

ANALYSIS OF TRANSISTOR LASER
INTRA-CAVITY PHOTON-ASSISTED TUNNELING FOR
DIRECT VOLTAGE MODULATION

BY

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THESIS

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Abstract

High-speed optical interconnect made with semiconductor lasers is expected to play an important role in the upcoming age of big data. The technology of diode laser has been limited by its current modulation scheme in which the carrier recombination lifetime in the active region governs the ultimate speed of operation. The transistor laser, due to its enhanced carrier recombination in the bipolar junction transistor base region, is a promising candidate to replace the diode laser for high-speed optical transmitters. It was recently found that the transistor laser offers a unique voltage modulation scheme through photon-assisted tunneling at the base-collector junction, which could potentially reshape the device operation principles. This work reports the quantitative analysis of the transistor laser photon-assisted tunneling effect and its implications for future optoelectronic applications.

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1. Introduction

1.1 Motivation

High-speed optical interconnects have been the crucial infrastructure for various communication networks ranging from global Ethernet to links within data centers. With the recent demand in cloud computing, big data, Internet of things (IoT), and the promotion of next-generation communication networks, an increasing portion of global data traffic will happen within the data center. Figures 1 and 2 illustrate the 5-year projection of data center traffic growth. At this demand of speed, due to high-frequency effects such as cross-talk and skin effects, electrical cables made of copper will incur much higher power loss per traveled distance, and therefore exponentially increase the power budget. Optical interconnects made with optical fibers, however, are free from these high-frequency effects and can operate at a much higher data rate. As a result, optical interconnects have been widely deployed in data centers for short-haul (< 300 m) communication.

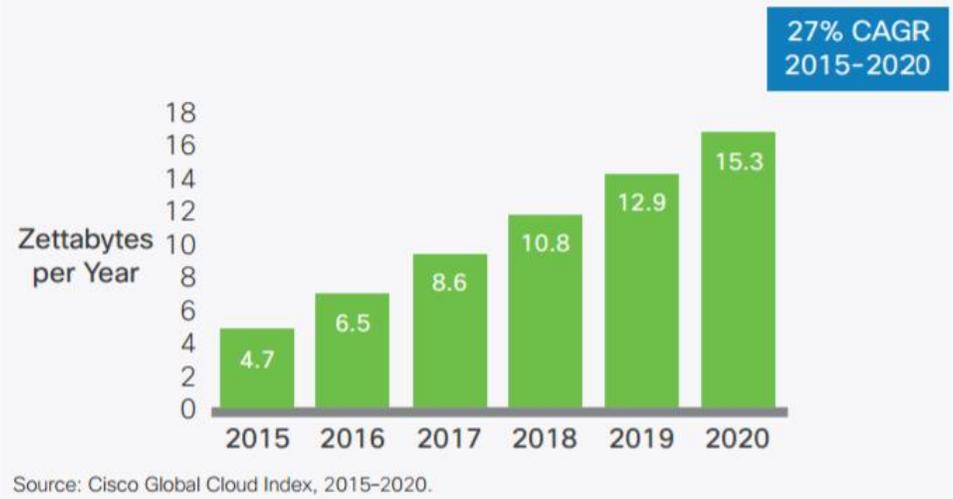


Fig. 1: Forecast of global data center IP traffic growth from 2015 to 2020.

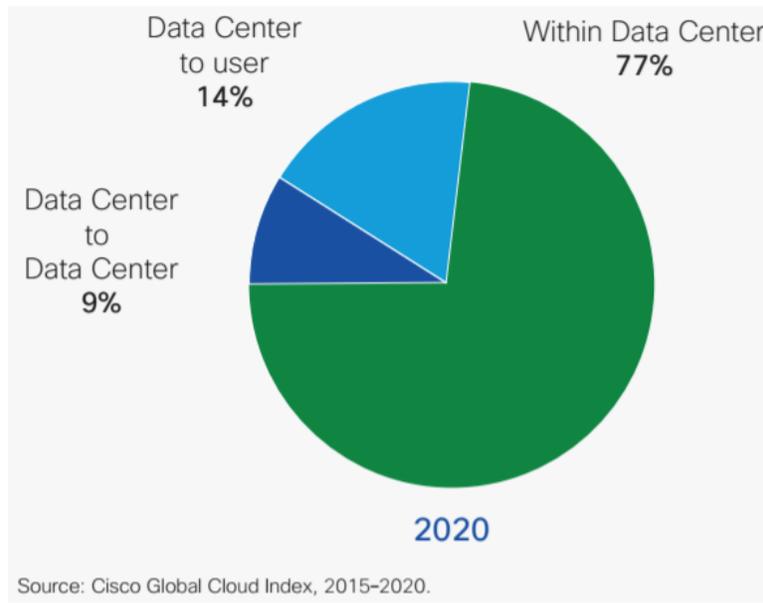


Fig. 2: Forecast of global data traffic breakdown in 2020.

