

High-Speed Modulation and Switching Characteristics of In(Ga)As–Al(Ga)As Self-Organized Quantum-Dot Lasers

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Invited Paper

Abstract—The dynamic characteristics, and in particular the modulation bandwidth, of high-speed semiconductor lasers are determined by intrinsic factors and extrinsic parameters. In particular, carrier transport through the heterostructure and thermalization, or quantum capture in the gain region, tend to play an important role. We have made a detailed study of carrier relaxation and quantum capture phenomena in In(Ga)As–Al(Ga)As self-organized quantum dots (QD's) and single-mode lasers incorporating such dots in the gain region through a variety of measurements. The modulation bandwidth of QD lasers is limited to 5–6 GHz at room temperature and increases to ~ 30 GHz only upon lowering the temperature to 100 K. This behavior is explained by considering electron-hole scattering as the dominant mechanisms of electron relaxation in QD's and the scattering rate seems to decrease with increase of temperature. The switching of the emission wavelength, from the ground state to an excited state, has been studied in coupled cavity devices. It is found that the switching speed is determined intrinsically by the relaxation time of carriers into the QD states. Fast switching from the ground to the excited state transition is observed. The electrooptic coefficients in the dots have been measured and linear coefficient $r = 2.58 \times 10^{-11}$ m/V. The characteristics of electrooptic modulators (EOM's) are also described.

Index Terms—High-speed lasers, quantum dot (QD), semiconductor lasers.

I. INTRODUCTION

THERE has been a lot of research recently devoted to realizing the predicted potential of zero-dimensional quantum-confined structures, or quantum dots (QD's) [1]. Because of their unique electronic structure and atom-like discrete states with a δ -function density of states, QD's are expected to have many interesting and useful properties for optoelectronic device applications. Therefore, a semiconductor laser with a QD active region [2] promises very high gain and differential gain, ultralow- and temperature-independent threshold currents, and high-frequency modulation with negli-

gible chirp. Also, by varying the dot composition and electronic properties, it should be possible to obtain laser emission over a wide range of frequencies.

Conceptually, the most straightforward technique to produce an array of QD's is to define suitably sized mesa-etched quantum wells (QW's) grown by molecular beam epitaxy (MBE) or vapor phase epitaxy (MOVPE). Unfortunately, a large density of nonradiative defects produced during etching renders the material unsuitable for light emitters. QD's, which are near-pyramidal in shape, are realized by strained layer hetero-epitaxy, in a *self-organized* growth mode [3]–[7]. The islands are formed in this strain-driven process when the misfit is larger than 1.7%. The areal density of the islands can be varied from 10^9 to 10^{12} dots/cm². Due to a 10%–15% size fluctuation (and some variation in shape) the photoluminescence from an array of such dots is inhomogeneously broadened. Researchers have demonstrated room-temperature linewidths from 30 to 70 meV. Multiple layers of *vertically coupled dots* [8]–[10] can be grown, in which the dots layers are separated by barrier layers of suitable thickness. Again, the strain field in and around the dots stack the dots vertically and, in the process, a significant size filtering occurs. This is evidenced by a considerable narrowing of the photoluminescence (PL) linewidth. QD transistors, photodetectors, and lasers have been demonstrated with self-organized dots. In a laser, single or multiple (vertically stacked) layers of dots form the gain region in exactly the same way as in a multi-QW laser. The structural characteristics of self-organized QD's grown in our laboratories are shown in Fig. 1.

Researchers have been extremely successful in demonstrating many of the predicted properties of QD lasers. Low-threshold current densities of 21 A/cm² [11], high T_0 up to 385 K, and differential gains of 10^{-14} cm² at room temperature (about ten times that of QW devices) have been demonstrated [12], [13]. In addition, 1.3- μ m lasing wavelengths have been demonstrated [14]. This is a very significant achievement for QD's, as it brings the GaAs substrate into the wavelength range useful for optoelectronic communications devices. Vertical cavity surface emitting lasers (VCSEL's) with QD gain regions have also been demonstrated [15].

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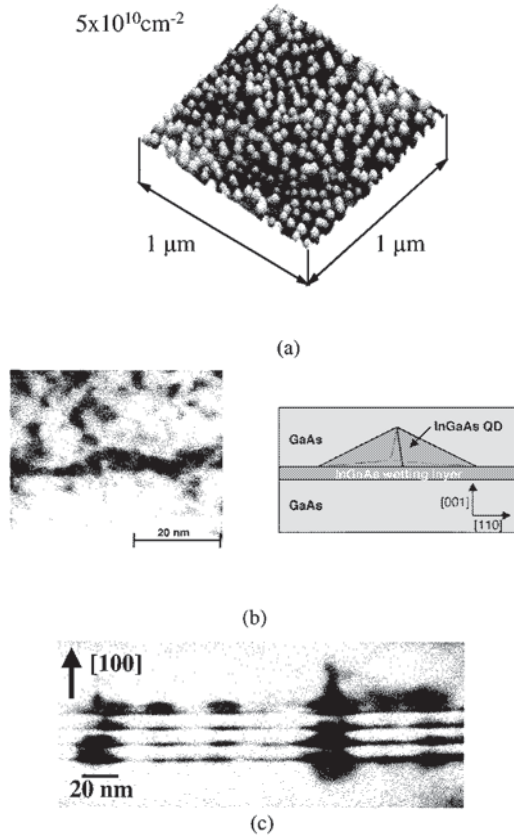


Fig. 1. Structural characteristics of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs self-organized QD's: (a) AFM image, (b) cross-sectional TEM image of single dot and its schematic, illustrating a near-pyramidal shape, and (c) XTEM image of 4 layers of vertically coupled dots with 15 Å of GaAs barrier layers in between.

However, directly modulated devices need high-speed capability as well as the ability to operate in the low-loss or low-dispersion regime of optical fibers. There has always been some theoretical question about the ultimate high-speed characteristics of QD's [16]. The capture/relaxation time of carriers in QD's τ_c is predicted to be much longer than in QW's, because of the lack of phonon scattering as a possible carrier relaxation mechanism. In this paper, we will focus on the carrier relaxation time in QD's, its probable mechanism, and the implications for the performance characteristics of directly modulated QD lasers.

In what follows, the growth of self-organized QD's is described briefly, since there exists considerable information on this aspect in published literature. A technique to reduce the linewidth of the dot emission will be described, together with a description of their electronic properties. The carrier dynamics and modulation properties of QD lasers are described next. This is followed by a description of high-speed wavelength switching and electrooptic modulation (EOM) of QD devices.

II. RECENT GROWTH TECHNIQUES FOR QD'S: WAVELENGTH TUNABILITY AND EMISSION LINEWIDTH CONTROL

Self-organized QD's, grown via the Stranski-Krastanow (SK) growth mode, have demonstrated characteristics favorable for their application to optoelectronic devices. Interband edge- and surface-emitting lasers [17]–[23], intersubband long

wavelength detectors [24], [25], and EOM's [26] have been demonstrated, sometimes with performance matching those of similar QW devices. However, it is expected, by virtue of the singular density of states of ideal QD's, that their characteristics should surpass those of QW devices [2]. The biggest hindrance to achieving this objective has been the growth mode itself—a $\sim 10\%$ inhomogeneity in size and associated fluctuations in shape and composition causes inhomogeneous broadening of the PL and severely limits the advantages of three-dimensional (3-D) confinement. For example, PL linewidths as narrow as $34 \mu\text{eV}$ have been observed for luminescence emission from single dots [27], whereas in a large ensemble, typical linewidths are 30–60 meV, even at cryogenic temperatures. Additionally, the interplay of surface kinetics and energetics on the surface randomizes the positioning of the dots [28], [29].

