DESIGN, FABRICATION, AND CHARACTERIZATION OF HIGH-SPEED LIGHT-EMITTING TRANSISTORS AND MICROCAVITY LASERS

BY

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DISSERTATION

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ABSTRACT

Carrier spontaneous recombination lifetime has been thought to be limited to ~1 ns in light-emitting diodes and diode lasers for the past forty years. In the present work the recombination lifetime demonstrated is able to be “tailored” (reduced) by the provided material system, cavity size, and layout design. In a light-emitting transistor or tilted-charge light-emitting diode, the effective carrier recombination lifetime can be readily reduced to 23 ps (spontaneous modulation bandwidth f_{3dB} = 7 GHz) by employing un-doped quantum wells in the highly-doped thin base region and allowing only “fast” recombining carriers to recombine through a reverse-biased base-collector junction boundary condition. A light-emitting transistor possesses, in addition, a unique three-terminal electrical-optical characteristic potentially leading to advantageous and useful features for high-speed short-range optical transmitters and interconnects. It has been shown that a microcavity vertical-cavity surface-emitting laser employing small aperture buried-oxide current and field confinement is also demonstrated with wider mode spacing and faster carrier recombination lifetime (enhanced Purcell factor ~ 2 to 8 times, but still limited cavity), lower threshold current, larger side mode suppression ratio, and higher photon density and temperature insensitivity.
To My Family
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1. INTRODUCTION

Semiconductor light-emitting diodes (LEDs) using direct gap III-V materials, and electron-hole injection and recombination,\textsuperscript{1-4} have over the years led to numerous applications in display and lightwave communications. Fast spontaneous lightwave transmitters can be an attractive solution for short range optical data communications and optical interconnections as their threshold-less operation, high fabrication yield and reduced complexity of driver and need for threshold feedback control are reduced significantly, thus reducing the overall cost, form-factor and power consumption of transmitters. Coupled with a proper cavity design, such as a resonant cavity, spontaneous light sources emitting at 980 nm have been shown to achieve external quantum efficiencies (\(\eta_{\text{ext}}\)) as high as 27% and an emission spectral width as narrow as 5 nm.\textsuperscript{5} However, the fastest spontaneous light source shown to date (a light-emitting diode) employs p-doping as high as \(7 \times 10^{19} \text{ cm}^{-3}\) to achieve a bandwidth of 1.7 GHz (i.e., recombination lifetime of \(\sim 100\) ps), at the cost of a reduced internal quantum efficiency to 10% or less.\textsuperscript{6} In practice, higher efficiency spontaneous devices such as LEDs or RCLEDs operate with bandwidths that are less than 1 GHz, restricting actual commercial application of spontaneous light transmitters (LEDs and RCLEDs) to less than 1 Gbits/s.

Earlier, we have proposed that the heterojunction bipolar light-emitting transistor (HBLET),\textsuperscript{7,8} which utilizes a high-speed heterojunction bipolar transistor (HBT) structure,\textsuperscript{9} could potentially function as a light source with speeds exceeding tens of GHz. The room temperature, continuous wave operation of a transistor laser (TL) further demonstrates that a practical radiative recombination center (i.e., undoped quantum well) can be incorporated in the heavily doped base region of a HBLET.\textsuperscript{10, 11, 12} The TL is
capable of achieving a modulation bandwidth of 13.5 GHz (despite a large cavity length of 400 µm) or even more, and absence of resonance frequency.13

1.1. Outline of Problem

Due to the short base effect of tilted charge population in transistors, the effective minority carrier lifetime in the base region of the HBLETs can be progressively reduced to sub-100 ps by tailoring the doping and incorporating QW(s).14 In the high-speed modulation of an HBLET, the extrinsic parasitic capacitive charging delay due to lateral extrinsic carrier transport effects ultimately limits the maximum optical bandwidth achievable and must therefore be taken into account. In practice, despite the high intrinsic speed of the HBT, the microwave performance of an HBLET is severely limited by parasitic capacitances, partly owing to the need to include light extraction features (such as oxide apertures) not present in traditional high-speed HBT devices. To reduce the parasitics, scaling effect will need to be reviewed during the design of improved light-emitting source. The characteristics of the HBLET can be understood by the microwave electrical and optical analysis of different layout design in order to provide the necessary information leading to the next stage—vertical cavity transistor lasers (VCTL).

1.2. Organization of Work

The organization of the thesis proposal is as follows:

In Chapter 2, we demonstrate a quantum-well base heterojunction bipolar light-emitting transistor (HBLET) operating in the common collector configuration with a 3 dB optical response bandwidth $f_{3\text{dB}}$ of 4.3 GHz. The HBLET has a current gain, $\beta = |\Delta I_C/\Delta I_B|$ as high as 30, and can be operated as a three-port device to provide
simultaneously an optical and electrical output with gain. The $f_{3dB}$ of 4.3 GHz corresponds to an effective carrier recombination lifetime of 37 ps, and shows that “fast” spontaneous recombination can be harnessed for high-speed modulation. In the high-speed modulation of an HBLET, the extrinsic parasitic capacitive charging delay due to lateral extrinsic carrier transport effects ultimately limits the maximum optical bandwidth achievable and must therefore be taken into account. In the present work, we verify this by showing that the extrinsic-parasitic-limitations on the recombination lifetime can be reduced sufficiently to give $\tau_B < 100$ ps by laterally scaling the emitter aperture width from 13 $\mu$m to 5 $\mu$m to reduce the extrinsic capacitive charging and simultaneously increase the current density. This work has resulted in the record performance of spontaneous optical modulation bandwidth as high as 4.3 GHz for a 5 $\mu$m emitter aperture HBLET.

In Chapter 3, we demonstrate a higher speed form of light-emitting diode (LED), an asymmetrical two-junction tilted-charge LED, utilizing an n-type buried “drain” layer beneath the p-type “base” quantum-well (carrier and photon) active region. The “drain” layer tilts and pins the charge in the manner of a heterojunction bipolar light-emitting transistor (HBLET), selecting and allowing only “fast” recombination (recombination lifetime, $\tau_B$, of the order of “base” transit time, $\tau_j$). The tilted-charge LED, simple in design and construction, is capable of operation at low current in spontaneous recombination at a 7 GHz bandwidth or even higher with more refinement. We also demonstrate a 4.3 GHz high-speed tilted-charge integrated 2 x 2 LED array. With an array of four LEDs operating in parallel, the optical output power can be as much as tripled while the peak high-speed performance of its individual LED component is
preserved. The gigahertz bandwidth is achieved by utilizing a “drain” layer, common to all the devices in the array, to enforce a “tilted-charge” condition where only fast recombination is employed for the modulation of optical output. The successful integration of four “tilted-charge” LEDs in a parallel array paves the way towards a simple viable solution for ultra-high-speed short range optical communication.

After having discussed the high speed operation of HBLET and tilted-charge LED, in Chapter 4, the microwave characteristics of a microcavity vertical-cavity surface light-emitting laser (VCSEL) incorporated with small oxide-confined aperture is presented. A sensitive microwave method is described to study the optical frequency response of a microcavity laser, demonstrating that a quantum-well VCSEL (~3 µm aperture, \( I_{TH} = 180 \mu A \)) can exhibit almost single-mode operation (nearly threshold free), and an electron-hole spontaneous lifetime Purcell enhancement of 2.08 times. The microwave-measurement method employing electrical-to-optical conversion, and distinct separation of electrical input and optical output, is more revealing than photoluminescence decay experiments (and the inconvenient overlap of optical input and output). By studying the optical microwave frequency response of a microcavity quantum-well VCSEL in the transition, over a low (a spread-out) mode density, from spontaneous to coherent operation, we resolve the dynamics (spontaneous to stimulated) of electron-hole recombination and reveal the existence of “fast” spontaneous recombination (\( \tau_{Spon} < 159 \) ps) in a carrier population generally characterized by a large average lifetime of ~1 ns (\( \Delta n/\tau_{AV} = \Delta n/\tau_{fast} + (\Delta n-\Delta n_1)/\tau_{slow}, \tau_{fast} < \tau_{slow} \)). The measured average spontaneous lifetime is not a constant but is altered by the device
size, geometry, and boundary conditions (e.g., cavity and current input-output boundary conditions).

In Chapter 5 we focus on the spectral and microwave behavior of the VCSEL form of microcavity laser. A microcavity provides better confinement of optical fields, i.e., higher Q, and leads to enhancement of the spontaneous emission rate due to the Purcell effect. By employing an oxide-confined cavity to modify the dipole-field coupling and reduce the density of available photon modes, we demonstrate improved microwave performance ($f_{3\text{dB}}$) and an eight-fold reduction in recombination lifetime ($\tau_{\text{rec}}$) owing to carriers occupying primarily a single (fundamental) mode of the microcavity laser. The device with smaller mode volume exhibits much lower threshold current, larger mode spacing and side-mode suppression ratio (SMSR), as well as higher modulation frequency bandwidth and data transmission speed. With single-mode operation and larger SMSR, the threshold current of a microcavity laser is less sensitive to change in the ambient temperature because of locked single-mode operation. In other words, “threshold-less” behavior is observed in a higher Q microcavity laser. A microwave method is used to analyze conveniently the reduction in recombination lifetime in a microcavity laser, based on constructing an equivalent small-signal model employing s-parameter measurements. Finally, we compare the quality of data transmission with the change in eye diagrams for single-mode and multimode lasers. The single-mode (microcavity) laser, because of reduced lifetimes (enhanced recombination), exhibits faster and flatter frequency response, thus yielding a “cleaner” eye diagram compared to multimode operation.
2. TOWARD MULTI-GHZ OPERATION LIGHT-EMITTING TRANSISTORS

2.1. Three-Port DC and RF Characteristics

In the present work, we move the device further towards its intrinsic limit of spontaneous optical speed (intrinsic spontaneous recombination lifetime) by reducing the lateral dimensions of the device using a quarter wavelength thick, 6 µm diameter, oxide aperture for current confinement, a thicker collector (2871 Å), and a common collector layout design to reduce significantly the peripheral (extrinsic) parasitic capacitances. In addition, we show that the three-terminal nature of the light-emitting transistor offers two input-output configurations for electrical-to-optical output conversion, e.g., via the common-collector BC- and EC-input ports, each with its own unique advantages.

The epitaxial layers of the crystal used for the HBLET consist of a 3000 Å $n$-type heavily doped GaAs buffer layer, followed by a 500 Å $n$-type Al$_{0.30}$Ga$_{0.60}$As layer, a graded Al$_{0.30}$Ga$_{0.70}$As to Al$_{0.90}$Ga$_{0.10}$As oxide buffer layer, a 600 Å $n$-type Al$_{0.98}$Ga$_{0.02}$As oxidizable layer, and then a graded Al$_{0.96}$Ga$_{0.10}$As to Al$_{0.30}$Ga$_{0.70}$As oxide buffer layer that completes the bottom cladding layers. These layers are followed by a 557 Å $n$-type subcollector layer, a 120 Å In$_{0.49}$Ga$_{0.51}$P etch stop layer, a 2871 Å undoped GaAs collector layer, and a 1358 Å average $p$-doped $3\times10^{19}$ cm$^{-3}$ AlGaAs/GaAs graded base layer (the active layer), which includes among other layers (in the base region) two undoped 112 Å InGaAs QWs (designed for $\lambda \approx 980$ nm). The epitaxial HBTL structure is completed with the growth of the upper cladding layers, which consist of a 511 Å $n$-type In$_{0.49}$Ga$_{0.51}$P wide-gap emitter layer, a graded Al$_{0.30}$Ga$_{0.70}$As to Al$_{0.90}$Ga$_{0.10}$As oxide buffer layer, a 600 Å $n$-type Al$_{0.98}$Ga$_{0.02}$As oxidizable layer, a graded Al$_{0.90}$Ga$_{0.10}$As to Al$_{0.30}$Ga$_{0.70}$As oxide buffer layer and a 500 Å $n$-type Al$_{0.30}$Ga$_{0.70}$As layer. Finally, the
HBLET structure is capped with a 2000 Å heavily doped $n$-type GaAs contact layer. After various standard etching and contact metallization steps, the completed devices have an oxide aperture diameter, $D_A$, of ~ 6 µm on 10 µm emitter mesas. A schematic of the device cross section and its top view layout are shown in Fig. 2.1.

The collector I-V and optical output characteristics are shown in Fig. 2.2. The device exhibits a current gain $\beta (= \Delta I_C/\Delta I_B)$ as high as 30 (or 30 dB), e.g., at $I_B = 2$ mA and $V_{CE} = 2$ V. The light emission in Fig. 2.2b is measured from the bottom of the device with a large-area photodetector. A light extraction efficiency of a single escape cone from the GaAs-air surface, assuming Fresnel reflection losses for normal incidence, is approximately 1.4%. The broad spectral characteristic of the optical output (FWHM = 76 nm) is indicative (the width) of the spontaneous recombination of the HBLET operation. The HBLET employed here does not incorporate a resonant cavity. For future work, the use of a resonant cavity could improve optical output extraction to much higher than that is currently possible in the HBLET of this work. 5

Operating the common-collector HBLET with the BC port as the rf-input allows for simultaneous electrical-to-optical output conversion, and electrical output gain at the EC output port. Due to its three-port nature, its optical output can also respond to input modulation signals at the EC-port, although in this configuration, the device does not provide a simultaneous electrical output gain at the BC-port. Deploying the EC-port as the rf-input has the advantage of better matched input impedance (50 Ω standard) for maximal power transfer. The BC-port input impedance is generally higher than the EC-input impedance due to the reverse-biased BC junction, and can be advantageous where high input impedances are desirable for maximizing circuit performances. In the present
work the optical response is measured with a high-speed p-i-n photodetector with bandwidth \( \geq 12 \) GHz and a 50-GHz electrical spectrum analyzer. A frequency generator (0.05 – 20 GHz) is used for the input signal to the device. The optical responses of the common-collector HBLET to BC and EC rf-input modulation at biases \( I_B = 2 \) mA and \( V_{BC} \approx 0 \) V (condition for reverse-biased BC junction) are shown in Fig. 2.3. In both cases the response bandwidth at -3 dB, \( f_{3\,\text{dB}} \), is 4.3 GHz. In Fig. 2.4, \( f_{3\,\text{dB}} \) improves from 2.8 to 4.3 GHz as \( I_B \) is increased from 1 to 2 mA. The optical output and response bandwidth are shown up to \( I_B = 2 \) mA where the optical output begins to degrade due to saturation and heating.