The optical interconnect is composed of semiconductor laser (transmitter), optical fiber (channel), and photodetector (receiver). The semiconductor laser converts incoming electrical signal into optical signal, which is then transmitted along the optical fiber, collected by the photodetector, and converted back into electrical signal. The performance of the link is typically limited by the bandwidth of the semiconductor laser. Currently the transmitters are made of vertical-cavity surface-emitting lasers (VCSEL), which is a well-developed technology that offers low threshold (low power consumption), high efficiency, high bandwidth, and good reliability. In fact, VCSELs have demonstrated a record performance of 57 Gb/s error-free data transmission [1], [2]. Commercially, for example, the current 100G Ethernet standard employs four channels of 25 Gb/s VCSELs.

VCSELs, or diode lasers [3] in general, are made of III-V semiconductor p-n junction plus the distributed Bragg reflector (DBR) mirrors. The p-n junction provides the location for the injected electrons and holes to recombine and generate photons, and typically a quantum-well structure is added to improve the carrier density and enhance the photon generation. Typically III-V semiconductors are used instead of silicon because III-V materials are direct-bandgap, which favors radiative recombination. The DBR mirrors form the optical cavity that allows the generated photons to resonate and reach stimulated emission, hence the lasing action.

The laser bandwidth is fundamentally limited by the carrier recombination lifetime. For diode lasers, the recombination center is the neutral junction region, which means all the electrons and holes need to be injected from the p- or n-terminals, and consequently a larger current injection is necessary to reach lower recombination lifetime. This dependence poses a serious limit to diode lasers because an arbitrarily large current injection is detrimental to the device reliability. As a result, the carrier recombination lifetime in diode lasers is limited in the nanosecond range. As the demand is pushing for higher and higher operating frequency, VCSELs are likely to fall off due to the physical limitations.

1.2 Transistor laser

The transistor laser was invented by Feng and Holonyak in 2004 [4], [5] by realizing that the III-V bipolar junction transistor base recombination current can be used for efficient photon generation. In this case, the recombination center becomes the transistor base region which can be doped very high, thereby improving the recombination lifetime significantly, pushing from nanosecond to picosecond range. Indeed it has been shown that the reduced recombination lifetime (~ 35 ps) in transistor lasers has led to the reduction of laser resonant peak caused by carrier choking effect [6], [7].

Another advantage the transistor laser offers over the diode laser is that it is a three-port device: it has three electrical terminals (from bipolar transistor: emitter, base, and collector), and one optical terminal (laser output). Normally the transistor laser operates under common-emitter setup in which the modulation is applied to the base-emitter junction. In this operation mode the applied voltage modulation controls the emitter-to-base electron injection current, which is similar to the diode laser operation. However, it was discovered earlier that when the collector voltage is above a certain level (well below breakdown voltage), the laser output will decrease while the collector current will increase. This phenomenon is due to photon-assisted tunneling, in which the fundamental absorption edge of the semiconductor is shifted by the electric field, and the electron band-to-band transition is aided by the energy of photons. As a result, as the base-collector junction electric field increases, photons are absorbed in the junction, and in the meantime electron-hole

pairs are generated in the junction, leading to the reduction of laser optical output and the increase of collector current [8].