Many techniques have been demonstrated to reduce the PL linewidth and spatial ordering of QD's, with reasonable success [30], [31]. By using patterned substrates, uniform arrays of dots have been demonstrated, but the dot densities are much smaller than 10^{10} cm^{-2} [32]. Sopanen *et al.* [33] have studied the strain field and luminescence characteristics produced by InP-GaAs stressor dots grown on a buried InGaAs-GaAs QW. It has also been shown that the surface strain in a capping layer by an initial ensemble of buried dots perturbs the adatom migration rates during growth of a subsequent dot layer, thereby influencing their size, shape and lateral ordering [34]. Such strain driven self-organized growth leads to spatial ordering and vertical coupling between dots in successive layers [10], [35], [36]. The vertical coupling of dots also reduces the PL linewidth—accompanied by a red shift of the emission wavelength—due to a size filtering effect [37]. PL linewidths as narrow as 25 meV have been reported for double-layer InAs dots [31]. Recent theoretical calculations also confirm that it is possible to grow a more uniform and regular arrangement of islands even on a nonuniform set of buried islands [38]. PL linewidths have also been reduced by postgrowth annealing [39], [40], and by overgrowth of a two-dimensional (2-D) layer (to limit interdiffusion effects) [41].

In the experiments reported till date, the stressor and overlying QD's, vertically coupled or otherwise, have the same composition. It would be more advantageous to have the two dot systems of different composition. The QD heterostructures are grown in our laboratory on (001) GaAs substrates. A typical heterostructure is shown in Fig. 2(a). The number of stressor and active dot layers and spacer layer thicknesses have been varied to optimize the PL characteristics. A $0.5\text{-}\mu\text{m}$ GaAs buffer layer is first grown at 630°C . The substrate temperature is then lowered to 530°C and the system of $\text{In}_{0.4}\text{Ga}_{0.3}\text{Al}_{0.3}\text{As}$ stressor QD layers, with GaAs spacer layers are grown. This is followed by the growth of the active $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ dot layers with GaAs spacer layers. Finally, a $0.1\text{-}\mu\text{m}$ GaAs cap layer is grown at 610°C . The presence and alignment of the dots were confirmed by cross-sectional transmission electron microscopy (XTEM). Temperature-dependent PL measurements in the range of 7–100 K yielded a strong emission peaking at 1.37 eV [Fig. 2(b)]. A linewidth [full-width at half-maximum (FWHM)] of 21 meV was measured at 7 K, for the 1.37 eV ($0.905 \mu\text{m}$) emission that remained virtually unchanged up to

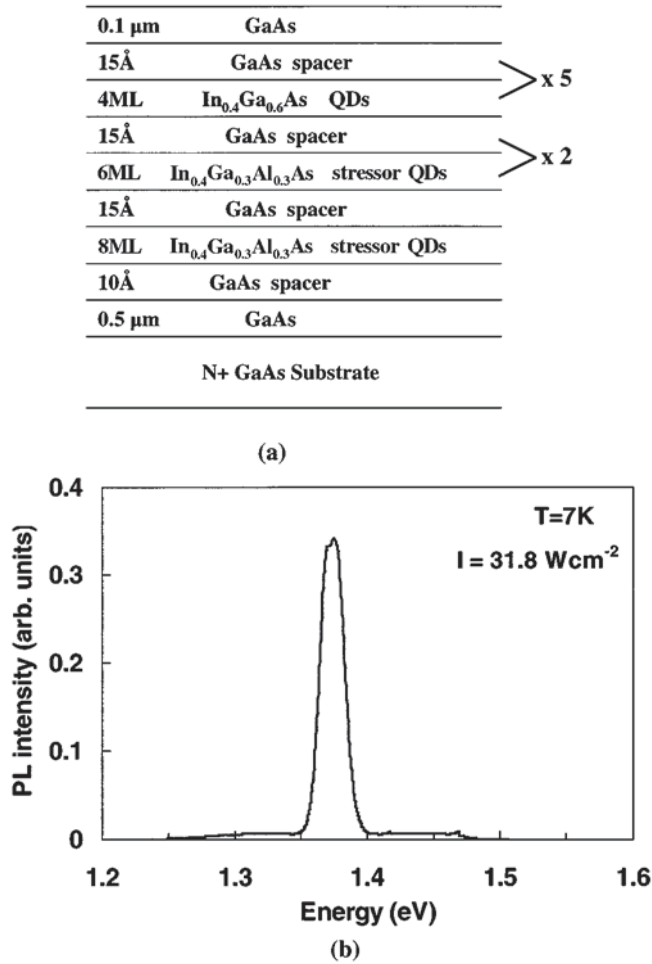


Fig. 2. (a) QD heterostructure incorporating stressor dots. (b) Low-temperature PL $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ QD's with $\text{In}_{0.4}\text{Ga}_{0.3}\text{Al}_{0.3}\text{As}$ stressor dots. The linewidth (FWHM) is 21 meV.

100 K, indicating that the linewidth is principally determined by inhomogeneous broadening. The blue shift of the peak, relative to similar samples grown without stressor dots, could originate from several factors. The active dots are smaller, being grown to a nominal thickness of 4 ML. Moreover, a small amount of Al diffusion from the stressor dots into the GaAs spacer layer could increase the effective barrier seen by the dots. A similar blue shift has been observed by Garcia *et al.* [29] for InAs–AlAs dots. It is clear that the technique of buried stressor dots yields desirable optoelectronic properties of the dots. Lasers with stressor dots in the contact and cladding layers are currently being grown.

While 1.55- μm transmission is going to remain the mainstay of long-haul lightwave networks, great interest exists in developing reliable and low-cost sources and detectors for operation at 1.3 μm . The two material systems that currently look most promising for 1.3 μm emission are InGaAsN–GaAs heterostructures [42], [43] and In(Ga)As–GaAs QD's [14], [44]. In particular, since the first demonstration of 1.3 μm emission at room temperature from InAs–GaAs short-period superlattices (SPS's) [45], several groups have reported 1.3 μm emission from ordered In (Ga)As alloys or short period $(\text{InAs})_m\text{--}(\text{GaAs})_n$ superlattices, (where m, n can be <1)

forming digital alloys [14], [44], [46]. There have also been reports of $\sim 1.3 \mu\text{m}$ emission from InAs QD's buried in an InGaAs well [47] or covered with an InGaAs or InAlAs layer [34]. Room temperature lasing at 1.3 μm and resonant cavity photodiodes [23], [48], using such heterostructures have also been demonstrated. It has been suggested by Mukai *et al.* [14], [49], [50] that these dots may be formed due to “compositional nonuniformities during 2-D growth,” rather than by the conventional strain driven SK growth. The growth and luminescence characteristics of cycled submonolayer InAs–GaAs QD's are briefly described here. A comparison is made with the characteristics of similar dots formed by conventional SK growth.

