Self-Consistent Modeling of a Transistor Vertical-Cavity Surface-Emitting Laser

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***Abstract*—A multiple quantum well (MQW) transistor vertical-cavity surface-emitting laser (T-VCSEL) is designed and numerically modeled. The quantum capture/escape process is simulated using a quantum-trap model. Both the steady state and frequency response of the T-VCSEL are calculated by a numerical and analytical approach.**

I. INTRODUCTION

The quantum well (QW) transistor laser is an integration of a transistor and a laser, a device that takes an electrical input signal and simultaneously outputs an electrical signal and an optical signal [1]. It is of great interest for high-frequency operation due to its unique carrier dynamics [2] and may find applications based on a simpler method of implementing feedback operation, a unique voltage-controlled mode [3], and a new optoelectronic integration scheme. By integrating the heterojunction bipolar trasistor (HBT) structure into a vertical optical cavity, we can combine the optoelectronic properties of the transistor laser with advantages of the vertical-cavity surface-emitting lasers (VCSELs).

II. DESIGN

The transistor VCSEL, as shown Fig. 1, has a n-p-n $In_{0.49}Ga_{0.51}P/GaAs$ HBT structure. The bottom and top distributed Bragg reflectors (DBRs) consist of 36 pairs and 24 paris of $Al_{0.85}Ga_{0.15}As/GaAs$, respectively. The base region plays a critical role in determinating the electrical and optical performance of a transistor VCSEL [4]. We use an asymmetric base doping profile in this design where the whole base region is composed of (from bottom to top) a 15 nm heavily doped ($1 \times 10^{19}\ cm^{-3}$) layer, a 30 nm doping grading layer, three intrinsic $In_{0.17}Ga_{0.83}As/GaAs$ QWs, another 30 nm doping grading layer, and a 40 nm heavily doped ($1 \times 10^{19}\ cm^{-3}$) base-contact layer. The heavily doped layers are aligned with the valleys of the longitudinal standing wave in the vertical optical cavity to reduce the optical absorption. A 6 μm oxide aperture is used.

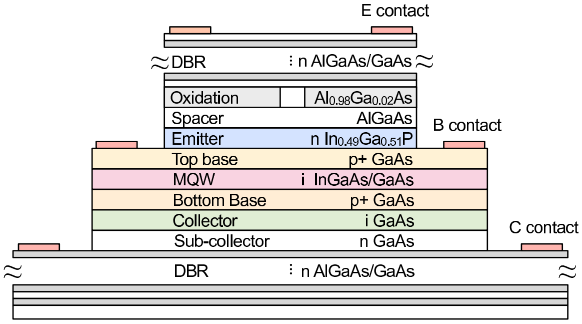

Fig. 1. Structure of the QW transistor VCSEL.

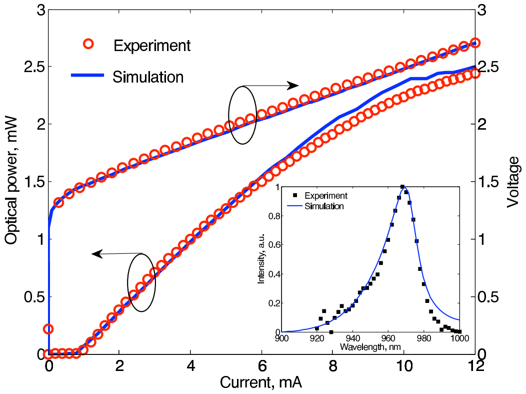

Fig. 2. Simulated and measured *L-I-V* curves of a 980-nm MQW VCSEL. The inset is the simulated and measured photoluminance spectrum.

III. MODELING AND DISCUSSIONS

To investigate the physics and performance of transistor VCSELs, we have used an advanced numerical simulation software that solves the electrical and optical models self-consistently [5]. To verify the models and determine the material parameters, we have simulated a conventional VCSEL that has the same QW structure, taking self-heating into consideration. As demonstrated in Fig. 2, the simulated results and experimental data show good agreement.

A. Quantum capture and escape

The QW capture/escape process has a significant effect on the electrical gain and frequency response of a transistor laser [6]. In this work, this process is described by a quantum-trap model in which the QWs are treated as carrier traps with trapping rates determined by the phonon scattering theory [7].