The optical response, \( H(f) \) may be expressed as

\[
H(f) = \frac{A_0}{1 + j\frac{f}{\tau_B}}, \tag{2.1}
\]

where \( A_0 \) is the electrical-to-optical conversion efficiency, and \( f_{3\,\text{dB}} \) is the bandwidth at -3 dB and is related to an effective base carrier recombination lifetime \( \tau_B \) (absent stimulated recombination but including the effects of undesirable parasitic RC-charging time) by the relation

\[
f_{3\,\text{dB}} = \frac{1}{2\pi\tau_B} \tag{2.2}
\]

A value for \( f_{3\,\text{dB}} \) of 4.3 GHz therefore corresponds to a \( \tau_B \) of 37 ps. Sub-100 ps recombination speeds are not readily achieved in a double heterojunction (DH) p-i-n light-emitting diode, because equal number densities of electrons (\( n \) cm\(^{-3}\)) and holes (\( p \) cm\(^{-3}\)) are injected into the neutral undoped active region to preserve charge neutrality; therefore, an extremely high injection level and, equivalently, a high charge population
(since \( I_{\text{inject}}q = B_{\text{rad}}n\cdot p\cdot \text{Vol} = n\cdot \text{Vol}/\tau_B \) ) are required in order to achieve high recombination speeds. In a HBLET, the holes are built-in by \( p \)-doping in the base, and re-supplied by an ohmic base current, while the (minority carrier) electrons are injected from the heterojunction emitter. Moreover, as opposed to the charge “pile-up” condition in a double heterojunction \( p-i-n \) diode, the dynamic “tilted” charge flow condition is maintained in the base of the transistor with the electrical collector (reverse-biased BC junction) in competition with base recombination. Because of the “tilted” base population, current flow is a function of the slope of the charge distribution, thus making possible high current densities without requiring extreme carrier densities. The heterojunction bipolar transistor (HBT) \( n-p-n \) structure, therefore, possesses intrinsic advantages (in how charge is handled) over the double heterojunction \( p-i-n \) structure. Because of the transistor action, i.e., the electrical collector junction collecting charge in reverse-bias in conjunction with the base quantum-well acting as an optical collector, collecting charge for radiative recombination, the injected minority carriers that do not recombine within the transit time from emitter to collector are “discharged” (removed) from the base region. Due to the thin base \( (W_B = 1358 \, \text{Å}) \), the intrinsic emitter-to-collector transit time given by the relation \( \tau_t = W_B^2/2D \) \( (D \approx 26 \, \text{cm}^2/\text{s}) \) is estimated to be 3.6 ps. The intrinsic recombination speed in the base of the transistor must therefore be of the same order of magnitude as the transit time.\(^{16}\) Therefore, the 37 ps lifetime demonstrated in our work can still be improved towards its intrinsic speed.

Concluding, the 37 ps carrier lifetime observed in the HBLET of this work indicates that spontaneous recombination can be “fast,” and higher modulation speeds are possible by further reducing the undesirable parasitics. In addition, due to the lesser
signal attenuation slope of -20 dB per decade beyond the 3 dB bandwidth in contrast to the -40 dB per decade slope of laser response, an HBLET could potentially be deployed at data rates much higher than 4.3 Gb/s. Together with the advantages of higher yield, reduced complexity, and three-terminal high-speed modulation capabilities as both a transistor (amplifier and switch) and electrical-to-optical converter, the HBLET could be an attractive solution for short range optical data communications. Its fast spontaneous recombination lifetime is advantageous for development of high-speed semiconductor lasers and for integrated optoelectronics.

2.2. Lateral Scaling Toward GHz Operation

In this work, the devices are fabricated employing standard etching and contact metallization steps, and the emitter aperture widths of 5 µm, 8 µm, and 13 µm are achieved by lateral oxidation of the \( n-Al_{0.98}Ga_{0.02}As \) layer.

The collector I-V characteristics for HBLETs with aperture widths of 5 and 13 µm and a tilted top view SEM micrograph of the HBLET are shown in Fig. 2.5. Figure 2.6 shows the corresponding optical light output characteristic \( L-I_B \) as measured from the bottom-side of the devices. At comparable base currents \( I_B \), the device with a 5 µm aperture achieves 2.4 times higher current gain than the 13 µm device. The 13 µm HBLET, however, produces an optical output 2.4 times higher. The current gain, \( \beta \), and optical output saturate at high bias conditions \( (V_{CE} \geq 2 \text{ V}) \) due to excessive heating as the devices are on semi-insulating substrate and operated without any temperature control. While total recombination radiation increases for the larger device, only a fraction of the radiative recombination occurs within the intrinsic transistor base region. Due to the
ring-like geometry (inset of Fig. 2.5) employed in the present work, the proper intrinsic transistor base spans a concentric region with a radius proportional to $D_A/2$, and an intrinsic device width (active edge) denoted by, say, $t$. Hence, the proportion of intrinsic base recombination to the total (extrinsic and intrinsic) recombination is roughly inversely proportional to the aperture width $D_A$, and hence, scales by the simple ratio, $\approx \frac{\pi D_A t}{\pi (D_A/2)^2} = \frac{4t}{D_A}$. As the device aperture size, $D_A$, is reduced, an increasingly large proportion of the injected carriers are confined to the intrinsic transistor base region (i.e., higher $4t/D_A$), resulting in higher current densities and enhanced current gains. However, with a larger lateral geometry (i.e., larger $D_A$ and, hence lower $4t/D_A$), the carrier contribution to extrinsic base (radiative and non-radiative) recombination increases, resulting in a lower $\beta$ and commensurately higher light output. A typical optical spectrum of the devices (inset of Fig. 2.6) shows a FWHM of 76 nm and demonstrates that the device is operating in spontaneous recombination. The light extraction of a single escape cone from the GaAs-air surface is highly inefficient. Assuming Fresnel reflection losses for normal incidence, the extraction efficiency is estimated to be 1.4%.\textsuperscript{15}

In Fig. 2.7 the HBLET is conveniently operated in the common-collector configuration with rf-input applied at the EC-port with $V_{BC} = 0$ V. Although in this configuration the device does not provide a simultaneous output electrical gain, the EC-input impedance, $Z_{EC}$, is well matched to the source impedance (50 $\Omega$ standard) for maximal power transfer. In the present work the optical response is measured with a 12 GHz $p-i-n$ photodetector and a 50-GHz electrical spectrum analyzer. A frequency sweep generator up to 20 GHz is used for the input signal to the device. Figure 2.7 shows the
maximum bandwidth optical response of 4.3, 2.8, and 1.8 GHz achieved by HBLETs of aperture size $D_A = 5, 8, \text{ and } 13 \mu m$, respectively. Higher bandwidths are attained with HBLETs employing a smaller aperture because a larger proportion of radiative recombination is confined to the intrinsic base of the HBLET where the intrinsic recombination speed of the carriers is faster, consistent with the observations derived from the collector I-V characteristics (Fig. 2.5) and optical L-1$_B$ (Fig. 2.6). The plot of the optical bandwidth vs. the bias base current 1$_B$ for HBLETs of various aperture sizes (Fig. 2.8) shows the increase in the optical bandwidth as the bias current (1$_B$ and hence, 1$_E$) is increased. The maximum bandwidth is achieved where the optical and electrical characteristics begin to saturate due to heating, as is evident from Figs. 2.5 and 2.6.

In the absence of stimulated recombination, we can simply express the optical response as a single-pole transfer function $H(f)$ with $f_{3\text{dB}}$ representing the -3 dB frequency. The value $f_{3\text{dB}}$ is related to an extrinsic base carrier recombination lifetime $\tau_B$ by $f_{3\text{dB}} = 1/(2\pi\tau_B)$. Therefore, an extrinsic $\tau_B$ of 37 ps is inferred from the value $f_{3\text{dB}} = 4.3 \text{ GHz} (D_A = 5 \mu m)$, while a $\tau_B$ of 88 ps is obtained for a 13-µm-aperture device. Lateral extrinsic recombination therefore forms an equivalent parasitic-like RC-charging time that limits the optical bandwidth of the device. Therefore, by lateral scaling, we can improve the device’s performance by “channeling” (via high current densities) and “limiting” (via smaller apertures) the carriers to feed only radiative recombination originating or emanating from the intrinsic transistor base. Due to the presence of a finite (parasitic) lateral edge in the device construction, the $\tau_B$ obtained of 37 ps is still dominated or limited extrinsically. This shows that the intrinsic transistor base
recombination lifetime can be much faster than 37 ps, and implies that an even higher spontaneous optical bandwidth is possible.

To compare the performance of light emitters of LEDs\textsuperscript{6,17,18} and LETs of this work, the optical bandwidth and the corresponding recombination lifetime are plotted as a function of the average volume current density, $J/d$ (A cm\textsuperscript{-3}), in Fig. 2.9. $J$ is the average recombination current density defined as $J = I_B/(\pi D_A^2/4)$ and $d$ is the thickness of the active region (i.e., the base region for an LET, and the active layer for a double heterostructure LED). The bimolecular recombination lifetime and the optical bandwidth of heavily doped double heterostructure LEDs under low level injection are generally found to be consistent with those predicted by the relation, $\tau_B = 1/(B_{\text{rad}}N_A)$, where $B_{\text{rad}} \sim 1.4 \times 10^{-10} \text{ cm}^3/\text{s}$ is the bimolecular recombination constant. A double heterojunction LED does not readily demonstrate sub-100 ps recombination speeds because it is a “charge pile-up” device, and hence extreme doping and (injected) minority carrier densities are required to achieve high recombination rates (and modulation speeds). Moreover, a heavily-doped active region ($N_A \sim 10^{20} \text{ cm}^{-3}$) results in low internal quantum efficiency due to impurity and defect recombination.

Concluding, we have demonstrated the lateral scaling of the heterojunction bipolar light-emitting transistor to improve both its electrical and optical characteristics. The fast recombination dynamics of the intrinsic transistor can be harnessed by scaling down the emitter aperture from 13 to 5 µm to reduce lateral extrinsic parasitic-like RC charging. We have thus shown that an overall extrinsic recombination lifetime of 37 ps ($f_{3\text{dB}} = 4.3$ GHz) can be achieved. Even higher bandwidths are possible by the further reduction of undesirable parasitic regions and charging time. The fast spontaneous modulation speeds,
together with the high yield and reliability due to ease of fabrication and threshold-less operation of the LET, offers an attractive alternative to laser sources, especially for use in short range optical data communications and interconnections.
2.3. Figures

Fig. 2.1 (a) Schematic device cross section, and (b) top view layout of the common-collector HBLET employed for this work.

Fig. 2.2 (a) Collector I-V characteristics, and (b) optical L-V and spectral characteristics (inset) of the HBLET of this work.
Fig. 2.3 Optical response of the common-collector HBLET to (a) EC rf-input, and (b) BC rf-input.

![Optical response graph](image)

Fig. 2.4 The 3 dB bandwidth $f_{3\text{ dB}}$ as recombination base current $I_B$ is increased while maintaining $V_{BC} = 0$ V, and (inset) typical optical output $L-I_B$ characteristic as measured from the device bottom.

![EC-modulation graph](image)
Fig. 2.5 HBLET collector I-V characteristics corresponding to emitter aperture sizes (a) $D_A=5 \, \mu m$ and (b) $D_A=13 \, \mu m$, and the scanning electron micrograph (SEM) of a $D_A=5 \, \mu m$ HBLET (inset).

Fig. 2.6 HBLET optical light output L-I$_B$ characteristics (device of Fig. 2.5) for $V_{BC} = 0$ V as measured from the bottom, and the optical spectrum (inset).
Fig. 2.7  The maximum optical response achieved by common-collector HBLETs with emitter aperture sizes $D_A = 5$, 8, and 13 $\mu$m.

Fig. 2.8  The dependence of HBLET optical bandwidth on aperture size and bias base current $I_B$ for $V_{BC} = 0$ V.
Fig. 2.9  Comparison of the optical bandwidth and corresponding effective recombination lifetime of the LETs of this work and the high-speed LEDs of Refs. 6, 17, and 18. The calculated LED bandwidth of 1.6 GHz and lifetime of 100 ps is based on the relation $\tau_B = 1/B_{rad}N_A$ and $N_A = 7 \times 10^{19} \text{ cm}^{-3}$. 
3. DESIGN OF MULTI-GHZ TILTED-CHARGE LIGHT-EMITTING DIODES

3.1. Theory and Characterization of Tilted-Charge LED

In the present work, we show how the action of the collector in a transistor may be extended and incorporated into the design of a carrier drain in light-emitting diodes (LEDs) to enable GHz bandwidth operation. We demonstrate a different form of light-emitting diode, an asymmetrical two-junction tilted-charge LED, utilizing an n-type “drain” layer beneath the p-type “base” quantum-well (carrier and photon) active region capable of modulation at a -3 dB bandwidth up to 7 GHz and an effective \( \tau_B \) of 23 ps.

In an n-p-n (and similarly p-n-p) transistor, the electrical base-collector (BC) junction in reverse bias establishes a zero base population density at the boundary of the base and the collector. Because minority carriers are injected and transported from the emitter (E), the boundary condition at the collector-“drain” end results in a tilted base charge population with charge flow of carriers from top to bottom of the QW base active region (Fig. 3.1). This follows from current continuity. The injected minority carriers that recombine in the base form the base current, \( I_B \), while carriers that are too “slow” to recombine within the transit time from the emitter to the collector-“drain”, \( \tau_t \), are removed by the base to drain junction reverse bias field (the “drain” current, \( I_D \), Fig. 3.1). Therefore, the charge population in the base of the transistor can be modulated at intrinsic (parasitic-free) speeds corresponding to an effective recombination lifetime \( \tau_B \sim \tau_t \).

Assuming a tilted triangular population, we approximate \( \tau_t \) as \( W_B^2/2D \) where \( W_B \) (Fig. 3.1) is the base width, or emitter-to-“drain” distance, and \( D \) is the diffusion constant. For a thin-base transistor where \( W_B \sim 1000 \text{ Å} \), \( \tau_t \) is typically on the order of several picoseconds. Taking into account the presence of parasitics due to finite non-zero
junction capacitances and ohmic losses, we expect $\tau_B$ in the sub-100 ps range. The possibility of “fast” picosecond recombination dynamics (induced with a tilted-charge base population) provides the basis for gigahertz modulation of the light-emitting transistor, and now, in the present work, the light-emitting diode.

