtained by solving the Schrödinger equation. The introduced potential due to electron occupation at quantized states is solved using Poisson equation. Iteratively the Schrödinger-Poisson solver gives the self-consistent electron wavefunctions and eigenenergies. In Fig. 2 the conduction subbands are plotted for a GaAs/AlGaAs lasing active region design with a lasing wavelength at 8.05μm.

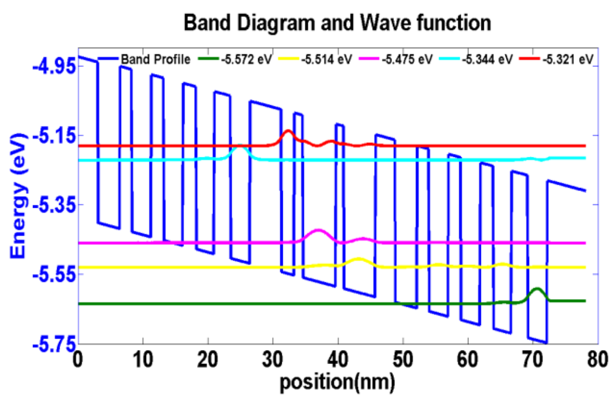

Figure 2. Active region and injector design in the quantum cascade region in TI-QCL. The lasing wavelength shown in the figure is 8.05μm.

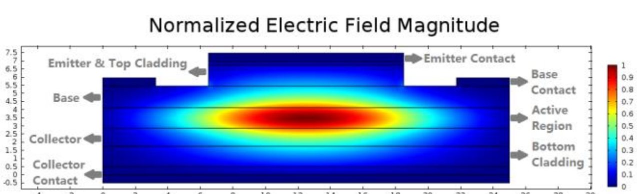

Figure 3. Normalized electric field magnitude in a cross section of TI-QCL. From the top: contact, top cladding layer, emitter, base, active region, collector, subcollector, bottom cladding layer, bottom contact.

C. Optical field simulation

In the transistor-injected quantum cascade laser we employ a doped emitter, base and collector as well as top and bottom cladding layers to provide good optical confinement. The optical field simulation is realized with COMSOL Multi-physics. In Fig. 3 the cross-sectional view of the transistor-injected quantum cascade laser with normalized electric field magnitude is shown. The device being simulated has a lasing wavelength of 8.05μm. The effective mode index of the fundamental mode is 3.11 with an optical confinement factor 0.68.

D. Electrical modeling of the transistor

The electrical characterization of the transistor is also explored with Synopsys TCAD. The transistor family of curves is shown in Fig. 4. As the base current is increased from 0.4mA to 5mA with a uniform step, the collector current gain β for a 23μm wide device decreases from 19.8 to 10.05.

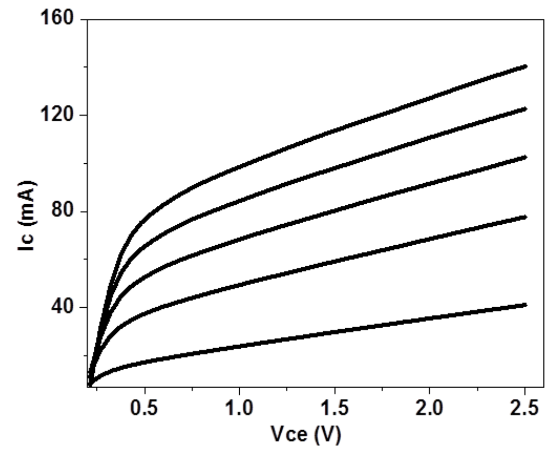

Figure 4.The transistor family of curves of the TI-QCL. The collector currents vs. the collector-emitter voltage are plotted.

III. Conclusion

Considering the inherent issues of the QCL, a new design of a transistor-injected quantum cascade laser is proposed. Numerical simulations have been implemented to design the lasing active region design using a self-consistent Schrödinger-Poisson solver. Optical field distribution within the laser cavity is simulated to optimize the waveguide design. Electrical modeling of the transistor family of curves is also provided to explain the design from the transistor's aspect.

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