# Direct Tunneling Modulation of Semiconductor Lasers

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**Abstract:** Direct tunneling modulation of semiconductor lasers is realized and demonstrated experimentally in the three-terminal transistor laser through the interaction between the photon absorption by voltage-controlled intra-cavity photon-assisted tunneling and the photon generation by quantum-well recombination.

**OCIS codes:** (140.5960) Semiconductor lasers, (240.7040) Tunneling

## 1. Introduction

Today, optical interconnects based on direct-modulated laser transmitters have been widely deployed in large-scale data centers and high-performance computers for energy-efficient high speed data transmission. Fundamentally the semiconductor diode laser modulation speed is limited by the carrier recombination lifetime in the active region, however in practice the self-heating effect associated with high-level current injection will raise the laser junction temperature and thus counteract the attempt. Therefore in state-of-the-art VCSELs the carrier spontaneous recombination lifetime is limited to around 200 *ps*, and the modulation bandwidth has been limited to around 30 *GHz* [1].

The transistor laser invented by Feng and Holonyak [2-4] overcomes the recombination lifetime limitation of diode lasers by placing the quantum-well recombination center in the highly doped transistor base. It is also found out the photons in the cavity can induce intra-cavity photon-assisted tunneling in the collector junction [5-7], which opens the new possibility to directly modulate the laser optical output with voltage bias, and the ultrafast tunneling process on the order of femtoseconds makes it possible to significantly improve the laser modulation speed beyond the recombination lifetime restriction. In this work we report the latest result of utilizing tunneling modulation in the transistor laser to achieve resonance-free frequency response with a modulation bandwidth of 11 *GHz* [8], and the analysis of tunneling carrier injection in the case of a resonant-cavity tunnel-junction light-emitting transistor [9].

## 2. Tunneling modulation of a vertical-cavity transistor laser

The oxide-confined vertical-cavity transistor laser (VCTL) has been developed as a small volume and high confinement transistor laser device structure [10]. Here we demonstrate the microwave modulation bandwidth of an oxide-confined VCTL with 4.7×5.4 $\mu m^2$ aperture under both the conventional current injection modulation and the novel tunneling modulation for comparison.

The VCTL structure and measurement results are shown in Fig. 1. The small optical cavity of 4.7×5.4 $\mu m^2$ allows for single-mode laser operation up to 4 *mA* with a current threshold of 2.4 *mA* at a collector voltage bias of 5 *V*. The frequency response of the VCTL is measured under both current modulation at the base terminal (BE-port, blue) and tunneling modulation at the collector terminal (CE-port, red), shown in Fig. 2. In all bias scenarios the tunneling modulation applied at the CE-port shows higher modulation bandwidth than the current modulation, with a peak bandwidth of 11.1 *GHz* at $I_B = 6$ *mA* and $V_{CE} = 5$ *V*. The resonance peaks in the frequency response plot are absent due to either the fast recombination (in the case of current modulation) or the fast tunneling process (in the case of tunneling modulation).

## 3. Tunneling modulation of a light-emitting transistor

The resonant-cavity light-emitting transistor (RCLET) structure is different from the VCTL in two aspects: the RCLET only has 4 pairs distributed Bragg reflector (DBR) at the top and thus the light emission is spontaneous; it also has a broken-band collector junction by design to further promote electron tunneling across the junction.

The RCLET measurement results are shown in Fig. 2. The collector junction IV curve clearly demonstrates the characteristic of a tunneling diode with a negative differential resistance region. The transistor optical output family curves in Fig. 2(c) shows the device switches between four operating modes with three tunneling mechanisms: electron collector-to-base tunneling, electron base-to-collector tunneling, and photon-assisted tunneling. The device optical output is shown to be affected by to the carrier tunneling injection from the collector junction upon further analysis, thus demonstrating the carrier dynamics in the transistor base region.

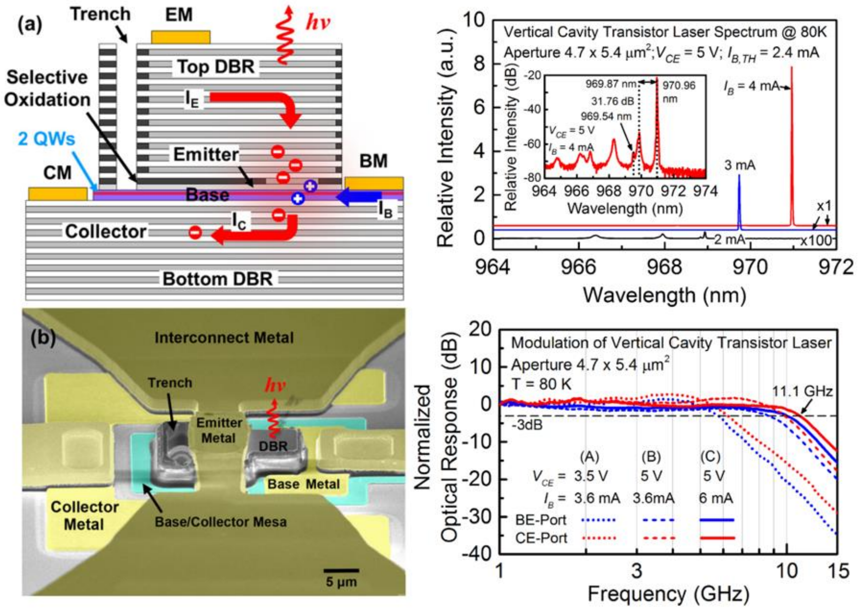

Figure 1: (a) VCTL cross-section schematic showing the carrier flow, optical output, and oxide confinement aperture; (b) fabricated VCTL device under SEM showing the laser emission area; (top right) VCTL emission spectrum showing single-mode laser operation at narrow linewidth; (bottom right) VCTL frequency response under both current modulation at the base terminal (BE-port, blue) and tunneling modulation at the collector terminal (CE-port, red) [8].

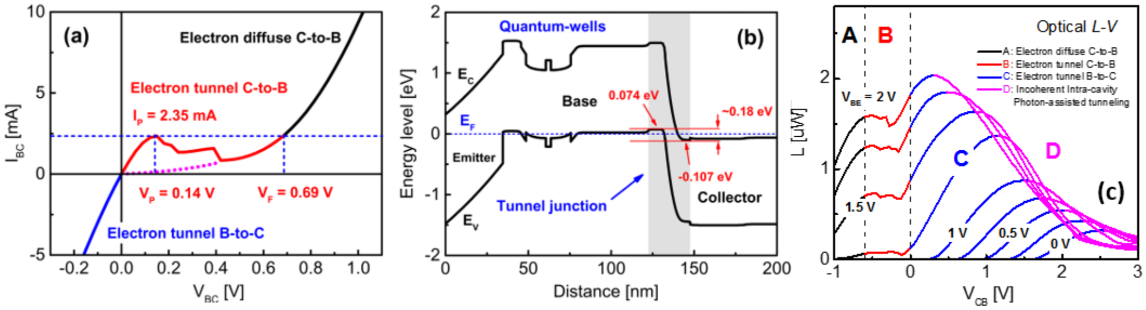

Figure 2: (a) RCLET collector junction IV curve showing the negative differential resistance region due to the tunnel junction; (b) simulated RCLET band diagram showing the broken-band design at the collector junction to promote tunneling; (c) RCLET optical output family curves as a function of the base and the collector junction bias voltage; the optical output is explained as the result of carrier injection from the collector junction tunneling mechanism [9].

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