The epitaxial layers of the crystal used for the asymmetric two-junction tilted-charge light-emitting diode consist, upward from the substrate, a 3000 Å $n$-type doped GaAs buffer layer, a 500 Å graded Al$_{0.30}$Ga$_{0.70}$As confining layer, a 213 Å graded Al$_{0.30}$Ga$_{0.70}$As to Al$_{0.90}$Ga$_{0.10}$As oxide buffer layer, a 595 Å $n$-type Al$_{0.98}$Ga$_{0.02}$As oxidizable aperture layer and another 213 Å graded Al$_{0.90}$Ga$_{0.10}$As to Al$_{0.30}$Ga$_{0.70}$As oxide buffer layer. A 557 Å $n$-type GaAs contact layer, a 120 Å InGaP etch stop layer, and a 2871 Å undoped “drain” layer are grown on top. The “drain” layer is just beneath the 1358 Å base layer, which includes two undoped 112 Å InGaAs quantum wells and an Al$_{0.05}$Ga$_{0.95}$As layer with average doping of $3 \times 10^{19}$ cm$^{-3}$. The heterostructure emitter consists of a 511 Å $n$-type In$_{0.49}$Ga$_{0.51}$P layer, a 213 Å graded Al$_{0.30}$Ga$_{0.70}$As to Al$_{0.90}$Ga$_{0.10}$As oxide buffer layer, a 595 Å $n$-type Al$_{0.98}$Ga$_{0.02}$As oxidizable aperture layer, another 213 Å graded Al$_{0.90}$Ga$_{0.10}$As to Al$_{0.30}$Ga$_{0.70}$As oxide buffer layer, and a 500 Å graded Al$_{0.30}$Ga$_{0.70}$As confining layer. The structure is completed with a 2000 Å GaAs top contact layer.

The asymmetric two-junction tilted-charge LED is fabricated by first performing wet etching steps to form emitter and base-“drain” mesas, followed by an isolation etch from the sub-“drain” layer to the substrate. Metallization steps are then performed to provide the required electrical contacts. For this work we do not employ any optical coatings. A diagram of the device in cross section is shown in Fig. 3.1. The completed LED has only
two terminals: (a) a contact to the emitter layer, and (b) another across the base and “drain” layers. The base-“drain” forms a p-n junction with a reverse built-in field that is maintained by a common potential (zero potential difference) obtained via a common contact metallization extending to the base (Fig. 3.1). The zero base-“drain” potential difference ensures that there is no base charge population density at the base-“drain” boundary, hence establishing a dynamic “tilted” emitter-to-“drain” population in the base.\textsuperscript{16} The “drain” layer performs therefore a role similar to the collector in a three-terminal HBLET. It allows excess minority carriers to be removed from the base ($I_D$), “swept” from base to “drain” by the built-in field at the base-“drain” p-n junction. Base carriers in transit from the emitter to the “drain” that do not recombine within the base transit time are removed, or “drained.” This enables fast modulation of the tilted-charge LED by preventing the build-up of “slow” charge in the base. The tilted-charge LED possesses the high-speed optical modulation characteristics of an HBLET.

The tilted-charge LED can be biased as a usual two-terminal device, simply operating faster. Externally the tilted-charge LED displays an electrical $I$-$V$ characteristic resembling that of a p-n junction diode (Fig. 3.2). The “turn-on” voltage is determined by the emitter-base potential difference since the base and “drain” are metalized and unified in potential. A scanning electron micrograph (top-view) of the completed tilted-charge LED is shown in the inset of Fig. 3.2. The $L$-$I_E$ optical output characteristic shown in Fig. 3.3 is obtained from the bottom emission (through the substrate) of the device. The broad radiative emission spectrum (FWHM ~ 96 nm) of the inset shows that the LED is operating in spontaneous recombination. The spectral peak occurs at $\lambda = 1000$ nm, corresponding to the ground state transition ($1.24$ eV) of the InGaAs quantum-
wells. The optical output saturates with $I_E$ beyond 10 mA as the internal “transistor” gain, $\beta = I_D/I_B$, increases resulting in the base (recombination) current, $I_B = I_E / (\beta+1)$ saturating. The measured optical output efficiency of the C-doped tilted-charge LED can be obtained readily from Fig. 3.3. The optical output is in the low microwatt range because the light extraction efficiency, assuming a single escape cone from the semiconductor GaAs-air interface, is only about $1.4\%$.\textsuperscript{15} The measured efficiency decreases from 1.03 $\mu$W/mA at the peak of the light output ($I_E = 20$ mA) to 0.23 $\mu$W/mA at 60 mA; however, the -3 dB bandwidth improves significantly from 1.2 to 7 GHz (Fig. 3.4). Considering the low light extraction efficiency of 1.4%, the “internal” optical efficiency is, actually, much higher. These diodes in future work can obviously be improved with reflecting coatings or by incorporating resonant cavities in the heterostructure crystal.\textsuperscript{5} Compared to the conventional C-doped LED with efficiency of 0.4 $\mu$W/mA and bandwidth of 1 GHz,\textsuperscript{17} the tilted-charge LED maintains a reasonable efficiency but has a considerably higher modulation speed owing to its capability to remove slowly-recombining excess carriers from the active region, allowing only “fast” recombination as a consequence of a drain layer beneath the quantum-well active layer.

In the present work, the optical output is obtained conveniently from the device top with a fiber, and is measured with a 12 GHz $p$-$i$-$n$ photodetector connected to an Agilent N5230A network analyzer. The optical response of the tilted-charge LED for $I_E = 40, 50,$ and 60 mA is shown in Fig. 3.4. The data show an excellent fit to a single-pole response of the form, $H(f) = A_o/(1+jf/f_{3\,dB})$ where $f_{3\,dB} = 1/(2\pi\tau_B)$. We obtain a -3 dB bandwidth, $f_{3\,dB}$, of 7 GHz at $I_E = 60$ mA, corresponding to an effective $\tau_B = 23$ ps.
Concluding, we have fabricated and demonstrated a different form of light-emitting diode, the tilted-charge LED, which is capable of multi-GHz modulation bandwidth. We show that the idea and role of a collector in a light-emitting transistor or triode can be adapted in the form of a “drain” layer in an LED to improve its speed. The tilted-charge LED, a two-terminal device, has, for some purposes, the advantage of using less crystal area, is simpler to fabricate at high yield, and is easy to package and use. The potential of multi-Gigabit spontaneous operation at low current level (no laser threshold) makes the tilted-charge LED attractive for use in short range optical data communication.

3.2. 4 GHz 2x2 Integrated LED Array

In the present work, we show that the tilted-charge LED can be operated in an array configuration without loss of speed and at much higher (multi-fold) output level.

To achieve maximum optical output power, the effective optical active (light-emitting) area can be increased by operating many LEDs in parallel as an integrated array. A parallel array structure is a simple solution to overcome current crowding as the optically active area is increased\(^{19}\) without loss of speed of an individual element, a single diode. The fabrication process of a tilted-charge LED consists of first performing the wet etching steps to form the emitter and base-drain mesas, followed by an isolation etch down to the semi-insulating substrate. The emitter and base-drain contacts are then deposited by standard lithography and metallization. Finally planarization, a via hole etch, and pad metallization are performed to complete the fabrication process. No optical coating and resonant cavity are employed in this work. The schematic of the completed
device cross section is shown in Fig. 3.5, which also shows the main device layers and the base-drain internal shorting.

Scanning electron micrographs (top view) of a tilted-charge single and a four-LED array are shown in Fig. 3.6. The emitter mesa diameter of the single LED is 10 µm, while the four-LED array consists four separate (electrically-isolated) single LEDs biased by a common electrical input, $I_E$. The distance between two adjacent LEDs is 30 µm. The purpose of the array design is to be able to combine the optical power with no loss of the modulation bandwidth of a single element, which is determined by the separate emitter top geometry, not the array common bottom geometry.

Figure 3.7 shows the optical power output ($L$) measured from the bottom of the devices with a large area detector versus bias current ($I_E$) for (a) a single LED and for (b) a four-LED array. The maximum optical output of the four-LED array and its corresponding bias current is about 3.3 times higher than that of the single LED. The current distribution is not fully uniform (3.3x signal vs. 4x) because of heating, especially at higher bias currents. Assuming a single escape cone from the semiconductor GaAs-air interface, we estimate a light extraction efficiency of 1.4%. Hence, the total light output of the LED is estimated to be 2.3 mW. As $I_E$ is increased beyond 10 mA for the single LED, the optical output starts to saturate as a consequence of the increasing internal transistor gain, $\beta = I_D/I_B$, which results in the base (recombination) current, $I_B = I_E / (\beta+1)$, remaining unchanged. The same observation applies to the array but at higher saturation current.

Figure 3.8 shows the electrical I-V characteristics of the tilted-charge LED. Because the base and drain layers are now held at equal potential, the turn-on voltage is the
emitter-base potential difference. The four-LED array has a lower “turn-on” voltage and lower resistance due to parallel operation of the multiple LEDs. The measured resistances of (a) the single and (b) the array LEDs at the point where the optical output starts to saturate are: (a) 6.7 Ω ($I_E = 30$ mA) and (b) 2.8 Ω ($I_E = 100$ mA), respectively.

The lower input impedance as a function of frequency is shown in the inset of Fig. 3.8, where the DC bias current $I_E$ is 100 mA for the four-LED array, and 30 mA for the single LED. The input impedance of the four-LED array is one third that of the single LED, which is poorer impedance-match (to 50 Ω) for rf modulation.

The optical response of the device is obtained from the aperture top emission via fiber coupling to a 12 GHz $p$-$i$-$n$ photodetector. The optical response of the tilted-charge single and four-LED array, and the corresponding curves fitted to a single-pole response, are shown in Fig. 3.9. The data show an excellent fit to the form, $H(f) = A_o/(1+jf/f_{3 \, dB})$.

Both the single LED and four-LED array, though less impedance-matched, show a -3 dB bandwidth, $f_{3\,db}$, of 4.3 GHz at similar $I_E$ current density. The 4.3 GHz modulation bandwidth of the four-LED array indicates that the array design indeed provides higher optical output with no loss in the modulation bandwidth.

Concluding, we have successfully integrated four tilted-charge LEDs into an array, and demonstrated more than a three times increase in the combined total optical output. The LED array can be modulated with a -3 dB bandwidth of 4.3 GHz, thus maintaining the highest performance of the individual components. At the expense only of occupying more chip space, an LED array offers a simple viable solution to increasing the intensity of the device optical output while preserving the high-speed performance of the individual components.
3.3. Figures

Fig. 3.1  Cross section (diagram) of a tilted-charge light-emitting diode (LED) with a p-type “base” quantum-well active region.

Fig. 3.2  The I-V characteristic of the tilted-charge LED (Fig. 3.1) and a device SEM picture (inset).
Fig. 3.3 Tilted-charge LED optical light output L-I characteristic measured from the device (Fig. 3.2) substrate bottom, and the output optical spectrum (inset).

Fig. 3.4 The optical output response of the tilted-charge LED (Fig. 3.2) at bias currents $I_E = 40, 50$, and $60$ mA showing the -3 dB frequency $f_{3dB}$ of $3.2$, $5$, and $7$ GHz, respectively.
Fig. 3.5  Schematic cross section of a tilted-charge light-emitting diode.

Fig. 3.6  Scanning electron micrograph (SEM) top view of (a) a single and (b) a four-LED array of the form of Fig. 3.5.
Fig. 3.7 (a) Tilted-charge single and (b) four-LED array optical light output L-I characteristics measured from the device bottom.

Fig. 3.8 The I-V characteristics of (a) tilted-charge single and (b) a four-LED array. The inset shows the device, (a) and (b), input impedance as a function of frequency.
Fig. 3.9 The optical response of (a) the single LED of Fig. 3.5 biased at $I_E = 30 \, \text{mA}$, and (b) the four-LED array biased at $I_E = 100 \, \text{mA}$. The -3 dB frequency response of both is $f_{3\,\text{dB}} = 4.3 \, \text{GHz}$. 
4. MICROCAVITY QUANTUM-WELL VERTICAL CAVITY SURFACE-EMITTING LASERS

4.1. Microwave Characterization of Purcell Enhancement

Microcavity light-emitting devices are of interest in the pursuit of threshold-free light-emitting diodes (LEDs or lasers) for optical communications at high modulation speeds. Purcell proposed (1946) that the upper-state, lower-state spontaneous transition rate of a “light”-emitting system could be enhanced (here electron-hole [e-h] spontaneous recombination rate) in a small volume microcavity with a high Q. The spontaneous e-h recombination lifetime reduction is usually observed by time-resolved (optical input-output) photoluminescence (PL) or phase-resolved spectroscopy experiments, with auxiliary spectral emission data revealing the reduction in optical modes and the narrower emission bandwidth of the cavity modes. This has been reported for various photopumped semiconductor systems employing quantum-dots (QDs) and micro-disks. In the present work we describe a more powerful microwave method, electrical input and optical output, a distinct advantage in signal separation, to probe directly and analyze in detail the microcavity resonance effects of a QW vertical cavity surface-emitting laser (VCSEL). We measure a Purcell enhancement factor of 2.08 times, in agreement with earlier more limited spectral emission data.

The devices employed in the present study are p-i-n diode VCSELs. The bottom mirror consists of 34 periods of n-doped Al$_{0.12}$Ga$_{0.88}$As/Al$_{0.9}$Ga$_{0.1}$As Bragg reflectors (DBR), followed by the active region consisting of three GaAs quantum wells embedded in an undoped Al$_{0.3}$Ga$_{0.7}$As separate confinement heterostructure (SCH) layer. The now standard buried optical- and population-defining oxide aperture layer consists of 300 Å Al$_{0.98}$Ga$_{0.12}$As, followed by a 22 period DBR of carbon-doped Al$_{0.12}$Ga$_{0.88}$As/Al$_{0.9}$Ga$_{0.1}$As
forming a vertical longitudinal cavity. The microcavity VCSELs are fabricated by first masking and forming the mesa with inductively coupled plasma dry etching. The oxide apertures are then formed as usual by wet oxidation and accurate calibration and close monitoring of the oxidation time. Dummy samples are used to calibrate the oxidation rate and aperture depth before every process. Aperture diameters are determined by taking scanning-electron micrographs (SEM) of dummy-sample cross-section. Standard metallization of p-contacts and n-contacts are then performed, followed by wafer planarization, via-hole etching, and pad metallizations to complete the devices.