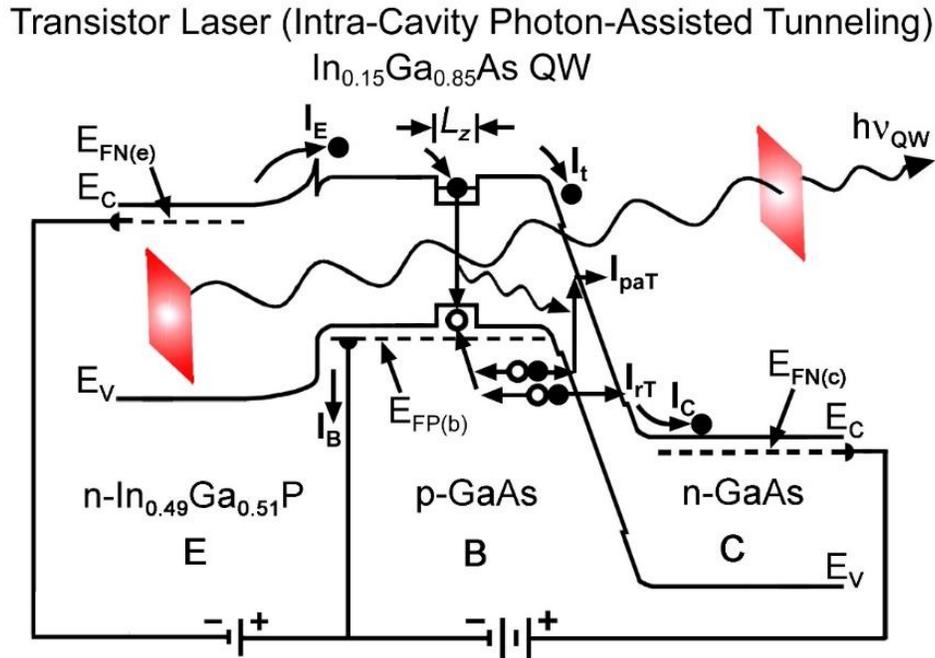


Fig. 3: Band diagram showing the transistor laser structure and the photon-to-electron conversion through photon-assisted tunneling at the base-collector junction.

Thus the transistor laser base-collector junction can function as an internal electroabsorption modulator (EAM), where the optical absorption is controlled directly by electric field (or voltage), as shown in Fig. 3. Typically external EAMs are used for long-haul fiber links where a higher power consumption can be tolerated. Seeing that the laser output can be suppressed by photon absorption inside the transistor laser under voltage control, the transistor laser can be viewed as an integrated device with both photon generation (due to base recombination) and photon absorption (due to tunneling in the base-collector junction), and it becomes possible to operate the laser under direct voltage modulation in the photon absorption mode, thereby breaking the limit of carrier recombination lifetime [9].

1.3 Photon-assisted tunneling

It was discovered by Franz-Keldysh [10] that the fundamental absorption edge of a semiconductor material can be changed by the electric field, which explains the exponentially decaying tail in the photodetector absorption spectrum, i.e. photons with energy slightly below the bandgap energy can still be detected. As shown in Fig. 4, even when the incoming photon energy is less than the energy required for electron transition from the valence band to the conduction band, the tilted band edge as a result of electric field will significantly increase the electron wavefunction overlap and thus assist the band-to-band electron tunneling.

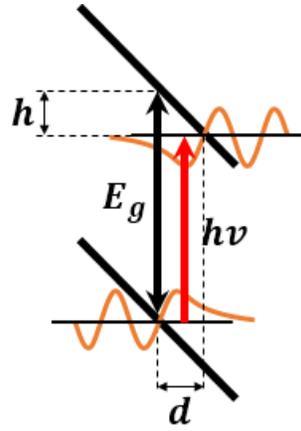


Fig. 4: Illustration of photon-assisted tunneling process. The tilted band edge as a result of the electric field allows finite wavefunction overlap; band-to-band transition is allowed with the addition of photon energy $h\nu$ despite being less than the bandgap energy E_g . Alternatively, it is equivalent to a triangular barrier with height $E_g - h\nu$ and distance d .

Tharmalingam [11] and Stillman [12] later formulated this electroabsorption effect in photodetectors, treating it as a secondary effect in photon detection and arriving at:

$$\alpha_{PAT} = 1 \times 10^4 (f/n) (2\mu/m)^{4/3} F^{1/3} \int_{\beta}^{\infty} |Ai(z)|^2 dz \quad (1)$$

where $\beta = 1.1 \times 10^5 (E_g - \hbar\omega) (2\mu/m)^{1/3} F^{-2/3}$. For α in cm^{-1} , F is electric field in V/cm , $(E_g - \hbar\omega)$ is in eV , $f \approx 1 + m/m_v$, m_v is valence band heavy hole effective mass, n is refractive index, μ is reduced electron-hole mass, and m is electron mass in free space.

Photon-assisted tunneling also happens in the transistor laser base-collector junction. In fact, the transistor laser operation favors photon-assisted tunneling because the laser cavity has huge photon density and the base-collector junction is reverse biased. While previously the photon-assisted tunneling effect has only been studied in the context of photodetectors, in transistor lasers it will be studied as a fundamental operation mode for voltage-controlled laser optical output modulation [13], [14].