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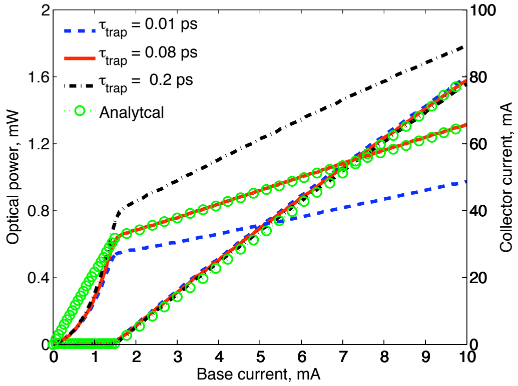

Fig. 3. Optical power and collector current as a function of base current at the collector-emitter voltage $V_{CE} = 4\ V$ with varied QW trapping time.

The QW capture rate is defined as

$$R_{cap} = \frac{n_{3D}}{\tau_{cap}} = \frac{n_{3D}(1 - f_{2D})}{\tau_{trap}} \tag{1}$$

where n_{3D}, τ_{cap}, f_{2D}, and τ_{trap} are the unbounded carrier density, capture time, occupancy at the bound-state quasi-fermi level, and trapping time, respectively. As shown in Fig. 3, while the LI curves are almost unaffected by the trapping time, the collector current is very sensitive to the capture/escape process. In the following simulation, we use $\tau_{trap} = 0.08\ ps$ that corresponds to a capture time of $\sim 1\ ps$ at threshold [6].

B. Voltage control

Due to the three-port operation and device geometry, the optical power of a T-VCSEL is controlled both by the base current (which dominates the total recombination current) and the collector-emitter voltage (that controls the effective current injected into the optical cavity) [3]. As shown in Fig. 4, the optical output follows the same trend as the collector current, which means that we can potentially monitor the optical performance by the electrical output. This voltage-controlled operation may find applications in optical communications and optoelectronic signal processing [8].

C. Frequency response

We use the analytical model developed in [2], [6] to study the modulation response of the T-VCSEL with the parameters extracted from the numerical modeling. Fig. 3 shows that the analytical model successfully matches the DC results from the numerical simulation. Fig. 5 shows the small-signal modulation response of the T-VCSEL in common-base (CB) and common-emitter (CE) configurations. The model predicts a -40 dB/dec decay after relaxation oscillation for the CB configuration and a removal of the laser damping which results in a bandwidth enhancement, albeit, a reduction of the DC gain by the transistor current gain [6].

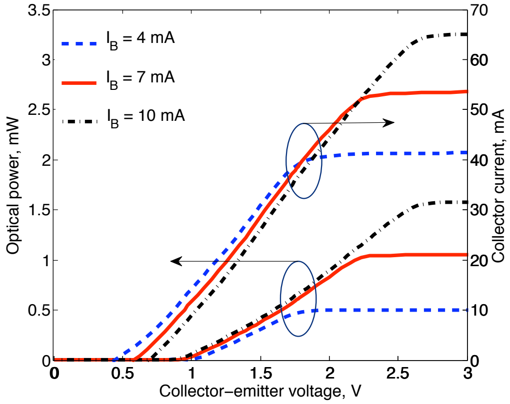

Fig. 4. Optical power and collector current as a function of the collector-emitter voltage with varied base current.

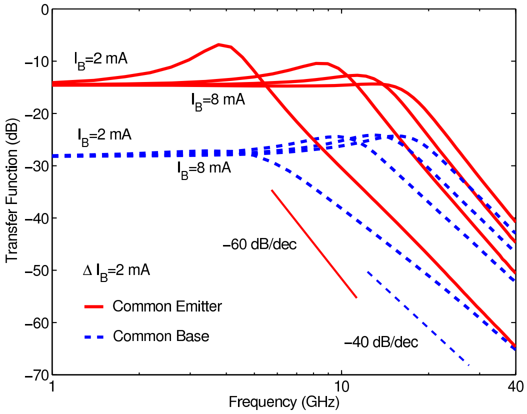

Fig. 5. Transfer function of the small-signal modulation of the T-VCSEL in common base and common emitter configurations.

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