In Fig. 4.1 the emission spectra are shown for VCSELs with two aperture sizes, \( d_A = 7 \) and 3 \( \mu \)m, operating in the sub-threshold (spontaneous) regime. The number of transverse optical modes is reduced from approximately ten for a 7 \( \mu \)m aperture (\( I = 600 \) \( \mu \)A) to one dominant fundamental mode with two weak higher order side-modes for a VCSEL with an aperture \( d_A = 3 \) \( \mu \)m operating below threshold at current \( I = 150 \) \( \mu \)A. The separation between the optical modes of the lowest and second lowest order of the VCSELs is 1.45 nm for aperture \( d_A = 3 \) \( \mu \)m, and 0.22 nm for \( d_A = 7 \) \( \mu \)m. By approximating the VCSEL structure (Fig. 4.1) as a circular waveguide, we can write the dispersion relation as \( k_z^2 = \frac{\omega^2 \mu e}{c} - \left( \frac{2 \xi_{mn}}{d_o} \right)^2 \), where \( k_z \) is the wave vector normal to the device plane, \( d_o \) is the modal diameter, and \( \xi_{mn} \) is the \( n \)th root of the \( m \)th order Bessel function. For the two lowest Bessel function roots, \( \xi_{01} = 2.4 \) and \( \xi_{11} = 3.8 \), the modal diameter, \( d_o \), is estimated as 4.2 \( \mu \)m for \( d_A = 3 \) \( \mu \)m, and 10.7 \( \mu \)m for \( d_A = 7 \) \( \mu \)m. The spontaneous spectrum of the 3 \( \mu \)m VCSEL at 90 \( \mu \)A exhibits an optical mode FWHM bandwidth \( \Delta \lambda_{cav} \) of 0.15 nm, giving a cavity \( Q = \frac{\lambda}{\Delta \lambda_{cav}} = 5700 \). The reduction in the threshold current \( I_{TH} \) is consistent with the reduction in device volume as the aperture size
is decreased. A plot of $I_{TH}$ vs. aperture area, $\pi d^2/4$ (Fig. 4.2), yields (consistently) a threshold current density $J_{TH} = 2$ kA/cm$^2$, showing that as the aperture size is decreased the non-radiative recombination remains fixed, and does not affect the effective spontaneous lifetime.

Spectral emission data allow us to estimate the Purcell enhancement factor $F_P$ as:

$$F_P = \frac{\tau_{bulk}}{\tau_{cavity}} = \frac{3Q}{4\pi^2 V_{eff}} \left( \frac{\lambda}{n_{index}} \right)^3,$$  \hspace{1cm} (4.1)

where $\tau_{bulk}$ is the bulk spontaneous radiative lifetime, $\tau_{cavity}$ is the cavity-enhanced spontaneous lifetime, $V_{eff}$ is the effective modal volume, and $n_{index}$ is the effective index of refraction. For the 3-μm-aperture $\lambda$-thickness cavity VCSEL, $V_{eff} = \pi (d_o/2)^2 (\lambda/n_{index})$, $n_{index}(\text{AlGaAs}) = 3$, and the Purcell factor is 2.53.

In addition to the enhancement in the spontaneous lifetime, microcavity resonators result in enhancement of the spontaneous emission factor, $\gamma$, which provides a measure of the fraction of the total spontaneous radiative emission power in the fundamental cavity mode. This offers another approach to estimate the Purcell factor. If we assume that the spontaneous radiation is uniform across the optical modes, the spontaneous emission factor can be estimated as one half the inverse of the number of modes in the spectrum,

$$\gamma = \frac{1}{2} \times \left( \text{number of modes in emission spectrum} \right)^{-1}.$$  \hspace{1cm} (4.2)

Since there are approximately three modes in the emission spectrum of the 3-μm device, $\gamma(3\mu)$ is estimated to be 16.7%. A more elaborate expression for the spontaneous emission factor is given by:

$$\gamma = \frac{1}{2} \times \left( \text{number of modes in emission spectrum} \right)^{-1}.$$
\( \gamma = \varepsilon \frac{\Gamma \lambda^4}{4\pi^2 n_{\text{index}}^3 V_{\text{active}} \Delta \lambda_s}, \)  
(4.3)

where \( \Delta \lambda_s \) is the FWHM bandwidth emission spectrum, \( V_{\text{active}} \) is the volume of the active medium, \( \varepsilon \) is a numerical factor related to the dipole orientation and the relative location of the active region in the cavity, and \( \Gamma \approx V_{\text{active}}/V_{\text{eff}} \) is the optical confinement factor. Because \( Q = \lambda/\Delta \lambda_{\text{cav}} \), we can go further in deriving the Purcell factor from the spontaneous emission factor and obtain

\[ \gamma \approx \frac{\varepsilon}{3} \frac{\Delta \lambda_{\text{cav}}}{\Delta \lambda_s} \frac{3\lambda^3 Q}{4\pi^2 n_{\text{index}}^3 V_{\text{eff}}} = \frac{\varepsilon}{3} \frac{\Delta \lambda_{\text{cav}}}{\Delta \lambda_s} F_p. \]  
(4.4)

Assuming that the QW active area is located near the peak of the fundamental cavity mode, we obtain for \( \varepsilon \) the magnitude \( \varepsilon \sim 3 \). For \( \Delta \lambda_s = 1.7 \text{ nm}, \Delta \lambda_{\text{cav}} = 0.15 \text{ nm}, \) and \( \gamma = 16.7\% \), an estimate for the Purcell factor is \( F_p \approx 3 \Delta \lambda_s/\Delta \lambda_{\text{cav}} \cdot \gamma/\varepsilon \approx 1.89 \). These values are used here merely as reference estimated values.

We show next that the microwave electrical-optical response of the microcavity VCSELs is in accord with the above calculations for the Purcell factor but has a basis to yield a more accurate measurement. The optical response, \( S_{21} \), and the electrical \( S_{11} \)-parameter of the 3-\( \mu \)m aperture and 7-\( \mu \)m VCSELs (Fig. 4.3) are measured instantaneously at each of the microwave frequencies from 0.1 GHz to 20 GHz using a two-port parametric network analyzer (PNA) set at various biases from below to beyond laser threshold. A sample of the microwave response is shown in Fig. 4.3. The bandwidth of the optical response above threshold is determined by both the photon density, \( N_{\text{ph}} \), and spontaneous recombination lifetime, \( \tau_{\text{spon}} \). While \( N_{\text{ph}} \) determines the bandwidth of the response, \( \tau_{\text{spon}} \) is responsible for “damping” out the relaxation
oscillations. Therefore, the spontaneous recombination lifetime of the VCSEL in full laser operation can be obtained by fitting the response to a model based on the coupled carrier-photon rate equations, written as

\[ \frac{dN}{dt} = I - \frac{N}{\tau_{Bson}} - \gamma N \frac{g}{\tau_{ph}}, \]  

(4.5)

and

\[ \frac{dN_{ph}}{dt} = \gamma g N_{ph} - \frac{N_{ph}}{\tau_{ph}} + \frac{N}{\tau_{Bson}}, \]  

(4.6)

where \( N \) is the population inversion number, \( \nu \) is the photon group velocity, and \( g \) is the QW gain. The intrinsic device parameters are determined by first extracting the pad parasitics (pad resistance, capacitance, and inductance) from two-port microwave measurements of the electrical SHORT, OPEN and THRU structures fabricated on the same wafer. The parasitics, together with the intrinsic VCSEL model, are shown in Fig. 4.3c. In Fig. 4.3 the 3-\( \mu \)m device measured microwave responses of (a) \( f_{3\text{dB}} = 10.8 \) GHz at \( I = 1.0 \) mA and (b) \( f_{3\text{dB}} = 7.9 \) GHz at 0.5 mA are fitted to the model. The intrinsic parameters that produce an excellent fit to the measured laser optical response corresponding to the \( L-I \) and \( I-V \) characteristics of the 3-\( \mu \)m VCSEL (Figs. 4.1 and 4.2) are: \( \tau_{ph(3)} = 3.7 \) ps, \( \tau_{Bson(3)} = 0.51 \) ns, \( \gamma(3) = 12\% \), \( g_{TH(3)} = 30 \) per cm, and \( \nu = 1 \times 10^8 \) m/s.

For the 7-\( \mu \)m VCSEL, the intrinsic parameters are: \( \tau_{ph(7)} = 6.3 \) ps, \( \tau_{Bson(7)} = 1.06 \) ns, \( \gamma(7) = 4\% \), and \( g_{TH(7)} = 18 \) per cm. The faster \( \tau_{Bson} \) of the 3-\( \mu \)m VCSEL and the larger \( \gamma \) result in “damped” resonance peaks of lesser magnitude. The spontaneous emission factors are also in close agreement with the values obtained from Eq. 4.2. The extracted values of \( \tau_{cavity} \approx \tau_{Bson(3)} \) and \( \tau_{bulk} \approx \tau_{Bson(7)} \) give a Purcell enhancement of 2.08 times, essentially in
accord with the values estimated using Eqs. 4.1 to 4.4. The bulk spontaneous recombination lifetime, $\tau_{\text{bulk}}$, can be approximated by $\tau_{\text{Bsp}}$ because Purcell enhancement is negligible in the large-aperture, $d_A = 7 \ \mu m$, VCSEL exhibiting a large spontaneous emission bandwidth, $\Delta \lambda_s = 1.7 \ \text{nm}$. The difference between these methods can be explained by the detuning of the cavity mode from the peak of the emission spectrum of the QW active region, possibly due to the non-uniformity in the aperture window resulting from the fabrication oxidation process, and non-uniformity in the distribution of the spectral energy over the optical modes. The Purcell enhancement factor of 2.08 times agrees also with that obtained by direct microwave measurements of $f_{3\text{dB}}$ for the 3-$\mu m$ and 7-$\mu m$ aperture devices operating at equal current densities below threshold as shown in Fig. 4.3. The spontaneous optical bandwidth at -3 dB for the 3 $\mu m$ device, $f_{3\text{dB}(3)} = 0.3 \ \text{GHz} \approx 1/(2\pi \tau_{\text{cavity}})$, is two times higher than for the 7-$\mu m$ device with $f_{3\text{dB}(7)} = 0.15 \ \text{GHz} \approx 1/(2\pi \tau_{\text{bulk}})$, or $F_p = \tau_{\text{bulk}} / \tau_{\text{cavity}} = 2$.

Concluding, we compare in Table 4.1 the Purcell enhancement factors for the microcavity VCSEL obtained using the four methods employed in this work. The microwave measurement method provides a direct RF probe of Purcell enhancement complementing indirect DC methods. The microwave measurement method of this work employs electrical-to-optical conversion, i.e., the advantage of distinct separation of electrical and optical signals, and, besides the high accuracy, a much more convenient method of measurement than photoluminescence decay experiments employing overlapping input and output optical signals.
4.2. Microwave Determination of Electron-Hole Recombination Dynamics from Spontaneous to Stimulated Emission

In the present work we study, via sensitive microwave measurements, microcavity QW vertical cavity surface-emitting lasers (VCSELs) operating strongly coupled into a small, reduced-spread spectral mode density, into faster recombination yielding a broader laser bandwidth, and damping the resonant peak. The microwave measurements reveal unambiguously the transition in recombination lifetimes from spontaneous to stimulated emission, to cut-off by parasitic elements (junction capacitance, etc.) and ancillary contact circuitry. We show that higher frequency response in the regime below laser threshold can be explained by the influence of the faster components of recombination.

The devices employed in the present study are p-i-n diode VCSELs. The bottom mirror consists of 34 periods of n-doped Al$_{0.12}$Ga$_{0.88}$As/Al$_{0.9}$Ga$_{0.1}$As Bragg reflector layers (DBR), followed by the active region with three GaAs quantum wells embedded in an undoped Al$_{0.3}$Ga$_{0.7}$As separate confinement heterostructure (SCH) layer. The oxide aperture layer$^{25}$ consists of 300 Å of Al$_{0.98}$Ga$_{0.02}$As, followed by a 22-period DBR of carbon-doped Al$_{0.12}$Ga$_{0.88}$As/Al$_{0.9}$Ga$_{0.1}$As forming a short vertical longitudinal cavity. The microcavity VCSELs are fabricated by first masking and forming diode mesas with inductively coupled plasma dry etching. The oxide apertures are then formed as usual by wet oxidation$^{25}$ and careful calibration and monitoring of the oxidation time. Standard metallization of p-contacts and n-contacts is then performed, followed by wafer planarization, via-hole etching, and pad metallization to complete the devices.

In Fig. 4.4 the optical emission spectra are shown for VCSELs with aperture size $d_A = 3 \, \mu$m operating in the sub-threshold (spontaneous) region, stimulated, and above
threshold \((I_{th} = 0.18 \text{ mA})\) as a laser. There is a dominant fundamental mode (labeled (a)) with two much weaker higher order side-modes below and above threshold (labeled (b)). The diode spontaneous recombination spectrum at 0.09 mA exhibits an optical mode FWHM bandwidth, \(\Delta \lambda_{cav}\), of 0.15 nm, giving a cavity \(Q = \lambda/\Delta \lambda_{cav} = 5700\). For laser operation at bias current \(I > 0.25 \text{ mA}\), the linewidth narrows to an apparent \(Q > 30,000\). The 3 \(\mu\text{m}\) microcavity VCSEL operates nearly as a single-mode laser with mode spacing \(\sim 1.45\) nm and with the relative intensity of the 2\(^{nd}\) order laser mode 25 dB below the fundamental mode.