2. Transistor laser intra-cavity photon-assisted tunneling

2.1 Device measurements

The transistor laser discussed in this work has an edge-emitting structure with a designed cavity length of 200 μm . As explained previously, the transistor laser has two electrical input ports (base-emitter bias V_{BE} , collector-emitter bias V_{CE}) and one optical output port (laser coherent light output). In the steady-state measurement setup, the base-emitter port is kept at a constant current level while the collector-emitter voltage V_{CE} is swept from low to high; in the meantime, the collector current is recorded and the transistor laser optical output is collected by the power meter, resulting in the set of two output characteristic plots shown in Fig. 5 and 6, respectively.

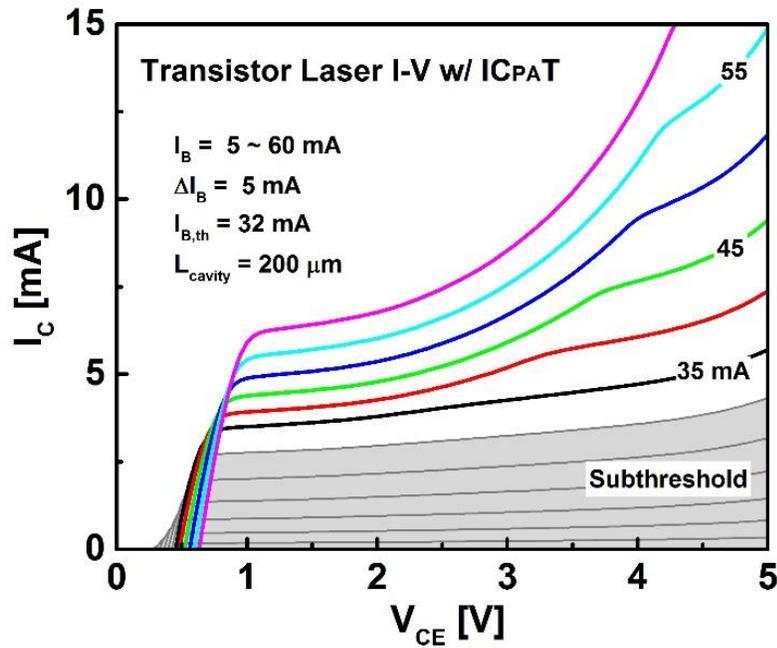


Fig. 5: Transistor laser collector current versus the collector-emitter bias at given constant base current levels, or the IV plot.

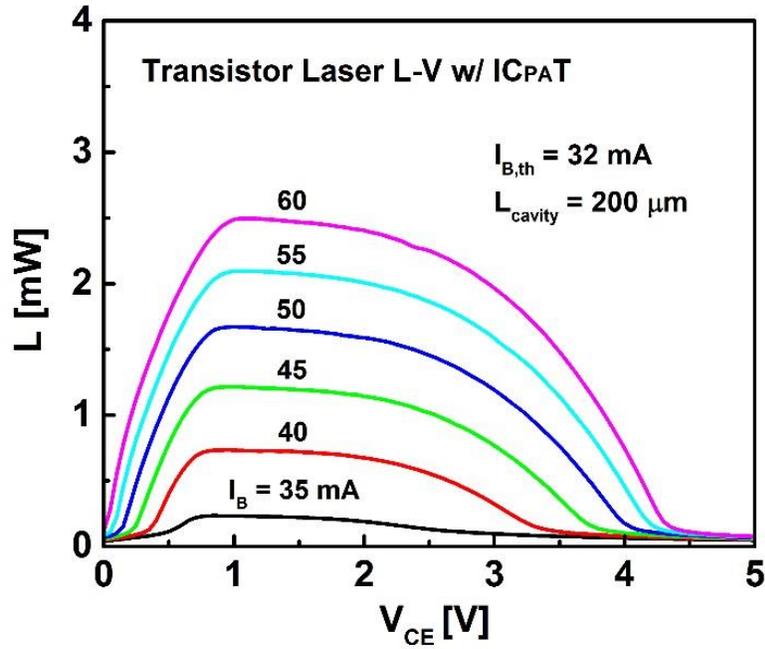


Fig. 6: Transistor laser coherent light output versus the collector-emitter bias at given constant base current levels, or the LV plot. The laser cavity length is 200 μm .

Since the transistor laser combines the operation principles of both a bipolar transistor and diode laser, we can identify the resemblance from these two output characteristic plots. First, the plot of collector current versus collector voltage for a bipolar transistor is called the transistor “family curve,” which is commonly used together with the Gummel plot to characterize the transistor. In a typical transistor family curve, the collector current (I_C) approaches a constant value as V_{CE} increases due to limited hole supply from the base-collector strong reverse bias. In real devices, however, the extrinsic device region will reduce the voltage delivered to the device junction and cause the family curve to have a small slope in the high V_{CE} regime. However, as shown in Fig. 5, in a transistor laser the collector current keep increasing almost exponentially beyond a certain bias point, indicating some sort of breakdown mechanism.