The experimental cycled submonolayer deposition (CSD) QD heterostructures were grown as follows. After the growth of a 0.5- μm GaAs buffer layer on (001) semi-insulating GaAs at 600 °C, the growth temperature was ramped down to 510 °C. Fractional monolayers (ML) of InAs (m) and GaAs (n) (m and n varying from 0.25 to 0.8) were then grown with a 5-s pause between the layers. The As_4 shutter was kept open during the pause. This cycle was then repeated several times. The substrate temperature was then raised to 600 °C and a 0.3- μm GaAs layer was grown. The entire heterostructure is undoped. For comparison purposes, $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ and InAs self-organized QD's were also grown by the conventional technique. Approximately 2 ML of InAs or InGaAs were deposited after the transformation of the *in situ* RHEED pattern from a streaky to a spotty one. We will refer to these as conventional samples. It was observed that the CSD dots are larger than conventional dots and the dot densities are lower ($\sim 10^{10} \text{ cm}^{-2}$). It is believed that compositional mixing and segregation are responsible for the formation of the CSD dots [51].

PL spectra of the QD samples were measured at different temperatures from 17 K to room temperature. PL data at 300 K and 17 K from a CSD sample with 16 periods of 0.25 ML InAs/0.25 ML GaAs are shown in Fig. 3(a) and (b), respectively. Multiple peaks and shoulders corresponding to ground and excited state transitions, respectively, are observed in the spectra. The peak corresponding to the ground state transition occurs at 1.3 μm . The energy separation between the ground and first excited state transition peaks is approximately 62 meV at room temperature and 66 meV at 17 K and the separation between the first and second excited states at 17 K is ~ 59 meV. These energy separations are in excellent agreement with electroluminescence data published earlier [47]. In contrast, the luminescence peak from the conventional sample occurs at about 1 μm , as shown in Fig. 3(c). A higher energy transition is observed with an energy separation of ~ 60 meV. The multiplicity of bound states, all with nearly equal separations of ~ 60 meV, may have interesting consequences to carrier relaxation and eventual laser modulation bandwidth.

III. MODULATION CHARACTERISTICS AND CARRIER RELAXATION TIME IN QD LASERS

A. Theory of Carrier Relaxation in QD's

There has always been an active theoretical debate about carrier relaxation in QD's, and the ultimate high-speed char-

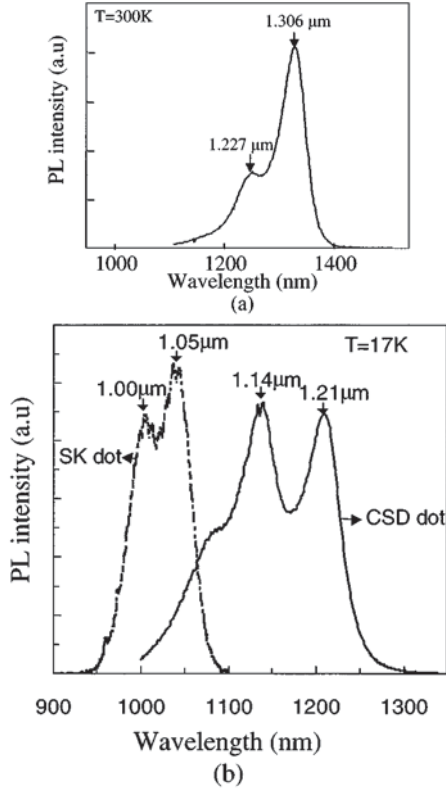


Fig. 3. (a) Room-temperature and (b) low-temperature PL from a cycled superlattice dot sample with 16 periods of 0.25 ML InAs/0.25 ML GaAs. Also shown in (b) is the PL of a single layer of conventional self-organized $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs dots.

acteristics of QD lasers [16]. Theoretical studies identified what has since become known as the “phonon bottleneck” in QD’s: since the excited and ground states are not typically separated by phonon energies of ~ 36 meV, single-phonon assisted relaxation events between these levels are forbidden. Multiple-phonon events, while permitted, are typically much slower (>1 ns). Because phonon scattering is very much suppressed in QD’s, the capture/relaxation time of carriers in QD’s τ_c is predicted to be much longer than in QW’s. If the only available mechanism for carrier relaxation were carrier-phonon scattering, the bandwidth of these QD lasers would be forever limited to a few gigahertz.

However, there are several other mechanisms for carrier relaxation, which have been suggested, that provide a much faster relaxation path. In particular, methods relying on carrier-carrier interaction rather than carrier-phonon interaction can take place more rapidly. Both Auger-like mechanisms, in which a relaxing electron transfers energy to another electron, which is promoted into the continuum [52], or electron-hole scattering, in which a relaxing electron transfers energy to a ground state hole [16], have been suggested. The experimental investigation into the mechanism of the carrier relaxation time is one of the most interesting questions raised by the demonstration of QD’s and fabrication of QD lasers.

B. Direct Pump-Probe Measurements

Pump-probe differential transmission spectroscopy measurements were made by Sosnowski *et al.* [53] on self-organized

QD’s grown in our laboratory. In these measurements, a pump laser was used to populate the cladding, and probe lasers were used to monitor the population of the cladding, ground, and excited states. The measurements were done at cryogenic temperatures, and showed transition times between the cladding and excited state of the dots of 1–3 ps and relaxation times from the excited state to the ground state of about 5.6 ps. This is much less than the >1 ns predicted from phonon scattering, and *thus conclusively demonstrated that mechanisms other than phonon scattering were controlling the relaxation of carriers.*

Because these measurements were made at very low carrier densities (1 electron-hole pair per 5–6 dots), it is unlikely that an Auger-like electron-electron scattering mechanism is involved; the most likely mechanism is electron-hole scattering. The value of relaxation time of about 8 ps is also very comparable to theoretical calculations of 10 ps done on dots of a similar size and composition at cryogenic temperature [16], based on an assumed electron-hole scattering mechanism [14].

The calculated energy levels for an $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs QD and the mechanism of electron-hole scattering are illustrated in Fig. 4. An excited electron interacts with a ground state hole, promoting it to an excited hole state. The excited hole then rapidly relaxes due to its greater mass down to the ground hole state (the measurement described in [53] also tentatively identified a hole relaxation time of 0.6 ps). Because the rate of the first step depends on the vacancy of the excited hole level, this electron relaxation is expected to be quicker when there are fewer thermally populated excited holes. In contrast, the relaxation times in QW lasers do not have strong temperature dependence because the phonon emission relaxation mechanism does not have strong temperature dependence.

C. Limitations on Laser Modulation Bandwidth

Before discussing in detail how the dynamics of QD’s affect directly modulated lasers, and the measurements and analysis, we would like to mention briefly what generally limits the bandwidth of semiconductor lasers and how the particulars change for QD devices. Typically, these lasers are analyzed using a three-rate equation model, in which the number of photons, carriers in the active region, and carriers in the core are modeled by three distinct equations [54]. This model gives rise to the following equation for optical modulation response $M(f)$ as a function of frequency f :

$$|M(f)|^2 \propto \frac{1}{((f_r^2 - f^2)^2 + \gamma^2 f^2)(1 + (2\pi f \tau_c)^2)}. \quad (1)$$

The relationship between resonance frequency f_r and damping factor γ defines the K -factors, as

$$\gamma = K f_r^2 + \frac{1}{\tau_{\text{eff}}} \quad (2)$$

where τ_{eff} is the spontaneous emission carrier lifetime.