The optical output \(L\) vs. \(I\) characteristic and the derivative \(dL/dI\) vs. \(I\) (Fig. 4.5) exhibit a laser threshold, the “kink” in the \(L-I\) characteristic, \(I_{th} = 0.18\) mA. There are three distinct regions of operation: (i) \(I < I_{th}\), spontaneous and amplified spontaneous emissions; (ii) \(I_{th} < I < 0.25\) mA, the transition to stimulated emission and laser oscillation; and (iii) \(I > 0.25\) mA, laser operation at constant \(dL/dI\). The behavior of \(dL/dI\) indicates the differential gain, as well as the transition of device operation mode. The superlinear characteristic of \(L-I\) is due to thermal effect caused by the temperature dependence of gain spectrum and detuning between gain peak and cavity resonance, which is more pronounced in the single-mode VCSEL due to smaller aperture and higher series resistance.

The microwave optical and electrical response of the microcavity VCSEL can be used to identify and resolve in detail the transition from spontaneous to stimulated emission. The optical response, \(S_{21}\), and electrical \(S_{11}\)-parameters of the VCSEL of Fig. 4.4 are measured instantaneously at each frequency from 0.1 GHz to 20 GHz using a two-port parametric network analyzer (PNA) set at various biases from below to beyond laser
threshold. The pad parasitics (pad resistance, capacitance, and inductance) then can be extracted from two-port microwave measurements of the electrical SHORT, OPEN and THRU structures fabricated on the same wafer.\textsuperscript{30} The extracted pad capacitance is 0.3 pF and inductance is 22 pH, while the series and parallel pad resistances are 0.3 and 7 Ω. The intrinsic VCSEL parameters can therefore be de-embedded together with these parasitics to form the device small signal model.\textsuperscript{31} The -3 dB bandwidth of the 850 nm detector is limited to 12 GHz; hence, the frequency response above 12 GHz is limited by the additional pole of the detector. The plot of f_{3dB} vs. J (Fig. 4.6) reveals three regions of operation corresponding to the L-I characteristic of Fig. 4.5.

The increase in the bandwidth in regions (ii) and (iii) of Fig. 4.6 is a result of stimulated emission and laser operation. As diode laser operation is approached, the coherent field becomes self-sustaining, gain is “clamped” to cavity loss, and incremental injected carriers re-supply both stimulated and spontaneous recombination. At this point the bandwidth of the optical response is determined by both the photon density, N_{ph}, and spontaneous recombination lifetime, \( \tau_{Bsp} \).\textsuperscript{16,32,33} While N_{ph} determines the bandwidth of the response, the fast recombination component (\( \tau_{Bsp} = \tau_{fast} \)) is responsible for “damping out” the relaxation oscillations, resulting in relatively flat frequency response in region (iii) of Figs. 4.6 and 4.7.

The diode microwave response below threshold in Fig. 4.7(i) is of particular interest. In this region the gain in stimulated emission due to the QW active medium is insufficient to overcome the loss of photons from the cavity. As a result, the coherent field (stimulated emission) will eventually decay at a rate determined by cavity loss, or photon lifetime, \( \tau_{ph} \). At low current densities (\( J < < 2 \text{ kA/cm}^2 \)) where gain is negligible,
the average spontaneous recombination lifetime is given by \(1/(2\pi f_{3\text{dB}}) = 1 \text{ ns} \) or \( f_{3\text{dB}} = 0.15 \text{ GHz} \). As gain is increased (more current) towards threshold, the coherent field exists longer before decaying (not yet self-sustaining) and thus assists in enhancing (reducing) the overall recombination lifetime and increasing the bandwidth \((f_{3\text{dB}})\). In other words, the diode response below threshold is a manifestation of both spontaneous and stimulated emission. The increasing spontaneous bandwidth at lower current densities (i.e. reducing cavity-enhanced spontaneous lifetime, \(\tau_{cavity}\)) can be correlated to the observed spectral narrowing (i.e. reducing \(\Delta \lambda_{cav}\)) from the Purcell enhancement factor \(F_p\) as

\[
F_p = \frac{\tau_{bulk}}{\tau_{cavity}} = \frac{3Q}{4\pi^2 V_{eff}} \left( \frac{\lambda}{n_{index}} \right)^3 \quad (4.7)
\]

where \(\tau_{bulk}\) is the bulk spontaneous radiative lifetime, \(V_{eff}\) is the effective modal volume, \(n_{index}\) is the effective index of refraction, and \(Q = \lambda/\Delta \lambda_{cav}\). As current is increased, more coherent photon \((N_{ph})\) is generated, resulting a narrower \(\Delta \lambda_{cav}\), and larger bandwidth.

To distinguish between diode spontaneous and stimulated-emission response, the optical output signal is “traced” from 0.1 to 20 GHz. Beyond the “corner” frequency \((f_{3\text{dB}})\), the diode stimulated-emission response (orange trace) has a characteristic slope of -40 dB per decade, or more (~ 60 dB per decade), while the spontaneous-emission response (blue) has a characteristic slope of -20 dB per decade (Fig. 4.7(i)). The diode optical signal response at lower frequencies (orange line) exhibits stimulated emission with the modulation amplitude higher and the slope beyond the corner frequency -40 dB per decade or steeper. As the response curve is traced to higher frequencies, the amplitude (lower) shifts (descends) by -20 dB per decade. Spontaneous recombination
emission is then the “faster” mode of recombination and can (at higher frequencies) respond with a larger modulation amplitude (Fig. 4.7(i), \( I = 0.12 \text{ mA} [f > 0.5 \text{ GHz}] \) and \( 0.15 \text{ mA} [f > 1 \text{ GHz}] \)). These data show that microwave response measurements can be employed to distinguish between the various components, slow vs. fast, of carrier recombination.

Spontaneous recombination lifetime is ordinarily expressed as an average parameter, analogous to the half-life of nuclear decay; therefore, as half of the electron-hole population “decays” (recombines) over an average “half-life,” there is a significant carrier population (although a fraction) that decays much faster than the average. It is the “faster” recombination carriers that respond to the higher microwave modulation frequencies. For \( f > 1 \text{ GHz} \), the carriers that can respond to the microwave signal (a significant fraction) possess a recombination “lifetime” as short as \( 1/(2 \pi f) = 159 \text{ ps} \). Microwave response measurements reveal in the overall population the faster components of recombination, particularly in the case of smaller devices of appropriate geometry and boundary conditions (for example, the cavity geometry and form of input-output contact geometry or a tilted charge population as in the light-emitting transistor or transistor laser).

Concluding, we have shown with optical microwave modulation response measurements of the excess carrier lifetime, \( \tau_{av} \) \( \Delta n/\tau_{av} = \Delta n_1/\tau_{fast} + (\Delta n - \Delta n_1)/\tau_{slow}, \) \( \tau_{fast} < \tau_{slow} \), on a low mode density microcavity VCSEL, that the slower \( (\tau_{slow}) \) and faster \( (\tau_{fast}) \) recombination can be separated, making it possible to distinguish unambiguously between spontaneous recombination and stimulated emission, including laser operation. It is clear that the size, geometry, and boundary conditions (optical cavity and current
contacts) of a crystal, e.g., typical of a microcavity laser, determine (reduce) the carrier lifetime (spontaneous or stimulated) and hence determine the optical microwave modulation response.
4.3. Table and Figures

Table 4.1 Comparison of Purcell factors obtained by various methods of this work.

<table>
<thead>
<tr>
<th>Method</th>
<th>Data Employed</th>
<th>Purcell Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Purcell formula</td>
<td>Spectral emission (DC)</td>
<td>2.53</td>
</tr>
<tr>
<td>(ii) Spontaneous emission factor</td>
<td>Spectral emission (DC)</td>
<td>1.89</td>
</tr>
<tr>
<td>(iii) Laser frequency response</td>
<td>Microwave response (RF)</td>
<td>2.08</td>
</tr>
<tr>
<td>(iv) Spontaneous frequency response</td>
<td>Microwave response (RF)</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average : 2.12 ± 11%</td>
</tr>
</tbody>
</table>

Fig. 4.1 Schematic cross section of small-diameter microcavity VCSEL illustrating the lowest order transverse modes (a) and (b). The spontaneous emission spectrum of a small-aperture device ($d_A = 3 \mu m$) is compared with that of a large-aperture device ($d_A = 7 \mu m$). The spontaneous emission bandwidth, $\Delta \lambda_s$, of the 7 \mu m device is 1.7 nm found by fitting a Lorentzian to the spectral emission. Spontaneous emission spectrum of the 3-\mu m-aperture VCSEL at the sub-threshold bias of 90 \mu A is shown fit to a Lorentzian function of width $\Delta \lambda = 0.15$ nm.
Fig. 4.2 Laser threshold, $I_{TH}$, of the VCSELs (of Fig. 4.1) vs. aperture area ($A = \pi d_A^2/4$) for various oxide-defined diameters of $d_A = 3, 6, 7$ and $11 \mu m$.

Fig. 4.3 Measured and calculated laser frequency response of the microcavity VCSELs of Figs. 4.1 and 4.2 for device (i) with $d_A = 3 \mu m$ at biases (a) $I = 1.0 \ mA$ ($f_{3dB} = 10.8$ GHz) and (b) $0.5 \ mA$ ($f_{3dB} = 7.9$ GHz), and device (ii) with $d_A = 7 \mu m$ at biases (c) $I = 4.0$ ($f_{3dB} = 9.7$ GHz) and (d) $2.0 \ mA$ ($f_{3dB} = 5.6$ GHz). Also shown are the measured spontaneous optical frequency response (below threshold) $f_{3dB} = 0.3$ GHz ($d_A = 3 \mu m$) and $0.15$ GHz ($d_A = 7 \mu m$), and (iii) the measured and the model of the electrical S-parameters for the device apertures and biases of (a) to (d) with the pad parasitics in series with the intrinsic laser. The series resistances are $R_{s(3)} = 370 \ \Omega$ and $R_{s(7)} = 88 \ \Omega$. 

\[ \text{Microcavity MQW VCSEL, } 25^\circ \text{C} \]
Fig. 4.3 Continued.
Fig. 4.4  (i) Schematic cross section of a microcavity VCSEL illustrating the lowest order transverse modes (a) and (b).  (ii) Spontaneous emission spectrum (experiment) of fundamental mode (a) and second-order mode (b) below laser threshold, \( I < I_{th} = 0.18 \) mA, for cavity diameter \( d_A = 3 \) μm. Laser spectrum for \( I > I_{th} \).
Fig. 4.5 Output light vs. current (L-I) characteristics of the microcavity VCSEL of Fig. 4.4 and derivative, \(dL/dI\) (W/A). The three regions of operation are: (i) \(I < I_{th} = 0.18\) mA, spontaneous and amplified spontaneous emission; (ii) \(I_{th} < I < 0.25\) mA, transition to laser operation, and (iii) \(I > 0.25\) mA, laser operation at constant \(dL/dI\).

Fig. 4.6 Measured optical microwave modulation bandwidth at -3 dB, \(f_{3dB}\) vs. current density, \(J = I/A\), for the VCSEL of Fig. 4.4. The three regions (i), (ii), (iii) correspond to the L-I curve in Fig. 4.5.
Fig. 4.7 Measured optical microwave response of the VCSEL ($d_A = 3 \, \mu m$) of Figs. 4.4 – 4.6 at current: (i) $I = 0.09 - 0.18 \, mA$ ($\Delta I = 0.01 \, mA$), spontaneous and amplified spontaneous recombination; (ii) $I = I_{th} = 0.18$ to 0.25 mA ($\Delta I = 0.01 \, mA$), transition to laser operation; (iii) $I = 0.5 - 1 \, mA$ ($\Delta I = 0.5 \, mA$) laser operation.
5. THE EFFECT OF MICROCAVITY LASER RECOMBINATION LIFETIME ON MICROWAVE BANDWIDTH AND EYE-DIAGRAM SIGNAL INTEGRITY

In the present work we focus on the spectral and microwave behavior of the VCSEL form of microcavity laser. A microcavity provides better confinement of optical fields, i.e., higher Q, and leads to enhancement of the spontaneous emission rate due to the Purcell effect. By employing an oxide-confined cavity to modify the dipole-field coupling and reduce the density of available photon modes, we demonstrate improved microwave performance ($f_{3db}$) and an eight-fold reduction in recombination lifetime ($\tau_{rec}$) owing to carriers occupying primarily a single (fundamental) mode of the microcavity laser. The device with smaller mode volume exhibits much lower threshold current, larger mode spacing and side-mode suppression ratio (SMSR), as well as higher modulation frequency bandwidth and data transmission speed. With single-mode operation and larger SMSR the threshold current of a microcavity laser is less sensitive to change in the ambient temperature because of locked single-mode operation. In other words, “threshold-less” behavior is observed in a higher Q microcavity laser. A microwave method is used to analyze conveniently the reduction in recombination lifetime in a microcavity laser, based on constructing an equivalent small-signal model employing S-parameter measurements. Finally, we compare the quality of data transmission with the change in eye diagrams for single-mode and multimode lasers. The single-mode (microcavity) laser, because of reduced lifetimes (enhanced recombination), exhibits faster and flatter frequency response, thus yielding a “cleaner” eye diagram compared to multimode operation.
5.1 Spectral Mode Spacing and Purcell Effect

A schematic cross section of a completed device is shown in Fig. 5.1. The schematic diagram Fig. 5.1(ii) indicates the possible optical modes introduced inside the microcavity: (a) 1\textsuperscript{st} order (fundamental), (b) 2\textsuperscript{nd} order, and (c) 3\textsuperscript{rd} order mode. The oxide aperture diameter is \(d_A\), and \(d_0\) is the lateral optical mode dimension.

After careful calibration and aperture oxidation, scanning electron microscope (SEM) images of three devices with different aperture sizes \(d_A\) are shown here: D1 (2 \(\mu\)m), D2 (2.5 \(\mu\)m), and D3 (3.5 \(\mu\)m). Figure 5.2 shows the diode laser L-I curves measured from a top fiber and I-V characteristics of three devices. The threshold currents, \(I_{TH}\), for D1, D2, and D3 are 0.13, 0.16, and 0.20 mA, respectively. The lowest threshold current (0.13 mA) is obtained without any specific heat dissipation attempt, e.g., lapping and thinning the substrate. The threshold current density, \(J_{TH}\), is linearly proportional to the aperture areas with the diameters ranging from 7 \(\mu\)m to 3\(\mu\)m; at still smaller diameters, thresholds increase due to excessive heat generation of the larger device resistance. The oxide-confined aperture improves the overlap of electrical and optical gain owing to better confinement of the optical field and the current injection, further defining the lateral optical mode dimension. Together with the vertical DBR mirror, a microcavity laser is readily formed without suffering high input impedance and optical scattering loss using a pillar structure. The merit of the microcavity is in providing a low laser threshold due to “easier” single-mode operation, and finally threshold-less operation.