Next, we can compare the transistor laser optical output plot to that of the diode laser. The diode laser operates under current injection, which produces the laser light output versus current (or LI) curve. The transistor laser has both current (base current) and voltage (collector voltage) control, thus again giving a family of curves shown in Fig. 6. At a given base current level, the laser is

turned on above a certain V_{CE} level, which is again due to the base-collector junction reverse bias condition. Interestingly, this indicates the transistor laser has a “voltage threshold.” Another way to put it is the lasing threshold is voltage-dependent. We shall see later that this dependency can be properly explained by the optical absorption due to photon-assisted tunneling. Finally, at constant V_{CE} level, the laser output increases approximately linearly with base current level, which is consistent with the diode laser basic operation principle.

The remarkable difference is exhibited in the high V_{CE} regime: in the transistor laser IV curve this region shows an exponential increase of collector current, whereas in the transistor laser LV curve this region shows a significant reduction of optical output. From the viewpoint of conservation of particles, this phenomenon indicates an electric field-enhanced photon-to-electron conversion inside the laser cavity that is capable of completely shutting down the laser optical output. This observation will become the foundation for transistor laser direct voltage modulation.

2.2 Data analysis

We proceed to analyze the transistor laser photon-assisted tunneling from the measured IV and LV plots. As initially discussed by Stillman [12], the photon-assisted tunneling effect introduces an additional absorption coefficient to the photodetector. Following the same argument, we can consider the same approach inside the laser cavity by introducing a term α_{PAT} which is dependent on the base-collector junction electric field. However, the transistor laser device under discussion has an edge-emitting structure in which the base-collector junction only partially coincides with the laser beam; we will add a confinement factor Γ to reflect this issue.

Thus the transistor laser cavity contains three loss terms: the intrinsic loss α_i , the mirror loss α_m , and the photon-assisted tunneling loss $\Gamma\alpha_{PAT}$. The introduction of a new absorption term has a few implications: First, the laser threshold will increase proportionally according to:

$$I_{th} \propto \alpha_i + \alpha_m + \Gamma\alpha_{PAT} \quad (2)$$

which conceptually means the increase of cavity loss will cause the increase of lasing threshold due to the fact that the gain must equal the loss. This assertion corresponds to the previous

observation from the transistor laser LV curve in which the threshold current is voltage-dependent, a unique property of the transistor laser. In diode lasers, $I_{th} \propto \alpha_i + \alpha_m$, where both the intrinsic loss α_i and the mirror loss α_m are constants related to the device physical structure. In other words, the transistor laser allows, for the first time, the direct tuning of laser cavity loss and laser threshold through applied voltage.

Secondly, the laser optical output is modified by the addition of the photon-assisted tunneling loss term $\Gamma\alpha_{PAT}$. Previously in diode lasers, the optical output could be formulated as:

$$L = \frac{1}{2} \frac{\hbar\omega}{q} \frac{\alpha_m}{\alpha_i + \alpha_m} \eta_i (I - I_{th}) \quad (3)$$

where L is the laser output, $\hbar\omega$ is the emission photon energy, η_i is the internal quantum efficiency, I is the applied current injection, and I_{th} is the laser threshold current. We recognize

the term $\frac{1}{2} \frac{\alpha_m}{\alpha_i + \alpha_m}$ physically describes the probability of photons escaping the cavity and getting captured by the photodetector (the $1/2$ ratio accounts for edge-emitting laser two-way optical output).

For transistor lasers, given the total cavity loss is increased by the additional term α_{PAT} , we expect the laser output to decrease according to a ratio of $\frac{1}{2} \frac{\alpha_m}{\alpha_i + \alpha_m + \Gamma\alpha_{PAT}}$. As discussed earlier,

transistor lasers have voltage-dependent threshold current, so we can replace I_{th} with $I_{th,PAT}$ to indicate the voltage dependence due to photon-assisted tunneling, and finally arrive at:

$$L_{TL} = \frac{1}{2} \frac{\hbar\omega}{q} \frac{\alpha_m}{\alpha_i + \alpha_m + \Gamma\alpha_{PAT}} \eta_i (I - I_{th,PAT}) \quad (4)$$

A qualitative analysis can quickly show that when V_{CE} increases, both $I_{th,PAT}$ and α_{PAT} will increase, causing the transistor laser optical output to drop, which corresponds to the measured transistor laser LV plot in Fig. 6.