This model defines two fundamental limits to the modulation bandwidth in lasers. The capture time limit $f_{-3\text{dB-capture}}$ is the limit imposed by carrier relaxation in the QD, and the K -factor limit $f_{-3\text{dB-K}}$ comes from the fundamental dynamics, such as

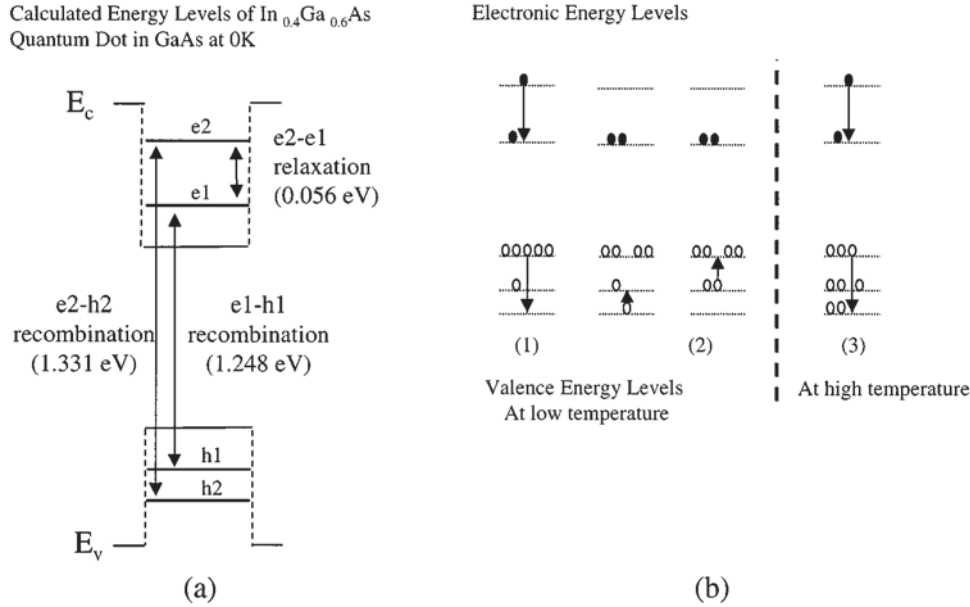


Fig. 4. (a) Electron and hole bound states and transition energies of $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs dots (from [14]). (b) Schematic illustration of the mechanism of electron-hole scattering at different temperatures.

differential gain and gain compression. Mathematically, these limits are

$$f_{-3\text{dB-capture}} = 1/2\pi\tau_c$$

$$f_{-3\text{dB-K}} \approx 9/K$$

$$K = 4\pi^2 \left(\frac{\varepsilon}{\frac{dg}{dn} v_g} + \tau_p \right) = 4\pi^2 (\tau_c \eta_{\text{eq}}^2 + \tau_p) \quad (3)$$

with ε being gain compression, dg/dn the differential gain, τ_p the photon lifetime, τ_{eff} the spontaneous emission lifetime, v_g the group velocity, and η_{eq} the equilibrium ratio of carriers in the cladding to carriers in the active region. The K -factor and the capture time are both determined by fitting measurements of the optical modulation response or small-signal electrical modulation response to forms derived from the rate equations [54], [55]. Although the differential gain is expected to be much increased in QD lasers [due to the atomic-like zero-dimensional (0-D) density of states], by itself it does not necessarily increase the bandwidth, as the bandwidth limit from the K -factor depends on the ratio between differential gain and gain compression.

The expression for K -factor as a function of capture time is derived based on assuming a well-barrier hole burning mechanism for gain compression [56] in which $\varepsilon = \eta_{\text{eq}}^2 dg/dn \tau_c$. However, this relationship is supported experimentally for both QD and QW lasers in measurements in which the differential gain is changed through changing the temperature [57]. The relationship between gain compression, differential gain, and capture time can be understood intuitively. Gain compression results from lost carriers. Hence, it is expected to be larger if either the differential gain is high and each lost carrier has more significance, or if the capture time τ_c (loosely, the carrier replenishment time) is long. The simple relationship between K -factor

and capture time encapsulated in (3) explains most of the temperature dependent modulation behavior in both QD's and QW devices.

This three-rate-equation model, which was derived initially for QW lasers, gives reasonable results when applied to experimental measurements on QD lasers. Values of capture times and differential gain determined from experiments are larger than typical values determined for QW lasers, but the measurements are in good agreement with theoretical predictions.

D. Optical Modulation Measurements

In order to gain more insight into the mechanism for carrier relaxation, the small signal optical modulation characteristics are measured as a function of temperature for single mode, ridge waveguide QD lasers. A typical QD laser heterostructure, in which the multiple dot layers are formed by self-organized growth, is shown in Fig. 5. Modulation response was typically measured with a network analyzer, high-speed (New Focus 1011) photoreceiver, and 26-GHz Miteq amplifier. The measured response was corrected for the measured frequency response of the cables and amplifiers, and the manufacturers supplied calibration curve for the photoreceiver. Cryogenic results were made with an adapted cryogenic microwave two-port test station, which had provision for manipulating two Cascade-type microwave probes over a sample which was cooled with a helium cryostat. For laser modulation measurements, a special fiber feedthrough was constructed. The laser was biased and modulated with one of the microwave probes, and the fiber was mounted to the other probe arm and aligned in front of the device to collect the modulated light.

Fig. 6(a)–(c) shows the measured modulation response of a QD laser at various temperatures 245, 155, and 80 K. The maximum modulation bandwidth increases from 5 to 6 GHz at room temperature to 7 GHz at 245 K and >20 GHz at 80 K. This factor of four increase in the ultimate modulation bandwidth is

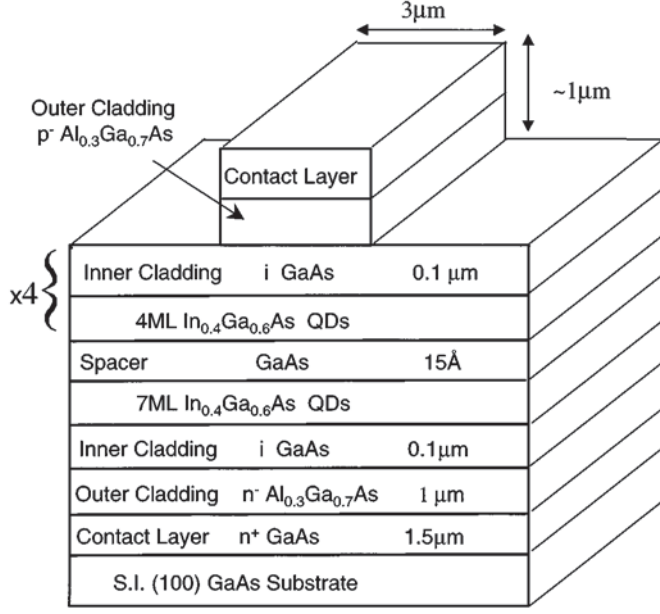


Fig. 5. Schematic illustration of a QD laser heterostructure processed into a single mode ridge waveguide laser.

accompanied by a dramatic change in shape of the curves, from a highly capture-time limited response at room temperature to a “typical” semiconductor laser response at cryogenic temperatures. We believe this is due to the temperature dependence of the carrier capture mechanism and the consequent temperature dependence of gain compression.