By adjusting the cavity volume, we can control the optical mode existing in the microcavity QW laser by a classical electrodynamics determination. A smaller cavity allows the electromagnetic wave to exist only in a few modes, say, the fundamental mode
and a couple of higher order modes as shown in Fig. 5.1(ii). For an oxide-confined microcavity VCSEL of aperture size \( d_A > 5 \ \mu m \) the optical mode is approximately circular, but for smaller aperture size \( d_A < 5 \ \mu m \) the optical mode profile will be elliptical-like owing to the sensitivity of the oxidation procedure and crystal anisotropy.

Ideally, from spectral data on different modes, we can extract the lateral modal profile by solving the Helmholtz equation numerically under given boundary condition. For a rough estimate we assume the optical field is confined laterally inside the mode boundary, and approximate the optical mode profile as rectangular with width \( a \) and length \( b \). Since the carrier distribution and optical lateral dimension profile will change at different bias current levels, it is necessary to calculate \( a \), \( b \), and \( L \) for each bias current. By solving the Helmholtz equation

\[
\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} E(x, y) + (k_0^2 \bar{n}^2 - k_z^2) E(x, y) = 0,
\]

we obtain the Eigen-mode solution satisfying the expression for both the transverse electrical and transverse magnetic field,

\[
k_0^2 = \frac{\omega^2}{c^2} = \frac{1}{\bar{n}^2} \left( k_z^2 + \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2 \right).
\]

Here \( k_z = l(\pi/L) \), and \( m, n, l \) are positive integers. The quantity \( k_0(m, n) \) is the propagation constant in vacuum, \( L \) is the upper and lower Bragg reflector spacing in the vertical direction, and \( \bar{n} = 3.3 \) is the effective refractive index inside the aperture.

Figure 5.3 shows the spectral data for the D1 microcavity laser \( (I_{TH} = 0.13 \ mA) \) at different bias currents. The 1\textsuperscript{st} (fundamental) mode is labeled as (a), and the 2\textsuperscript{nd} order mode (b) is 2.45 nm shorter with 32.5 dB suppression at bias current \( I = 0.8 \ mA \). The still higher order mode intensity is too weak to be observed. We denote the wavelength
of each optical mode as follows, 1st (fundamental) mode at $\lambda(1,1)$, 2nd order modes at $\lambda(1,2)$ and $\lambda(2,1)$, and 3rd order modes at $\lambda(2,2)$, $\lambda(1,3)$ and $\lambda(3,1)$. From spectral data we estimate the mode dimensions $a$, $b$, and $L$ using Eqs. (5.3) to (5.5) as

$$k_0^2(2,1) - k_0^2(1,1) = \left[ \frac{2\pi}{\lambda(2,1)} \right]^2 - \left[ \frac{2\pi}{\lambda(1,1)} \right]^2 = \frac{3\pi^2}{\tilde{n}^2 a^2}, \quad (5.3)$$

$$k_0^2(1,2) - k_0^2(1,1) = \left[ \frac{2\pi}{\lambda(1,2)} \right]^2 - \left[ \frac{2\pi}{\lambda(1,1)} \right]^2 = \frac{3\pi^2}{\tilde{n}^2 b^2}, \quad (5.4)$$

$$L = \frac{2\pi}{k_z} = \frac{2\pi}{\sqrt{\left[ \frac{2\pi\tilde{n}}{\lambda(1,1)} \right]^2 - \left( \frac{\pi}{a} \right)^2 - \left( \frac{\pi}{b} \right)^2}}. \quad (5.5)$$

In Table 5.1 we summarize the calculated mode dimensions $a$, $b$, and $L$ for three different aperture sizes at bias current $I = 0.8$ mA. The data show the cavity vertical distance $L$ is more than 10 times smaller than the lateral dimension $a$ and $b$; hence, the fundamental mode wavelength is mainly determined by $L$ as $\lambda(1,1) \approx \tilde{n}L$. The mode dimensions $a$ and $b$ determine the mode spacing $\Delta\lambda$ between the fundamental mode and the 2nd order modes. As shown in Table 5.1, oxide-aperture size reduction decreases the lateral mode dimensions and enlarges the mode spacing $\Delta\lambda$. This shows that optical mode control can be achieved by “tuning” the oxide aperture size as well as by the vertical cavity length.

In order to achieve lower threshold current VCSELs, we design the position of the maximum gain profile aligned with the fundamental cavity modes. For devices with larger mode spacing, $\Delta\lambda$, there are fewer modes within the gain profile; i.e., the fundamental mode will contribute mainly to the increase in optical intensity (photon density). Carrier re-adjustment in the mode acts as a positive feedback mechanism
“tuning” stimulated emission and providing more photon generation in the fundamental mode. With larger mode spacing, the carrier injection is more “efficiently” concentrated in only one mode. This behavior can be observed from the spectral data in Fig. 5.3. The “fast” increase in the fundamental mode results in a larger side-mode suppression ratio (SMSR) between the fundamental (1\textsuperscript{st}) and the higher order (2\textsuperscript{nd}, 3\textsuperscript{rd} ... ) cavity modes. These data explain also why a device with larger mode spacing will have a lower threshold current and steeper SMSR slope below saturation as shown in Fig. 5.4.

Figure 5.4 shows the SMSR between the fundamental mode and 2\textsuperscript{nd} order modes as a function of bias current for three devices. The SMSR can be clearly separated into three regions. For region (I) at bias current I < 0.25 mA, the SMSR increases linearly with current, indicating that the photon density increases superlinearly with bias current. In this region the quality factor Q of the fundamental mode (Q = \frac{\lambda}{\Delta\lambda_{\text{cav}}}) quickly increases from around 5500 to above 30000 as the bias current increases and the lateral modal dimension (a, b) decreases. The data show that for the smallest mode-volume device (D1) most of the injected carriers will be concentrated in the fundamental mode, thus giving a steeper slope. Generally the smaller the aperture, the steeper the SMSR will increase for given bias current increase. For region (II) bias current at 0.25 < I < 0.4 mA, the SMSR reaches its maximum value of ~ 36 dB for D1 (\Delta\lambda = 2.45 nm); ~27.5 dB for D2 (\Delta\lambda = 1.6 nm); and ~19 dB for D3 (\Delta\lambda = 1.0 nm). In this region higher-order modes start to contribute to the intensity due to saturation of the ground state quantum-well gain profile. Succeeding carriers (higher level) will then start to participate both in the ground and 1\textsuperscript{st} excited state transitions, resulting in saturation of the SMSR. For region (III) bias current at I > 0.4 mA, the differential gain of the fundamental mode is lower than on the 2\textsuperscript{nd} order
modes. Hence the carriers will tend to populate, to a larger extent, to higher order modes. As a consequence the intensities of the 2\textsuperscript{nd} order modes are amplified and the SMSR decreases with larger current. The data indicate that a smaller mode spacing device will lead to a faster decay of SMSR with increasing current. This can be explained by the gain competition with more higher-order optical modes, favoring laser operation on higher order modes.

Purcell in 1946 predicted in general that the spontaneous transition rate between the upper state and lower state in a small volume cavity will be enhanced in the case of a high cavity Q.\textsuperscript{20} In the present work, we compare a large area VCSEL with an assumed, large, bulk spontaneous lifetime, $\tau_{\text{bulk}}$, to the case of a microcavity laser with reduced electron-hole spontaneous recombination lifetime, $\tau_{\text{cavity}}$, by a factor $F_P$,

$$F_P = \frac{\tau_{\text{bulk}}}{\tau_{\text{cavity}}} = \frac{3Q}{4\pi^2V_{\text{eff}}} \left( \frac{\lambda}{\tilde{n}} \right)^3.$$ (5.6)

The Purcell formula indicates that below threshold, $F_P$ can be estimated from the effective mode volume $V_{\text{eff}}$, mode wavelength $\lambda$, cavity material index $\tilde{n}$, and cavity $Q = \frac{\lambda}{\Delta \lambda_{\text{cav}}}$. Previous work on the Purcell enhancement factor $F_P$ was extracted from time-resolved photoluminescence or phase resolved spectroscopy experiments.\textsuperscript{21-24} Both methods require optical input-output data, not necessarily making it easy to achieve signal-separation. In contrast, the electrical current driven on microcavity QW laser method, and microwave bandwidth measurement on microcavity QW laser below threshold method, provide excellent isolation via an electrical-input and optical-output to analyze the Purcell effect. In Table 5.2 we summarize the $F_P$ data for three different aperture size devices at bias current $I = 0.1$ mA ($< I_{\text{th}}$). The data indicate that a smaller
oxide aperture device will have a larger Purcell effect and higher cavity Q. With a faster electron-hole spontaneous emission recombination rate (smaller lifetime), the device can demonstrate ultra-low threshold current. The spontaneous emission lifetime can also be extracted from the microwave frequency response below threshold; the extracted Purcell factor obtained by microwave measurements is consistent with that estimated from spectral measurements.\textsuperscript{33}

5.2 Temperature Insensitive Characteristics

The temperature-dependence of operation is, of course, important for characterizing a microcavity laser performance.\textsuperscript{34,35} For reliable operation in optical communications we need the optical mode wavelength to be as temperature-insensitive as possible. Otherwise an extra and complex temperature control circuit is needed and increases system complexity and cost. In the present experiments we use a Newport 3150 temperature controller to adjust the temperature of a Peltier thermal-electric cooler, which is attached to the device in close thermal contact. A typical temperature dependent L-I and I-V curve of D2 ($d_A= 2.5 \, \mu m$) is shown in Fig. 5.5. As the temperature is increased from $15 \, ^\circ C$ to $40 \, ^\circ C$, the threshold current $I_{TH}$ changes from 0.155 to 0.177 mA. The threshold current and temperature dependence, $dI_{TH}/dT$, for the three devices D1, D2, and D3 are summarized in Table 5.3. Similar to the trend seen in the SMSR, the smaller the mode-volume of the device is, owing to the better “coupling” of the carrier recombination to the mode, the stronger the tendency to “temperature-insensitive” laser operation. This is seen by comparing the smaller $dI_{TH}/dT$ of D1 (0.614 $\mu A/^\circ C$) to that of the larger devices D2 (0.883 $\mu A/^\circ C$) and D3 (1.516 $\mu A/^\circ C$). The cavity mode is no longer aligned
with the gain peak position when the temperature is changed due to different slopes in the
temperature shift.\(^{36}\) At high temperature more carrier injection is needed to overcome
material loss, which is consistent with the lower quantum efficiency \((dL/dI)\) observed at
higher temperature in Fig. 5.5.

Figure 5.6 shows the mode wavelength shift as a function of bias current for the
D2 device at different ambient temperatures. Since the mode spacing of this device is 1.6
nm, much larger than the smooth temperature-induced shift, we conclude that there is no
mode hopping. The data (Table 5.3) show that the temperature-induced fundamental
mode wavelength shift for D1, D2, and D3 is almost the same or about 0.05 nm\(^{\circ}\)C. These data indicate that the wavelength shift originates from the change in the material
(crystal) refractive index at different temperatures. According to the spectral data and the
effective cavity volume (Table 5.1), i.e., the cavity length \(L\) (0.2546 \(\mu\)m) more than 10
times smaller than the lateral mode dimensions \(a\) and \(b\), we can approximate the
fundamental mode wavelength as \(\lambda(1,1) \approx \tilde{n}L\). This gives

\[
\frac{d\lambda(1,1)}{dT} = \lambda(1,1) \left( \frac{1}{\tilde{n}} \frac{d\tilde{n}}{dT} + \frac{1}{L} \frac{dL}{dT} \right),
\]

The first term of the right-hand side is the temperature-induced refractive index change,
and the second term the material thermal expansion coefficient \(\beta \equiv dL / LdT\). Kisting \textit{et al.}\(^{37}\) report that \(d\tilde{n} / \tilde{n}dT\) is about \(1\times10^{-4}/\circ\)C and the thermal expansion coefficient \(\beta\) for
GaAs is about \(6.5\times10^{-6}/\circ\)C. This shows that the fundamental mode wavelength shift is
mainly owing to the refractive index change.\(^{38}\) From Eq. (7) we estimate the wavelength
shift as about 0.088 nm\(^{\circ}\)C, which is larger than the measured 0.055 nm\(^{\circ}\)C. The
discrepancy is caused mainly by the temperature gradient between the Peltier thermal-electric controller and the actual device junction temperature.

In addition, we observe that the fundamental mode wavelength will result in “red-shift” with increasing injection current for $I > 0.25$ mA. This occurs because of current-induced junction self-heating. The shift in the slope $d\lambda/dI$ is 0.52 (nm/mA) for D1, 0.445 for D2, and 0.338 for D3. The series resistance increases as $d_4$ becomes smaller, contributing more heat generation at a given injection current and thus higher junction temperature.

5.3 Microwave Bandwidth and Eye-Diagram Signal Integrity

In the following we discuss the microwave behavior of microcavity VCSELs with two different aperture sizes: $d_4 = 3$ µm (microcavity) and 7 µm (considered as the “bulk” reference). We use both the electrical ($S_{11}$) and optical ($S_{21}$) frequency response, which are measured by an Agilent E8364B Parameter Network Analyzer (PNA), to estimate the enhanced recombination rate and reduced recombination lifetime inside a microcavity laser.

To understand the electrical and optical behavior of the device, we start from the coupled carrier-photon rate equations, which were first formulated by Statz and deMars in 1960,

\[
\begin{align*}
\frac{dN}{dt} &= \frac{I_d}{q} - \frac{N}{\tau_{rec}} - GN_{ph}, \\
\frac{dN_{ph}}{dt} &= GN_{ph} - \frac{N_{ph}}{\tau_{ph}} + \gamma \frac{N}{\tau_{rec}}.
\end{align*}
\]

(5.8)
Here $N$ is the total carrier population inversion, $N_{ph}$ is the photon population inside the cavity, and $I_d$ is the injection current. The quantity $\tau_{rec} (~ns)$ is the carrier recombination lifetime, and $\tau_{ph} (~ps)$ is the photon lifetime inside the cavity. The expression $G = \Gamma \nu_g \alpha (N/V - n_0)$ is the effective optical gain, where $\Gamma$, $\nu_g$ and $\alpha$ are the confinement factor, group velocity, and QW gain constant, respectively. The quantity $V$ is the active region volume, and $n_0$ is the carrier density at transparency. Here $\gamma$ is a spontaneous emission coupling factor, indicating the fraction of photons (number) coupled into the cavity mode relative to the total number of photons. As the bias current extends beyond threshold, gain is clamped to the cavity loss $G = \tau_{ph}^{-1}$, and the coherent field becomes self-sustaining.