Additionally, by calculating how much the transistor laser optical output deviates from the expected behavior should photon-assisted tunneling not happen, we can isolate and quantify the

$I_{th,PAT}$ and $\Gamma\alpha_{PAT}$ terms. The optical reduction caused by photon-assisted tunneling can be written as:

$$\Delta L = L - L_{TL} = \frac{1}{2} \frac{\hbar\omega}{q} \eta_i \alpha_m \left[\frac{I - I_{th}}{\alpha_i + \alpha_m} - \frac{I - I_{th,PAT}}{\alpha_i + \alpha_m + \Gamma\alpha_{PAT}} \right] \quad (5)$$

The value of α_i can be estimated with the given material structure ($\sim 2 \text{ cm}^{-1}$), and the value of α_m can be calculated given the material refractive index and the cavity length ($\sim 59 \text{ cm}^{-1}$); the internal quantum efficiency η_i and a list of $I_{th,PAT}$ values as a function of base-collector junction bias can be obtained from the transistor laser LI plot generated by slicing the LV plot at constant voltage levels (results shown in Table 1, Fig. 7, and Fig. 8).

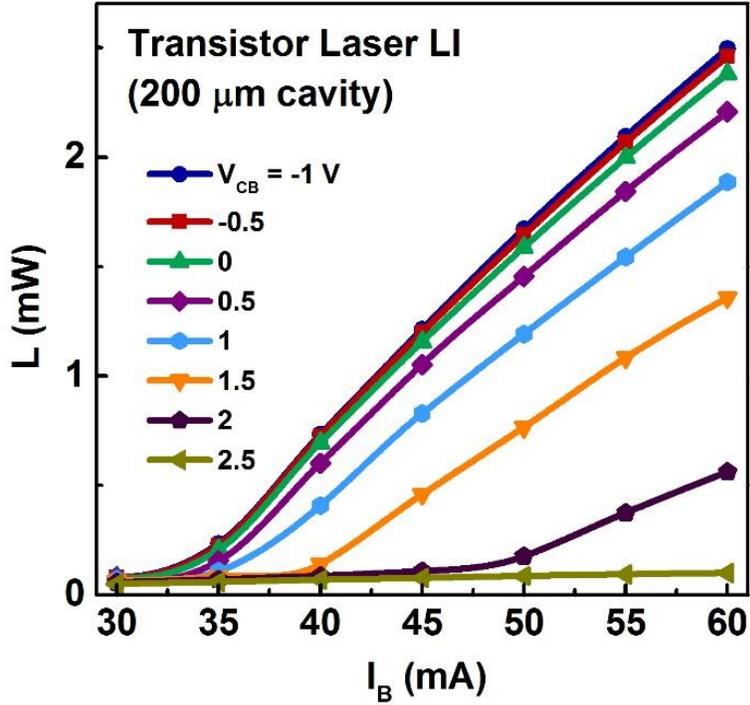


Fig. 7: Transistor laser coherent light output versus the base current at given base-emitter voltage bias levels, or the LI plot. This is derived from the transistor laser LV plot in Fig. 6.

Table 1: List of transistor laser internal quantum efficiencies at give base current level, obtained from the transistor laser LI curves.

I_B (mA)	60	55	50	45	40	35
η_i	14.47%	14.85%	15.2%	15.5%	15.67%	16.02%

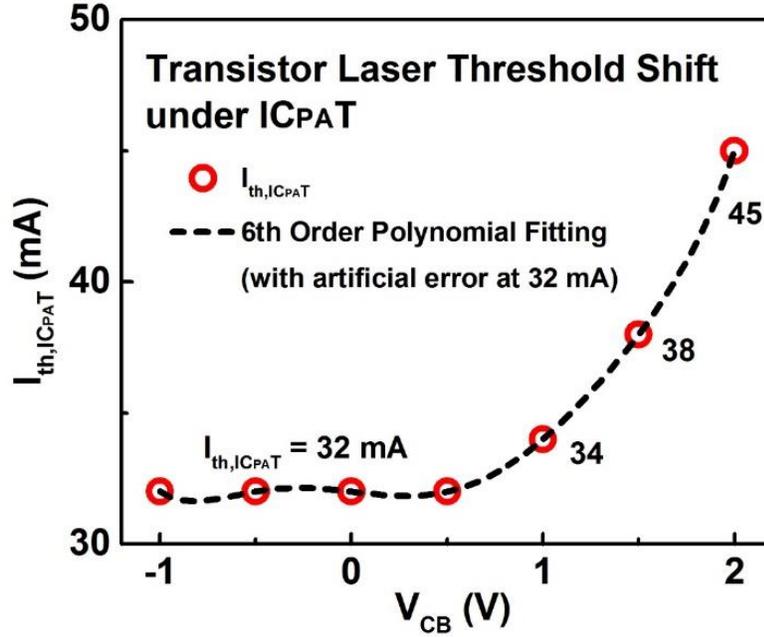


Fig. 8: Transistor laser threshold current as a function of collector voltage, obtained from the transistor laser LI plot in Fig. 7.