From the dependence of resonance frequency on injection current, the differential gain was calculated as a function of temperature and the results are given in Fig. 7. The differential gain increased from about 10^{14} cm² at room temperature to 10^{12} cm² at cryogenic temperatures, and a modulation response of >20 GHz was recorded with an injection current of only 25 mA. It may be noted that the differential gain values at both room temperature and cryogenic temperature agree very well with the calculations of Kirstaedter *et al.* [58] and Willatzen *et al.* [59], respectively, wherein, inhomogeneous broadening effects were taken into account. At temperatures below 100 K, there exists a nonequilibrium distribution of carriers amongst the dots and the measurements reflect the properties of a smaller (homogeneous) collection of dots. The differential gain is therefore very large.

E. Temperature Dependence of the K -Factor

From the relationship between the fit damping factor and resonance frequency at different currents [see (2)] the K -factor was extracted at different temperatures. Fig. 7 also depicts the K -factor for a QD laser as a function of temperature, and, for comparison, the measured K -factor for some high-speed 1-μm InGaAs–GaAs ($f_{-3\text{dB}} > 40$ GHz at room temperature) and 1.55-μm InGaAsP–InP ($f_{-3\text{dB}} > 20$ GHz at room temperature). In contrast to QW devices, where the K -factor is roughly independent of temperature, the measured K -factor increases by about a factor of five for QD devices over the temperature range of 100 K to room temperature.

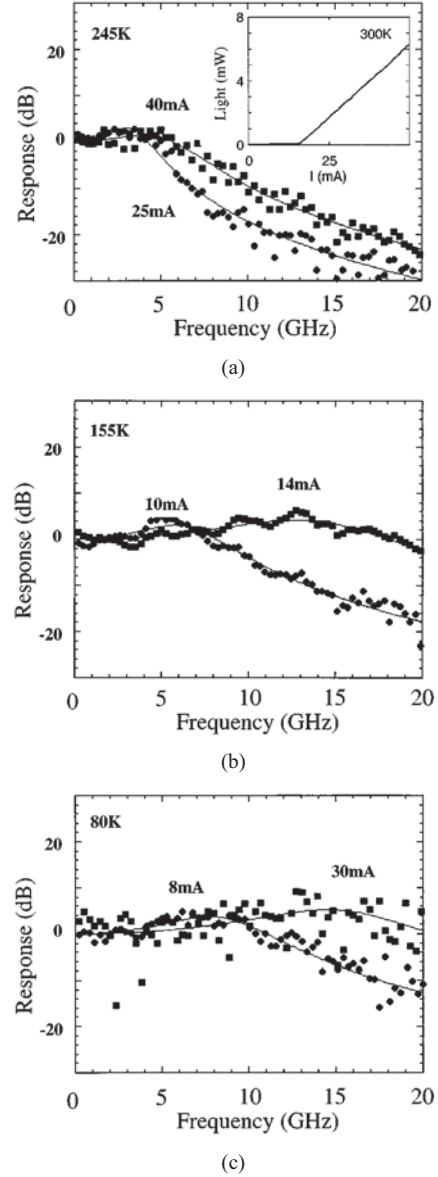


Fig. 6. Measured modulation response of 200 μm long single-mode In_{0.4}Ga_{0.6}As–GaAs four-dot layer laser ($\lambda = 1$ μm) at (a) 245 K, (b) 155 K, and (c) 80 K. The measured light-current characteristic at 245 K is also shown.

This can be quantitatively explained in terms of our understanding of the temperature dependence of the capture time in QD's. From the model proposed in [56], which is incorporated in (3), the K -factor scales with the capture time. As illustrated in Fig. 4(b), the rate of the carrier relaxation depends on the thermal occupation of the excited hole states. Hence, it is reasonable to assume that the scattering time should depend inversely on the number of hole vacancies at that energy level: the presence of thermally activated holes inhibits the promotion of new holes. Assuming that the holes are thermally distributed and that the quasi-Fermi level for holes is the ground hole state, the measured K -factor as a function of temperature can be fit to an expression based on Fermi statistics

$$\tau_c \propto \frac{1}{1 + \exp(\delta E/kT)}$$

$$K(T) = a\tau_c(T) + b \quad (4)$$

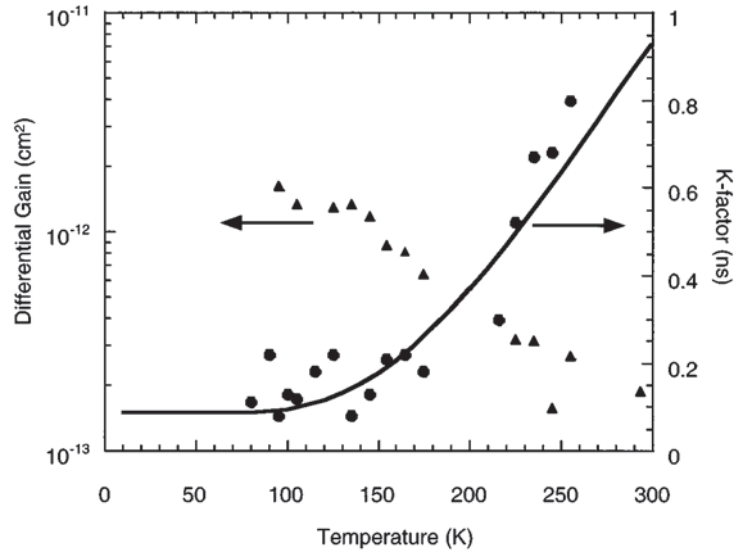


Fig. 7. Differential gain and K -factor of QD layers as a function of temperature, derived from the small-signal modulation data.

for the number of vacancies at the energy separation δE between the excited and ground electron states, with a , b , and δE as fit parameters. The parameter δE is the energy separation between the excited and ground electronic state. The extracted separation is 60 meV, and the line is the best fit curve. This should be compared to the value of 56 meV calculated using an eight-band k-p model [60] for $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs dots. *This agreement between calculated and experimental value is excellent corroboration for both the calculated energy level spacing and the determined, dominant mechanism for carrier capture being electron-hole scattering.* This model is based only on the static Fermi-Dirac distribution of holes in the QD's and its temperature dependence. The measured temperature-dependent modulation characteristics are described quite well considering only the hole distribution, but for a complete understanding, the interaction of the QD levels with the bulk material, and the temperature dependence of other relaxation processes (such as carrier-phonon scattering) should be considered as well.

On the curve of K -factor versus temperature, the position where the thermal hole levels start to be significantly populated appears as a "knee" at about 150 K. Below this point, the modulation characteristics are roughly independent of temperature. As the temperature increase above 150 K, the K -factor (and modulation bandwidth) decreases as the thermal hole population starts to significantly lengthen the relaxation time.