Injected carriers supply both the stimulated and spontaneous carrier recombination. By solving Eq. 5.8, we obtain the optical frequency response as a transfer function

$$S_{21, \text{intrinsic}}(f) = \frac{A_0}{(f - f_R + j\xi)(f + f_R + j\xi)}.$$ (5.9)

Here $f_R \equiv \frac{1}{2\pi} \sqrt{\frac{1 + \Gamma \nu_g \alpha n_0 \tau_{ph}}{\tau_{rec} \tau_{ph} \left( \frac{I}{I_{th}} - 1 \right)}}$ is the resonance frequency, and $\xi = \frac{1}{4\pi \tau_{rec}} + \pi \tau_{ph} f_R^2$ is the damping factor which determines the oscillation relaxation.

An approximation to the -3 dB bandwidth is $f_{-3dB} \sim 1.55 \times f_R$. The intrinsic bandwidth of the optical response is determined by both the photon density, $N_{ph}/V = (I - I_{th}) \tau_{ph}/qV$, and the spontaneous recombination lifetime, $\tau_{rec}$. The photon density $N_{ph}/V$ inside of the cavity determines the bandwidth of the response, and the recombination lifetime, $\tau_{rec}$, influences the damping of the relaxation oscillations and the bandwidth.
When the optical mode volume becomes smaller and smaller, we excite fewer modes within the gain profile, resulting in the enhancement of the stimulated emission photon rate, $G_{N\text{ph}}$, and lowering the threshold current. Hence, the intrinsic modulation speed for a microcavity laser can be improved. On the other hand, the microcavity can also enhance the spontaneous recombination rate $\tau_{\text{rec}}^{-1}$ (by the Purcell effect), which increases the damping factor, yielding a smaller resonance peak and increasing the bandwidth.

The measured optical frequency responses of two devices (3$\mu$m and 7$\mu$m) at similar bias current densities are plotted in Fig. 5.7. The threshold current for 3 $\mu$m and 7 $\mu$m devices are 0.18 mA and 0.8 mA, respectively. The -3 dB bandwidth for the 3 $\mu$m device is $f_{3\text{dB}} = 15.8$ GHz at 1 mA with a resonance peak of 5.8 dB. Compared to the 3 $\mu$m microcavity laser, the -3 dB bandwidth of the 7 $\mu$m device is $f_{3\text{dB}} = 12.4$ GHz at 4 mA, with a much larger resonance peak of 14.7 dB. The flatter resonance peak for the 3 $\mu$m device indicates a smaller recombination lifetime than for the 7 $\mu$m device.\textsuperscript{16, 29, 32} From the measured data we calculate an estimated recombination lifetime via the rate equations by extracting all the relevant parameters from the small-signal model of the microcavity lasers.

Figure 5.8 shows the comparison of the modulation current efficiency factor (MCEF) of two devices. Theoretically, the MCEF can be expressed as\textsuperscript{39}

$$MCEF = \frac{f_{3\text{dB}}}{\sqrt{I-I_{\text{TH}}}} \approx 1.55 \frac{f_R}{\sqrt{I-I_{\text{TH}}}} = 1.55 \frac{\Gamma_{\text{vgs}} \alpha}{2\pi \sqrt{qV}} .$$  \hspace{1cm} (5.10)

The behavior of the -3 dB frequency as a function of $(I - I_{\text{TH}})^{1/2}$ for the 3 $\mu$m and the 7 $\mu$m device is shown in Fig. 5.8 with the slope obtained defined as MCEF. The MCEF data provide a “cleaner” way to understand the intrinsic carrier-photon dynamics and see
how it relates to the effect of the optical volume. Compared to the “bulk” laser without any enhancement of $\tau_{\text{rec}}$, the 3 \(\mu\)m microcavity laser has a MCEF = 17.47 GHz/mA$^{1/2}$, which is 2.5 times more efficient than the 7 \(\mu\)m VCSEL laser with MCEF = 6.76 GHz/mA$^{1/2}$.

In the method of direct laser modulation, the most important issue is the existence of the resonance bump, which affects the data transmission integrity of the system. The resonance peak frequency $f_R$ gives rise to “ringing” in the time-domain output waveform of the laser and limits the available modulation bandwidth. If resonance is present, the highest data rate is limited by the resonance frequency, $f_R$, due to waveform distortion by the “overshoot” and “undershoot,” further resulting in a “closed” eye diagram. Without the resonance bump, the available bandwidth is much improved and determined by $f_{-3\text{dB}}$, which is easily observed in the modulation of a transistor laser.\textsuperscript{32} Besides an increase in the maximum transmittable data rate, resonance-free operation leads also to better signal quality, which can be shown by an eye diagram measurement. We use an Agilent N4901 Serial BERT to generate a 13.5 Gbit/s (equipment limited) NRZ $2^7$-1 bit-length pseudorandom binary series pattern, and an Agilent 86100 DCA high-speed wideband oscilloscope to record the actual eye diagram.

A large signal modulation eye diagram measurement is different from the small signal frequency response behavior. Devices with higher frequency bandwidth cannot guarantee the larger data transmission rate and better integrity of an eye diagram. To illustrate this point, in Fig. 5.9 we compare eye diagrams at 10 Gb/s without filtering process for a 3 \(\mu\)m microcavity laser at the bias of 0.5 mA and a poorer 7 \(\mu\)m “bulk” reference device at a bias of 4 mA. In Fig. 5.7 we show that the 7 \(\mu\)m device at 4 mA has
a larger bandwidth (~ 12.4 GHz) but also higher resonance peak (~ 14.7 dB) than the 3\(\mu\)m device at 0.5 mA (~ 9.8 GHz with only a 6 dB resonance peak). Though the -3 dB bandwidth is larger for the former, its larger resonance peak degrades the eye-diagram integrity. In Fig. 5.9 the 3 \(\mu\)m microcavity device has a smaller signal distortion at the sampling instant, a smaller crossover width, as well as a larger open eye. These indicate that the 3\(\mu\)m microcavity laser has larger signal-to-noise ratio, smaller power consumption, and a longer time interval for successfully sampling the waveform. It shows therefore that the larger bandwidth alone cannot give rise to higher data transmission speed. The resonance peak in the RF response curve plays a crucial role in limiting the data transmission rate.

To illustrate the mode volume effect on the data transmission rate, we compare (in Fig. 5.10) the eye diagrams of two devices at a data transmission rate of 13.5 Gb/s (instrument limited). At similar bias current density, the 3 \(\mu\)m microcavity device presents a “cleaner” eye diagram compared to the degraded eye diagram of the 7 \(\mu\)m device. Again, this is owing to the large resonance peak (~ 15 dB) in the response curve of the 7 \(\mu\)m device at 4 mA, which causes the large “overshoot” and “undershoot” and leads to the eye diagram closure. The eye diagram comparison shows clearly that the smaller optical mode volume is of benefit for a higher data transmission speed owing to the smaller carrier spontaneous lifetime and the larger damping factor of a higher Q microcavity. In contrast, for the larger “bulk” reference device and multimode operation, higher bias current and carrier injection (thus higher photon density \(N_{ph}\)) is required and more power consumption to extend the bandwidth and reduce the resonance peak.
5.4 Microwave Small-Signal Model

The measured microcavity laser microwave bandwidth to determine the optical response is not only dependent on the ideal intrinsic device bandwidth, but also is influenced by extrinsic device parasitic electrical parameters. We show in Fig. 5.11 the schematic microcavity device cross section with all the related extrinsic parasitic parameters. The intrinsic device region enclosed by the red-dashed rectangle is the intrinsic forward biased junction resistance \( R_j \) and diffusion capacitance \( C_{\text{diff}} \). The pad extrinsic elements \( C_p \) and \( R_p \) are the contact pad capacitance and resistance. The semiconductor extrinsic elements \( R_s \) and \( R_n \) are the DBR mirror resistances. The semiconductor parasitic capacitance \( C_a \) is the sum of series \( C_{\text{ox}} \) and \( C_{\text{dep}} \), oxide and junction depletion capacitances.

From two-port network theory, we can express the reflection coefficient, \( S_{11} \), and transfer function, \( H_{\text{ext}}(f) \), as

\[
S_{11} = \frac{i_{\text{tot}}^-(f)}{i_{\text{tot}}^+(f)} = \frac{i_{\text{tot}}^+(f) - i_{\text{tot}}^-(f)}{i_{\text{tot}}^+(f)} ,
\]

and

\[
H_{\text{ext}}(f) = \frac{i_d(f)}{i_{\text{tot}}^+(f)} = \frac{i_d(f)}{i_{\text{tot}}^+(f)} \cdot (1 - S_{11}) ,
\]

where \( i_{\text{tot}}^+(f) \) is the incident current wave and \( i_{\text{tot}}^-(f) \) is the reflected current wave. The total modulation current from the probe at frequency \( f \) is \( i_{\text{tot}}(f) = i_{\text{tot}}^+(f) - i_{\text{tot}}^-(f) \), and \( i_d(f) \) is the small-signal modulation current through the intrinsic diode region at the same frequency. By fitting of \( S_{11} \), we can extract all the parasitic parameters as listed in Table 5.4. We find that the major contribution to signal time delay causing bandwidth
limitations arises from the junction diffusion capacitance, which is proportional to the device aperture area and current density.

In order to obtain the intrinsic modulation bandwidth to then determine the recombination lifetime for a microcavity laser based on the rate equations, we have to subtract the parasitic contributions. Thus, the overall frequency modulation response can be expressed as

$$S_{21,\text{overall}}(f) = \frac{N_{ph}(f)}{i_{tot}^+(f)} \times \frac{N_{ph}(f)}{i_{d}(f)} = H_{ext}(f) \cdot S_{21,\text{intrinsic}}(f).$$  \hspace{1cm} (5.13)

The first term is the external parasitic transfer function, which characterizes the efficiency of delivery of the microwave signal to the intrinsic active region. The second term is the intrinsic part of the transfer function, which determines the efficiency of the photon modulation based on the input electrical signal to the active region. This term is also the same as shown in Eq. (5.9), and can be written as

$$S_{21,\text{intrinsic}}(f) = \frac{A_0}{(f - f_R^+ + j\xi)(f + f_R^+ + j\xi)}.$$  \hspace{1cm} (5.9)

From fitting of the microwave $S_{11}$ parameter at different bias points, we extract the required parameters and obtain the extrinsic transfer function $H_{ext}(f)$. These can be subtracted from the measured data to get the intrinsic response behavior $S_{21,\text{intrinsic}}$. The extrinsic transfer function $H_{ext}(f)$ depends on the device layout structure, operating frequencies, and bias currents. Large input impedance mismatch of the 3 µm microcavity laser causes higher reflection of the input signal at the low frequency range. Transmitted microwave signal to the intrinsic part of the device (Fig. 5.11) increases gradually with input frequency owing to more impedance match (to 50 Ω) resulting from the capacitance effect. To obtain the intrinsic $N_{ph}$ vs. $I_d$ behavior we fit the resonance frequency
and damping parameter 
\[ \zeta = \frac{1}{4\pi \tau_{\text{rec}}} + \pi \tau_{\text{ph}} f^2 \]
for each bias current, and extract the recombination lifetime and the photon lifetime, which are 
\( \tau_{\text{rec}} = 0.4 \text{ ns} \) and 
\( \tau_{\text{ph}} = 4.2 \text{ ps} \) for the 3 \( \mu \text{m} \) diameter microcavity device, and 
\( \tau_{\text{rec}} = 0.82 \text{ ns} \) and 
\( \tau_{\text{ph}} = 4.8 \text{ ps} \) for the 7 \( \mu \text{m} \) device. For the 3 \( \mu \text{m} \) microcavity laser the “enhanced” (reduced) recombination lifetime changes from the usual 0.82 ns reference value to the reduced value 0.4 ns, or Purcell factor, \( F_p \sim 2 \). The microwave method described here for determination of carrier lifetime is consistent with previous spectral analyses, e.g., for the 
\( d_A = 3.5 \mu \text{m} \) device giving an \( F_p \sim 1.5 \) (see Table 5.2). The microwave method of measurement has the advantage of being simpler and more efficient in separating input and output signals since it employs an electrical-input and optical-output, and no complex optical-to-optical pump-probe time-resolved techniques.

The small-signal model employed here can also provide comprehensive information on device parameters for layout design and process optimization to enhance the optical modulation bandwidth. Figure 5.12 shows the measured optical response curves, \( S_{21} \), of the 3 \( \mu \text{m} \) microcavity laser and the corresponding model shows curves fitted to the measured data. The model projected curves with a reduced device parasitic capacitance and resistance are also plotted in Fig. 5.12. With the reduction of the parasitics from the actual devices (e.g., pad capacitance \( C_p \) to \( C_p/4 \), parasitic capacitance \( C_a \) to \( C_a/4 \), and resistances \( R_n + R_s \) to \( (R_n + R_s)/2 \), the optical modulation bandwidth for the 3 \( \mu \text{m} \) microcavity laser is expected to improve to \( \sim 20 \text{ GHz} \) for \( I = 1 \text{ mA} \). The projected (enhanced) bandwidths of the 3 \( \mu \text{m} \) and the 7 \( \mu \text{m} \) devices at three bias currents are listed
in Table 5.4. With still more refined process steps and layout design, the optical microwave performance can be further improved.