The optical output reduction ΔL corresponds to the difference between the solid line and the dashed line in Fig. 9, because the light output is supposed to maintain a constant level due to limited hole supply from base-collector junction reverse bias, which is the same argument being made for bipolar transistor current-voltage relation. Thus we can conveniently obtain and plot ΔL in Fig. 10. With all the parameters known in Eqn. (5), we can then directly extract $\Gamma\alpha_{PAT}$. Note that it is both difficult and unnecessary to isolate the effect of the confinement factor Γ . The result is shown in Fig. 11.

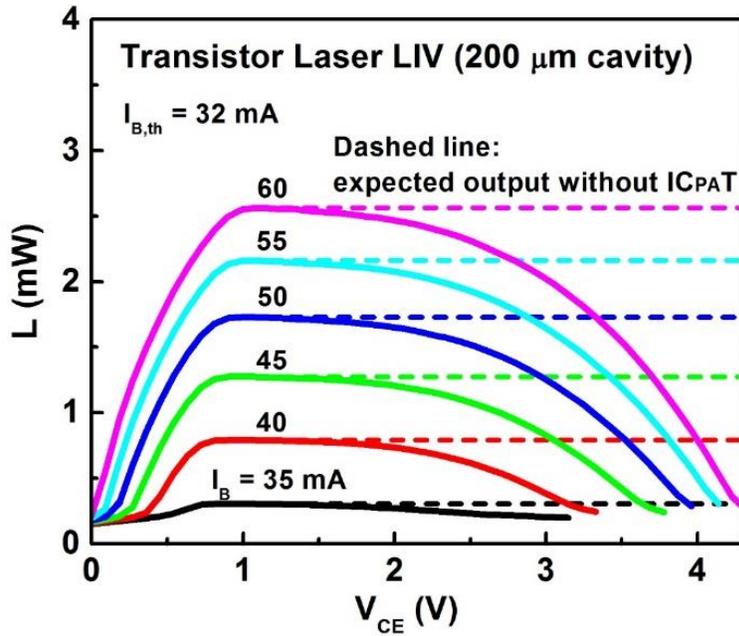


Fig. 9: Transistor laser LV plot showing the expected optical output without the photon-assisted tunneling effect (dashed lines).

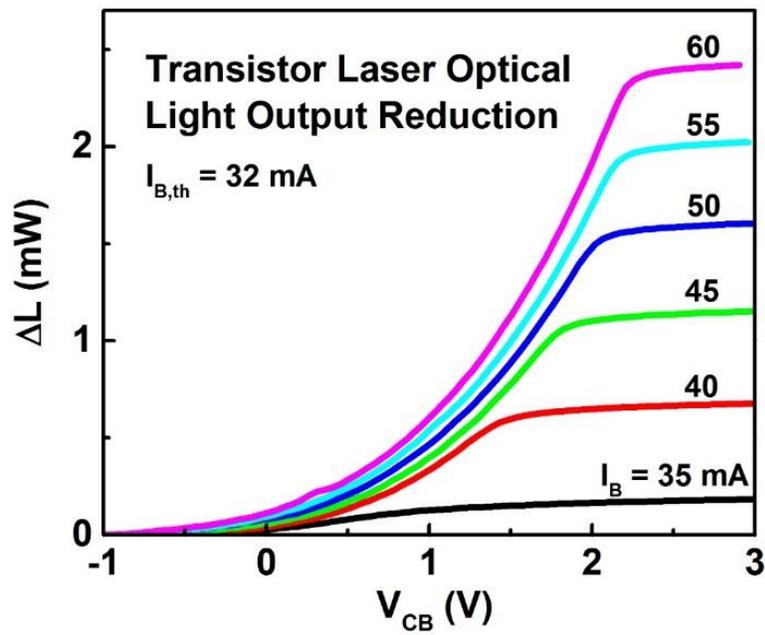


Fig. 10: Transistor laser optical output reduction ΔL due to photon-assisted tunneling, obtained by comparing the difference between the solid lines (measured) and the dashed lines (expected) in the transistor LV plot in Fig. 9.