F. Direct Measurements of K -Factor and Capture Time in QD Lasers

The increased capture time in QD lasers impacts the laser modulation response in two ways. First, by increasing the single pole falloff associated directly with capture and modulation [see (1)], and second, by increasing the K -factor or ratio of differential gain to gain compression, [see (2)]. In modulation measurements, these factors appear together and it can be difficult to isolate the effects of each. However, both the K -factor and capture time can be observed independently with other experimental techniques.

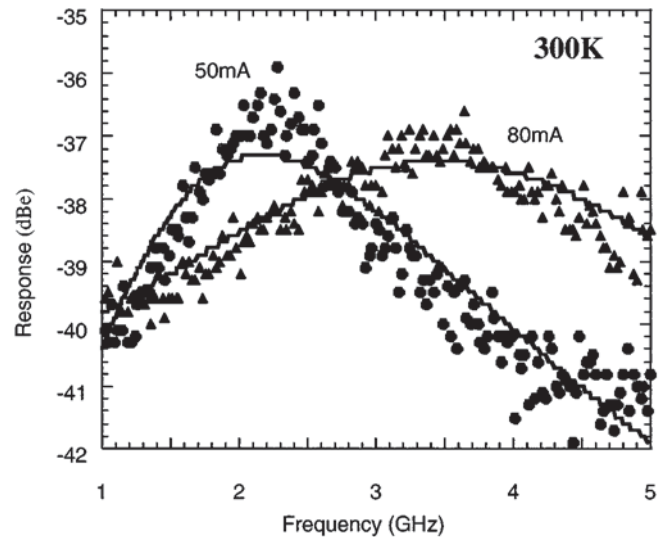


Fig. 8. RIN spectra of single-mode $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs QD laser ($\lambda = 1 \mu\text{m}$) at different injection currents and at room temperature.

The K -factor can be determined through relative intensity noise (RIN) measurements, which are independent of transport and depend only on the intrinsic dynamics of the active region. Fig. 8 shows the RIN measurement of a multilayer QD laser at various currents. The K -factor extracted from fits to these curves is about 1 ns, very consistent with typical values of K -factor at room temperature determined through analysis of small signal modulation measurements. This demonstrates that the long relaxation time affects the gain compression and K -factor directly, and that its impact on the modulation response is not just through a single-pole falloff.

The carrier capture time can also be determined more directly through analysis of the small-signal electrical impedance. The impedance is fit to an expression that is derived from a three rate equation model [55] which is much less sensitive to the intrinsic dynamics than the modulation response equation (1). Fig. 9 shows the measured small-signal impedance and the fit

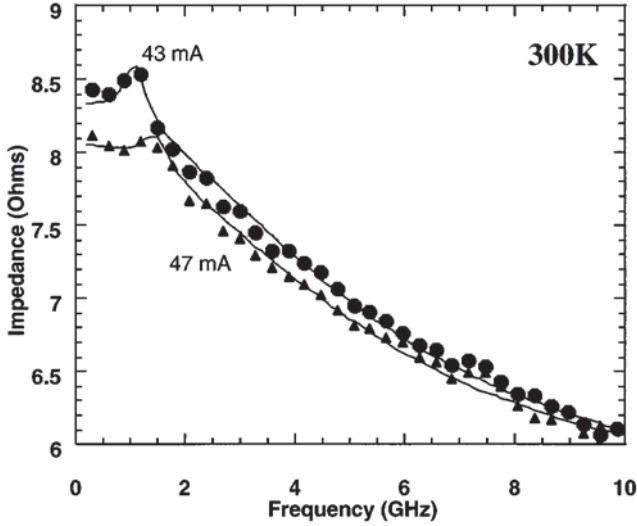


Fig. 9. Small-signal impedance measurement of a four-layer $\text{In}_{0.4}\text{Ga}_{0.6}\text{As-GaAs}$ QD laser at room temperature with an extracted capture time of ~ 30 ps.

curve. The fit to magnitude is quite good and reproduces the position of the resonance peak observed in the optical modulation response. The capture time obtained varies from 30 to 60 ps [61], consistent with the typical maximum measured bandwidths of 5–6 GHz at room temperature. In contrast, values for capture time obtained with this technique from high-speed QW lasers are < 10 ps [62].

The values for K -factor and capture time obtained are both consistent with ones obtained from direct modulation, and corroborate the understanding of device behavior obtained from analysis of modulation characteristics alone.

G. Summary of High-Speed Characteristics

In summary, the measurements of capture time and directly modulated QD laser performance are consistent with the mechanism of carrier relaxation in QD's being electron-hole scattering. Calculated theoretical values of 30 ps at cryogenic temperature and 70 ps at room temperature [16] are similar in magnitude and trend to directly measured values of 8 ps at cryogenic temperature (from pump-probe measurements) and 30–60 ps at room temperature (from electrical impedance measurements). These measured capture times are quite consistent with the maximum bandwidths attained of > 20 GHz at cryogenic temperature and 5–7 GHz at room temperature. The actual increase in K -factor (from 0.2 ns to 1 ns) is about the right order as the increase in capture time from 10 to 30 ps, and the rest of the difference could be explained by the moderate thermal dependence of η_{eq} .

In addition, a model based on the temperature dependence of the capture time (and hence the K -factor) being determined by the thermal population of the excited hole levels gave rise to a calculated electronic level spacing of 60 meV, compared to a theoretically calculated 56 meV. This agreement between experiment and theory is an excellent corroboration for both the electron-hole scattering mechanism and the calculated value of the electronic level spacing.

Based on this electron-hole capture mechanism for relaxation, we can loosely predict how the modulation response in QD's depends on the temperature and on the structure and composition (through their effect on the electronic level spacing). The dependence on temperature has been shown clearly through these measurements of modulation characteristics at different temperatures: despite the slower relaxation mechanism, at low temperatures, QD lasers had excellent modulation bandwidths of > 20 GHz. The relaxation time in the QD also depends critically on the separation between the first excited and ground electronic state in the QD [see (4)]. Tailoring this separation (through adjusting the composition or the size of the dots) will impact the modulation characteristics directly. Devices with QD's in which the separation between the first excited and ground electronic state equals to a single or multiple phonon energy may retain high-speed modulation characteristics up to room temperature. With the realization of 1.3 μm wavelength as well, that would bring QD lasers into the speed and wavelength range commercially useful for optoelectronic communications.

IV. HIGH-SPEED WAVELENGTH SWITCHING IN QD LASERS WITH INTRACAVITY SATURABLE ABSORBERS

Light-emitting devices with the capability of electrically controlled wavelength switching will be important for wavelength-division multiplexing (WDM), chip-to-chip interconnects, and for read-and-write operations [63]–[67]. As is evident from what has been said earlier, self-organized $(\text{In,Ga})\text{As-(Al,Ga)As}$ QD's generally exhibit two or more distinct transitions in the PL spectra, each separated by 50–60 meV. Such distinctly separated transitions are generally not observed in QW luminescence or lasing. In order to investigate the switching behavior, we have used a coupled-cavity system, fabricated with a QD laser heterostructure containing multiple coupled dot layers in the active region. In principle, it is possible to switch the lasing from the ground state to an excited state by increasing the injection current or by varying the cavity loss. The latter is achieved in a coupled-cavity device in which the two section are separately biased. By varying the bias across the absorbing region, the overall cavity loss can be made high enough so that the ground state gain can be made zero or negative and the excited state gain remains positive.