We show that for a microcavity laser the recombination rate can be enhanced by the Purcell effect (~ 2×), but is still only a limited cavity improvement. The device is still limited by charge storage and photon-charge resonance. Recently, however, the tilted-charge operation of a transistor laser has manifested a fast extrinsic spontaneous recombination lifetime (τ_{rec} ~ 26 ps), compared to the diode laser case of ~ 1 ns. Intrinsically the transistor laser can have a much larger bandwidth and flat frequency response owing to the “fast” collector removal of slower-recombining carriers.\(^\text{32}\)

Concluding, we have presented DC and RF measurement data on QW microcavity lasers showing the effect of the cavity volume on the device performance. We demonstrate that as the optical volume is shrunk, the mode spacing and Purcell enhancement factor increase. With higher cavity Q and a faster spontaneous emission rate, laser threshold \(I_{TH}\) is lower and the side-mode suppression ratio (SMSR) larger. Simultaneously the intrinsic frequency-modulation bandwidth above threshold will increase due to the higher photon density and faster spontaneous recombination rate. In addition, a “fast” spontaneous emission rate (smaller lifetime) gives “fast” damping and a tendency to resonance-free response in high frequency modulation, thus improving the data bit error rate and eye-diagram quality in high-speed data transmission. With respect to low power consumption and high data transmission speed, a microcavity laser design is useful for short distance optical communication. The threshold current of a smaller volume microcavity laser is less sensitive to temperature owing to the greater carrier concentration in the fundamental mode. On the other hand, a smaller volume suffers
more from the greater heat generation at a given current density, as well as a larger wavelength shift, which is not desired for reliable optical communications.
5.5 Tables and Figures

Table 5.1 Microcavity VCSEL Optical Mode Dimension, $d_0$, at Bias Current $I = 0.8$ mA.

<table>
<thead>
<tr>
<th></th>
<th>$I_{TH}$ (mA)</th>
<th>$\Delta \lambda$ (nm)</th>
<th>$a$ (Width, $\mu$m)</th>
<th>$b$ (Length, $\mu$m)</th>
<th>$L$ ($\sim \lambda/\bar{n}$, $\mu$m)</th>
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</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.13</td>
<td>2.45</td>
<td>2.65</td>
<td>2.90</td>
<td>0.2546</td>
</tr>
<tr>
<td>D2</td>
<td>0.16</td>
<td>1.6</td>
<td>3.28</td>
<td>3.53</td>
<td>0.2546</td>
</tr>
<tr>
<td>D3</td>
<td>0.20</td>
<td>1.0</td>
<td>4.41</td>
<td>4.59</td>
<td>0.2546</td>
</tr>
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</table>

Table 5.2 Microcavity VCSEL Purcell Enhancement Factor $F_P$ at Bias $I = 0.1$ mA.

<table>
<thead>
<tr>
<th></th>
<th>$I_{TH}$ (mA)</th>
<th>$V_{eff} = abL$ ($\mu$m$^3$)</th>
<th>$Q = \lambda/\Delta\lambda_{cav}$ (@ $I = 0.1$ mA)</th>
<th>$F_P$ (Purcell Factor)</th>
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</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.13</td>
<td>2.0</td>
<td>12800</td>
<td>8.0</td>
</tr>
<tr>
<td>D2</td>
<td>0.16</td>
<td>3.0</td>
<td>10300</td>
<td>4.3</td>
</tr>
<tr>
<td>D3</td>
<td>0.20</td>
<td>5.3</td>
<td>6200</td>
<td>1.5</td>
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</table>

Table 5.3 Microcavity VCSEL Temperature Characteristics.

<table>
<thead>
<tr>
<th></th>
<th>$dI_{TH}/dT$ ($\mu$A/$^\circ$C)</th>
<th>$d\lambda/dT$ ($\text{nm}^\circ$C)</th>
<th>$d\lambda/dI$ ($\text{nm}/\text{mA}$)</th>
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</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.614</td>
<td>0.053</td>
<td>0.520</td>
</tr>
<tr>
<td>D2</td>
<td>0.883</td>
<td>0.055</td>
<td>0.445</td>
</tr>
<tr>
<td>D3</td>
<td>1.516</td>
<td>0.051</td>
<td>0.338</td>
</tr>
</tbody>
</table>

Table 5.4 Parameters for a Small-Signal Model of the Microcavity VCSEL.

<table>
<thead>
<tr>
<th>$d_A$ (\mu$m$)</th>
<th>I (mA)</th>
<th>$C_p$ (fF)</th>
<th>$R_p$ (\Omega)</th>
<th>$R_n + R_s$ (\Omega)</th>
<th>$C_a$ (fF)</th>
<th>$C_{\text{diff}}$ (fF)</th>
<th>$R_j$ (\Omega)</th>
<th>$f_{-3\text{dB, measured}}$ (GHz)</th>
<th>$f_{-3\text{dB, projected}}$ (GHz)</th>
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</thead>
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<tr>
<td>3</td>
<td>0.25</td>
<td>360</td>
<td>4.5</td>
<td>213</td>
<td>54</td>
<td>186</td>
<td>366</td>
<td>4.4</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>360</td>
<td>4.5</td>
<td>190</td>
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<tr>
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<td>1.0</td>
<td>360</td>
<td>4.5</td>
<td>154</td>
<td>54</td>
<td>253</td>
<td>143</td>
<td>15.8</td>
<td>19.9</td>
</tr>
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<td>7</td>
<td>1.0</td>
<td>330</td>
<td>3</td>
<td>68</td>
<td>57</td>
<td>563</td>
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<tr>
<td></td>
<td>4.0</td>
<td>330</td>
<td>3</td>
<td>55</td>
<td>57</td>
<td>753</td>
<td>18.5</td>
<td>12.4</td>
<td>15.2</td>
</tr>
</tbody>
</table>

* Projected bandwidth by reducing the pad capacitance $C_p$ to $C_p/4$, $C_a$ to $C_a/4$ and the mirror resistance $R_n + R_s$ to $(R_n + R_s)/2$. 

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Fig. 5.1 (i) Schematic cross-section of UIUC microcavity VCSEL device. (ii) Microcavity schematic diagram showing the allowed optical modes: (a) 1st order mode, (b) 2nd order mode, and (c) 3rd order mode.

Fig. 5.2 L-I and I-V curves for three different diameter microcavity lasers at 25 °C. The aperture sizes for the three devices are: \(d_A = 2 \, \mu\text{m}\) for D1, \(d_A = 2.5 \, \mu\text{m}\) for D2, and \(d_A = 3.5 \, \mu\text{m}\) for D3.
Fig. 5.3 Optical spectra of a microcavity VCSEL device ($I_{TH} = 0.13$ mA) at different bias currents. The fundamental mode is labeled (a) (shown in Fig. 5.1), and the 2$^{nd}$ order mode (b) at 2.45 nm longer wavelength and 32.5 dB suppression. The 3$^{rd}$ order mode intensity is too weak to be recorded.

Fig. 5.4 Side mode suppression ratio (SMSR) vs. bias current for three different microcavity VCSEL devices: (1) D1 with mode spacing (MS) $\Delta\lambda \sim 2.45$ nm, (2) D2 with $\Delta\lambda \sim 1.6$ nm, and (3) D3 with $\Delta\lambda \sim 1.0$ nm. The smaller the aperture, the larger $\Delta\lambda$ and the smaller the threshold current, as well as the larger the SMSR slope before lasing.
Fig. 5.5 Temperature dependence of the L-I-V curves for the D2 \((d_A = 2.5 \, \mu m)\) microcavity laser.

Fig. 5.6 Microcavity laser fundamental mode wavelength, \(\lambda(1,1)\), versus injection current for D2 device \((d_A = 2.5 \, \mu m)\) at different temperatures ranging from 15 °C to 40 °C. The measured \(d\lambda/dT\) is 0.055 nm/°C and \(d\lambda/dI\) is 0.445 nm/mA.
Fig. 5.7  Frequency response of 3 μm and 7 μm microcavity VCSEL devices at various bias currents: (a) 3 μm device biased at current $I = 0.25, 0.5, 1$ mA, and -3 dB bandwidth $f_{3db} = 15.8$ GHz at 1 mA with resonance peak of 5.8 dB. (b) 7 μm device at various bias currents, and -3 dB bandwidth $f_{3db} = 12.4$ GHz at 4 mA with resonance peak of 14.7 dB.

Fig. 5.8  A -3 dB frequency ($f_{3db}$) versus $(I-I_{TH})^{1/2}$ comparison of 3 μm and 7 μm microcavity lasers. The slope for the modulation current efficiency factor (MCEF) is 17.47 and 6.76 GHz/mA$^{1/2}$ for the 3 μm and 7 μm devices, respectively.
Fig. 5.9  Eye diagrams of 3 \( \mu \)m and 7 \( \mu \)m microcavity lasers at 10 Gb/s: (a) 3 \( \mu \)m aperture diameter device at bias current 0.5 mA; (b) 7 \( \mu \)m aperture diameter device at bias current \( I = 4 \) mA.

Fig. 5.10  Eye diagrams of 3 \( \mu \)m and 7 \( \mu \)m microcavity lasers at 13.5 Gb/s: (a) 3 \( \mu \)m aperture diameter device at bias current 1 mA; (b) 7 \( \mu \)m aperture diameter device at bias current \( I = 4 \) mA.
Fig. 5.11  Typical diode VCSEL microcavity lasers with the equivalent intrinsic and extrinsic RC parameters identified as follows: $R_j$, junction resistance; $C_{\text{dep}}$, depletion capacitance; $C_{\text{diff}}$, diffusion capacitance; $R_s$, p-type DBR series resistance (with oxide confinement); $R_n$, n-type DBR series resistance (without oxide confinement); $C_p$ and $R_p$ are the extrinsic pad capacitance and resistance. $C_a$ is the series capacitance of $C_{\text{ox}}$ and $C_{\text{dep}}$ for modeling convenience. The intrinsic part of the laser operation is identified by the dashed line (red) rectangle.

Fig. 5.12  Measured optical response, $S_{21}$, of 3 $\mu$m aperture diameter microcavity laser and model fitting as well as the model projected optical response $f_{-3dB} \sim 20$ GHz with a reduced device parasitic capacitance $C_p/4$, and resistances $(R_n+R_s)/2$. 

$d_A = 3 \mu$m @ 25°C  
$I = 1$ mA

-3dB

0.5

0.25

Optical Response, $S_{21}$ (dB)

Frequency (GHz)

Measured

Model

Projection

74
6. CONCLUSION

It is shown that un-doped quantum wells (QWs) embedded in the base region of a heterojunction bipolar transistor (HBT) structure can enhance the light output and reduce experimentally, under dynamic tilted-charge boundary condition, the effective carrier recombination lifetime of injected minority carriers in the base region as an improved novel high-speed optical device—the light-emitting transistor (LET). A unique three-terminal electrical and optical characteristic of the LET offers a promising method for photonics integration and short-range optical transmitter and interconnect.

The enhanced recombination rate and reduced recombination lifetime of a LET is demonstrated by simultaneously operating multi-GHz electrical and optical signal output through a common-collector device design, resulting in a better matched impedance (50 Ω) owing to reverse-biased base-collector junction as an rf signal input terminal. The effective recombination lifetime, corresponding to the optical spontaneous modulation bandwidth $f_{3dB}$, is reduced (i.e., bandwidth is enhanced) by laterally scaling the extrinsic parasitic part of an oxide-confined aperture LET. With a smaller aperture and an increased intrinsic portion, the light output as well as the electrical gain ($\beta = \Delta I_C/\Delta I_B$) of an LET are improved.

Inherited from a common-collector design of LET, a tilted-charge LED is proposed by incorporating a “drain” layer underneath the QW-embedded base region to “drain away” excessive slow-recombining carriers with a reverse built-in field at base-“drain” junction maintained by a common potential obtained via a common contact metallization design. The zero base-“drain” potential difference ensures that there is no base charge population density at the base-“drain” boundary, hence establishing a dynamic “tilted” emitter-to-
“drain” population in the base. The “drain” layer performs therefore a role similar to the collector in a three-terminal LET. Base carriers in transit from the emitter to the “drain” that do not recombine within the base transit time are removed, or “drained.” This enables fast modulation of the tilted-charge LED by preventing the build-up of “slow” charge in the base. The tilted-charge LED possesses the high speed optical modulation characteristics of a LET.

Microcavity light-emitting devices with reduced spontaneous recombination lifetimes (faster band-to-band recombination) are of great interest in the pursuit of threshold-less lasers and LEDs for potential use in optical communications at high modulation speed. Some reduced spontaneous lifetime, $< 500$ ps ($\sim 2$ x lower than bulk values, $\sim 1$ ns), is observed in the Purcell effect in which the upper-state to lower-state transition rate is enhanced by a high-Q microcavity of reduced optical mode density. A sensitive microwave method has been used to characterize a quantum-well vertical cavity surface emitting laser ($d_A \sim 3$ $\mu$m aperture, $I_{TH} = 0.18$ mA) exhibiting almost single-mode operation and 2.08 times reduction in electron-hole spontaneous lifetime (enhanced recombination rate) by the Purcell effect. By studying the optical microwave frequency response of microcavity VCSELs in the transition from spontaneous to coherent operation, we resolve the dynamics of electron-hole recombination (spontaneous to stimulated) and reveal the existence of “fast” spontaneous recombination lifetime ($\sim 150$ ps) in a carrier population generally characterized by a large average lifetime of $\sim 1$ ns.

Via the three-terminal heterojunction bipolar transistor laser and its “tilted” base charge, a pinned non-floating source of recombination because of the zero-charge boundary condition at the reverse-biased collector junction, we have also recently
identified an even faster spontaneous lifetime of < 25 ps (~ 40 times reduction from bulk values). It clearly is possible with the choice of the microcavity device geometry and the cavity boundary conditions to favor the faster carrier recombination process (reduced recombination lifetime) to enhance high speed direct modulation of a semiconductor laser.

The demand for faster laser speeds is propelled by the increasing demands for next generation high-speed data communication (100 Gbit Ethernet and more), high bandwidth interconnects for data centers and high-throughput, high-density interconnects in high performance computing systems. From previous experimental results presented in this work, we demonstrated the world-record speed for spontaneous bandwidth modulation of the HBLET, as well as the subsequent tilted-charge LED. Because of their short spontaneous recombination lifetime (23 ps), though limited by extrinsic parasitics, in conjunction with stimulated enhancement due to proper cavity design, ultra-fast, resonance-free vertical-cavity transistor lasers (VCTLs) can serve in applications for the next generation of optical interconnects, fiber communication systems, and opto-electronic integrated circuits.
REFERENCES

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