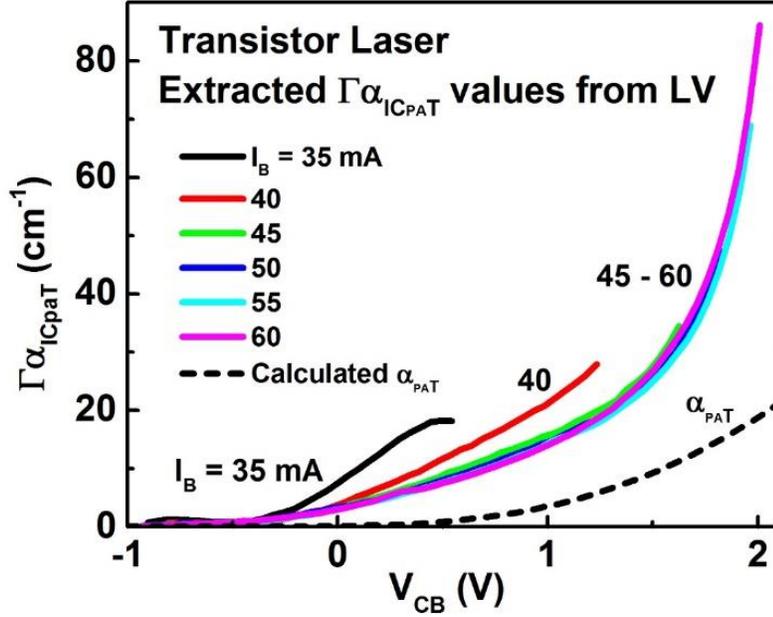


Fig. 11: Extracted transistor laser photon-assisted tunneling optical absorption coefficient $\Gamma\alpha_{PAT}$ as a function of both the base current level and the collector junction voltage. The dashed line shows the calculated values in a photodetector according to Stillman [12].

Note that at smaller base current levels, the data is cut off earlier because the laser output drops to zero at smaller voltage bias. Despite this, Fig. 11 shows a clear electric field-enhance effect of the photon-assisted tunneling optical absorption. Firstly, at given current level, the absorption coefficient increases with junction bias, which is consistent with the photon-assisted tunneling theory; secondly, at a given voltage level, the absorption coefficient decreases with base current injection, indicating a more coherent cavity photon state and less overlap between the laser beam and the base-collector absorption junction.

Additionally, we can compare the obtained $\Gamma\alpha_{PAT}$ values with Stillman's calculation (shown in black dashed line) and observe a significant enhancement as well. This enhancement is suspected to originate from the laser optical cavity confining photon modes, equivalent to a multi-pass photon absorption compared with a single-pass absorption in a regular photodetector. Thus we have demonstrated and quantified both the cavity-enhancement effect and the electric field-enhancement effect of photon-assisted tunneling optical absorption in the transistor laser. In order to distinguish from the regular photon-assisted tunneling in the context of photodetectors, we

proposed to name this effect “intra-cavity” photon-assisted tunneling to signify its uniqueness in transistor lasers.

3. Conclusion and future work

In conclusion, this work has analyzed the transistor laser electrical and optical outputs based on measured data, examined the photon-electron conversion inside the laser cavity at high voltage regime, formulated the transistor laser output characteristics under photon-assisted tunneling effect, and extracted the optical absorption coefficient as a function of both the injection current and junction voltage. The result has demonstrated cavity-enhancement and electric field-enhancement effect due to the unique transistor laser structure, which contributes to the efficient direct voltage-modulation of the laser through tunneling.

Subsequently, it will be an intriguing topic to study the transistor laser high-frequency performance under collector direct voltage modulation with photon-assisted tunneling. Ideally, the tunneling process is inherently fast and the tunneling time negligible, indicating a very high intrinsic bandwidth. In reality the device response will be slowed by the carrier transit time, but in this case the location of action shifts from the base region to the base-collector junction, indicating the carrier actions are unaffected by the limit of recombination lifetime, thus suggesting a significant improvement over current modulation.

However, to fabricate and measure a transistor laser device under a collector voltage modulation scheme is not trivial. The current device structure is optimized for base current modulation, and as a device structure design tradeoff, the collector junction capacitance is very large, causing the parasitic RC constant to dominate the frequency response should we do collector voltage modulation. Thus it is almost mandatory to redesign the device layout in order to further explore the potential of voltage modulation. In addition, a full equivalent circuit small-signal microwave model is required to de-embed the intrinsic device performance after device measurement. It can also be used to identify potential device issues and improve device design in the future.

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