A typical laser heterostructure fabricated into a coupled cavity device is schematically shown in Fig. 10. By collecting the light exiting from the SA end, the light-current (L - I) characteristics of the coupled-cavity device was measured for different values of saturable absorber (SA) bias V_A . It was observed that the threshold current increased linearly from the lowest value of 18 mA as the SA bias is tuned to increase the cavity losses. Also, a distinct discontinuity (reduction in slope efficiency) was observed in the L - I characteristics at higher output powers. These two features are attributed, respectively, to nonsaturable and saturable losses in the SA [68].

The measured spectral switching characteristics are displayed in Fig. 11 for a coupled-cavity device with QD layers in the active region. The laser current is kept constant when the SA voltage V_A is changed from -4 to 2 V, and the output

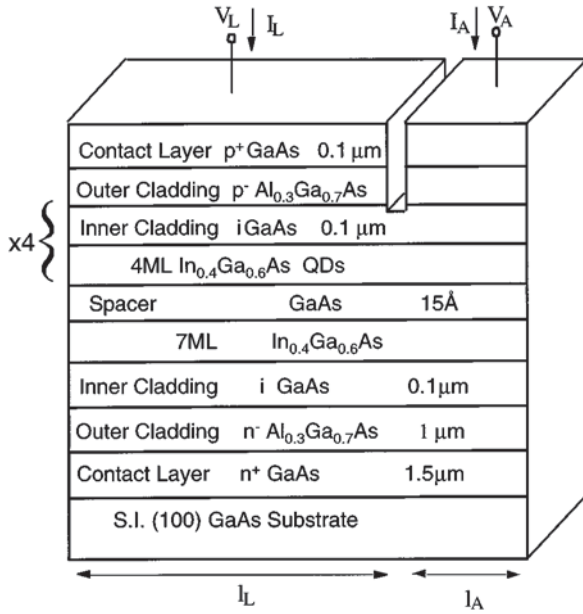


Fig. 10. Schematic of a coupled-cavity laser-saturable absorber made with a QD laser heterostructure.

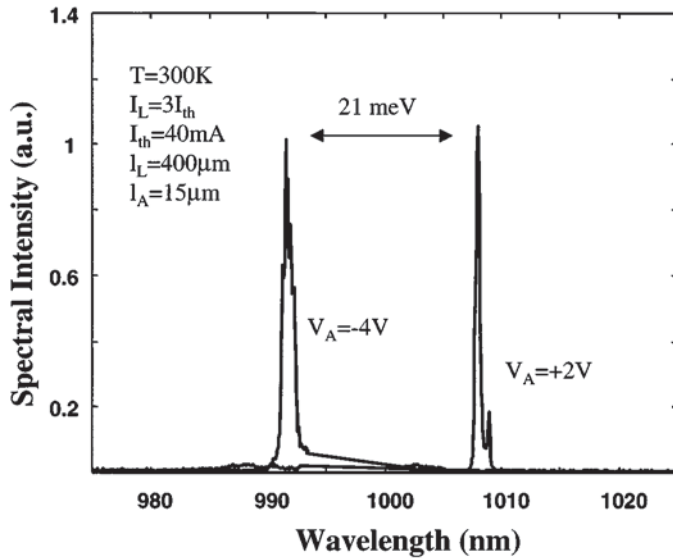
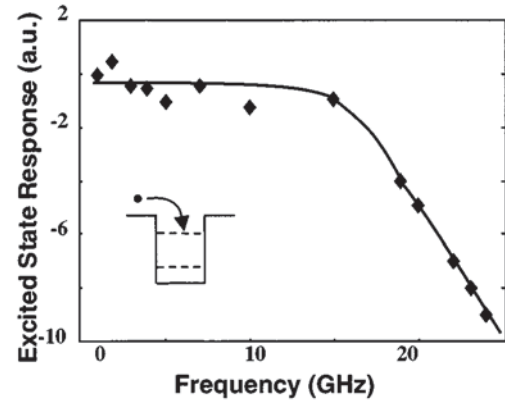


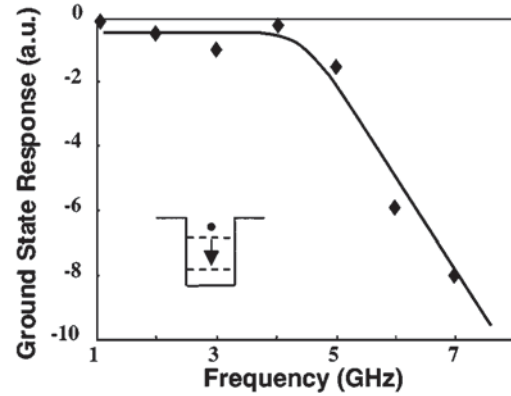
Fig. 11. Wavelength switching of QD laser by changing the cavity losses (saturable absorber bias). Only the dominant laser emission peaks at each bias are shown.

switches from 0.99 to 1.01 μm . The shift corresponds to almost 20 meV. This switching behavior is observed from both three- and five-dot layer samples. It was also observed that the discrete wavelength switching becomes easier and more pronounced when the ratio of l_A/l_L increases. The multiple peaks in the output spectra, which are separated by energies larger than the longitudinal-mode separation, are characteristic of QD laser outputs. They are believed to originate from interference effects caused by waveguide leakage into the substrate [69].

The discrete nature of the wavelength switching indicates that lasing shifts from one bound state to another. As to why the energy difference is only ~ 20 meV and not ~ 50 meV, there are a few possibilities. The bound states of the dots are made up



(a)



(b)

Fig. 12. Measured wavelength switching response of QD lasers. (a) Ground state to excited state. (b) Excited state to ground state emission. The corresponding carrier dynamics, which sets the intrinsic limit to the switching time, are shown in the inset.

of contributions from the various dot sizes and switching can occur from the ground state of larger dots to those of smaller dots, and not from ground to excited states. Another possibility is that we see switching from the uppermost ground states to the lowermost excited states of the dots, the spread in each subband being caused by the 15%–25% size nonuniformity.

We next studied the high-speed nature of the wavelength switching and the limitations imposed to high-speed operation by carrier dynamics. In the measurements made, the lasing section is dc biased and an ac signal is superimposed on a quiescent dc bias applied to the saturable absorber. The amplitude of the ac signal is chosen adequately such that the lasing can be switched to the excited state. When the absorber dc bias is such that the ground state emission is the quiescent state, then switching to the excited state is no longer observed when the frequency of the ac signal corresponds to a switching time of ~ 20 ps. The frequency response of the amplitude of the excited state transition is shown in Fig. 12(a). From analysis, we have determined that the switching time is limited by the equivalent circuit of the laser-saturable absorber. Intrinsically, the switching time is determined by the time required for electrons and holes to reach the respective bound excited states from the barrier layers. From the experiments described in

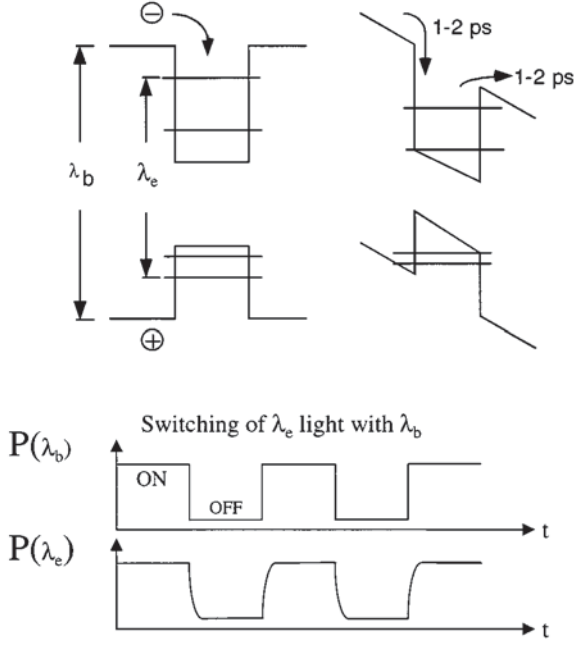


Fig. 13. Schematic illustration of photonic switching with QD's. The rise and fall times of $P(\lambda_e)$ can be ~ 1 ps.

Section III, the relaxation times to the excited states are ~ 1 ps. Hence, the switching to the excited state can be extremely fast.

On the other hand, when the laser/SA is so biased that excited state emission is observed under quiescent condition, then switching to the ground state (by making the absorber bias more positive) is much slower and from the frequency response, shown in Fig. 12(b), the switching time is estimated to be ~ 70 ps. Intrinsically, the limit to the switching speed is now set by the time required by carriers to relax to the ground states. From the laser impedance measurements, we have determined the electron relaxation times to be in the range 30–60 ps at room temperature. The value of 70 ps is close to this range. In addition to demonstrating the possibility of high-speed wavelength switching from ground to excited state emission in QD lasers, these experiments provide support to the values of carrier relaxation times estimated from other measurements.

The discrete nature of the QD transitions and the varied carrier dynamics can lend themselves to fast photonic switching schemes, as illustrated in Fig. 13. Here, the transmission of light, of wavelength λ_e , is switched with light of wavelength λ_b . When λ_b is off, λ_e is absorbed by the dots. When λ_b is switched on, then in ≤ 1 ps (which can be engineered) electrons and holes relax to the respective excited states and bleaches the absorption of λ_e . A fast turn-off in 1–2 ps can also occur due to tunneling or field-assisted tunneling of carriers from the excited state, as illustrated. With proper choice of QD and barrier materials, λ_e can be made equal to $1.3 \mu\text{m}$.

V. QD-EOM's

EOM's, which can be used both for phase and amplitude modulation can, in principle, demonstrate very high-modulation bandwidths and are generally limited by extrinsic factors.

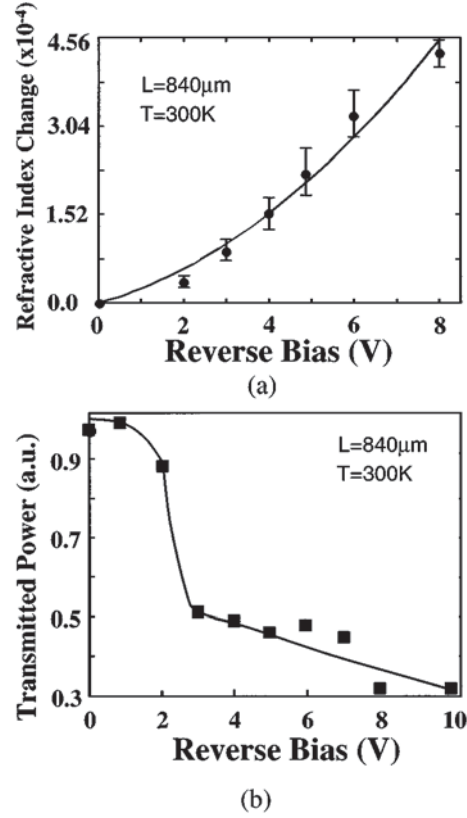


Fig. 14. (a) Measured electrooptic effect in $\text{In}_{0.4}\text{Ga}_{0.6}\text{As}$ -GaAs QD's. (b) Transmitted power as a function of bias in a QD-EOM.

Furthermore, low-dimensional quantum-confined structures such as quantum wires and dots are expected to exhibit enhanced optical nonlinearities and enhanced electrooptic effects. We have used a typical QD laser heterostructure and have measured the electrooptical coefficients by applying a reverse bias to the diode.

Measurement of the electrooptic coefficients was carried out by coupling $1.15 \mu\text{m}$ light from a He-Ne laser onto one end of a $840\text{-}\mu\text{m}$ long waveguide with a focusing lens. The polarization of the light is oriented, through use of an input polarizer, at 45° to the direction of the diode electric field with an applied reverse bias. The phase retardation of the transmitted light was measured with an analyzer and a Ge detector at the output end. The refractive index change as a function of reverse bias, obtained from the measured phase retardation, is shown in Fig. 14(a). The linear and quadratic electrooptic coefficients are obtained by fitting the measured phase retardation with the relation [70]

$$\Delta\Phi = \frac{\pi L n_0^3}{\lambda} [\Gamma_1 r E + \Gamma_q s E^2] \quad (5)$$

where

- n_0 average refractive index in the active region;
- E average electric field;
- r and s linear and quadratic electrooptic coefficients, respectively; and
- Γ_l and Γ_q linear and quadratic confinement factors, taking into account the fill factor of the QD array.

The confinement factors themselves are separated into those for the QD, the GaAs layers, and the $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ guiding layers which are, respectively, 1.25×10^{-2} , 0.415, and 0.456. The fill factor of the dots is estimated to be 0.242 using the technique described in [71]. The values of r and s obtained for the QD's are 2.58×10^{-11} m/V and 6.23×10^{-17} m²/V², respectively. Note that the linear electrooptic coefficient is larger than that of GaAs [72] or of GaAs and InP-based multi-QW's [73]–[76]. Similarly, the quadratic electrooptic coefficient is also very large compared to the QW's, in spite of a small fill factor. A multiple dot layer active region, commonly used in lasers, may yield even larger electrooptic coefficients. The bias-dependent transmission of the QD phase modulator is depicted in Fig. 14(b). A large change in transmission, almost by a factor of 2, is obtained for a small applied bias of 3 V. It is apparent, therefore, that with proper design, efficient and high-speed phase and amplitude modulators (AM's) can be made of QD's. Our group is in the process of realizing and characterizing such devices.

VI. CONCLUSION

Self-organized growth of In(Ga)As can form the active (gain) region of high-performance lasers and modulators. We have studied the high-speed modulation characteristics of SCH lasers made with such QD active regions. In particular, we have correlated the observed frequency response to the dynamics of injected hot carriers and their relaxation to the lasing states. From direct measurement of laser impedance and optoelectronic responses as function of frequency and from independent pump-probe measurements of carrier relaxation rates within the dots, it is apparent that electron-hole scattering is the dominant carrier relaxation mechanism. The modulation bandwidth of the lasers is limited to 6 GHz at room temperature, and increases to >20 GHz at cryogenic temperatures. High-speed wavelength switching of the lasing transition from ground to excited state and vice versa has also been studied. Finally, EOM's made with QD active regions are described. The electrooptic coefficients in the dots are much larger than in GaAs.

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