Broadband Laser for Optical Telecommunication

Mohammed Z. M. Khan

Optoelectronics Research Laboratory, Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Abstract

This article introduces a new class of broadband semiconductor lasers by presenting the perspective of their principle of operation and potential application in energy-efficient optical communication. Firstly, the working principle of a semiconductor laser is discussed, followed by the significant advancements in the form of quantum-confined active semiconductor materials and heterostructure laser devices. Then, the underlying principle of broadband emission, which are the broad gain-bandwidth active materials and the related carrier dynamics, are discussed in detail. Finally, the demonstration and status of broadband quantum-confined active region based semiconductor lasers, from the literature, are discussed. The article concludes by describing their utilization as a cohesive single light source in wavelength division multiplexed optical communication system.

Keywords: semiconductor lasers; quantum-confined nanostructures; broadband light sources; broadband lasers; optical communication

1 Introduction

In today's world, semiconductor light sources have become a necessity on which we rely on in several applications and fields. Semiconductor light sources, as the name indicates, are devices based on semiconductor materials that can emit light under certain conditions. These devices possess various features such as compactness, cost-effectiveness, energy efficiency, and small environmental fingerprint.
Said features made these devices ideal for employment in multiple applications, including metrology, medical laser surgery, and optical communications. Semiconductor light sources are typically light-emitting diodes (LEDs), superluminescent diodes (SLDs), and laser diodes (LDs). Traditionally, LEDs and SLDs emission spectrum span from tens to hundreds of nanometers while LDs are generally <5 nm, where the former two devices emit, respectively, under spontaneous and amplified spontaneous emission (ASE) while the latter under stimulated emission. Structurally, LEDs, SLDs, and LDs are similar where an active medium (where the generation of photons takes place as a result of electron-hole radiative recombination, resulting in light emission) is sandwiched between the doped layers. Moreover, SLDs and LDs are fabricated in the form of a waveguide to achieve light amplification and hence high power compared to LEDs.

Nonetheless, light sources can be made to achieve broad and ultra-broad emission spectra covering wide ranges of wavelengths and are becoming exceedingly attractive in several fields and applications. Typically, such broad emissions are achieved through nonlinear mechanisms in optical fibers, as shown in Figure 1. However, these methodologies are generally bulky, complex, and costly [1–3]. On the other hand, semiconductor light emitters, particularly SLDs, was found to be superior to the optical fibers counterpart, such as low-power consumption and high-quantum efficiency while being portable, compact, and low cost. Today, SLDs are being commercialized in a few fields of applications and play a vital role in optical coherent tomography (OCT) [4]. In terms of structure, they are similar to LDs, except that they inhibit optical feedback mechanisms within the typically longer cavities, which result in extremely large threshold
currents with ideally suppressed stimulated emission (i.e. lasing mechanism). Although these devices exhibit better optical power compared to LEDs, they are still inferior compared to the LDs, for example, having smaller average power spectral density (APSD), i.e. the ratio of optical power to the emission bandwidth coverage, and low quantum-efficiencies. This has driven the development of other broadband technological solutions, such as frequency conversion [5, 6], frequency comb generation [7, 8], etc., to address these multitudes of applications, and yet, complexity and cost issues remained to be solved. Hence, a compact, efficient, and high APSD broadband emitting device is preferred for practical applications.

In general, the generation of photons within a light source is achieved by the transition of an electron from an excited state to recombine with a hole in the ground state (GS). The energy difference between these states is called the energy bandgap and determines the wavelength (frequency) of the generated photon according to the well-known Planck's equation:

$$\lambda = \frac{hc}{E}$$

where $\lambda$ is the generated photons wavelength, $h$ is Planck's constant $6.626 \times 10^{-34}$ Js, $c$ is the free-space speed of light $3 \times 10^8$ m s$^{-1}$, and $E$ is the effective energy bandgap associated with the transition. In that respect, the controllability of the emission wavelength of a light source can be achieved by tuning the energy bandgap of the transitions.

Conventional narrowband semiconductor light sources generally are associated with a homogenous active medium that results in uniform energy bandgaps throughout the material structure where the generation of photons takes place through electron-hole pair recombination. Consequently, the entire emission of the light source is limited to that particular wavelength (with a small variance depending on the degree of material inhomogeneity). Conversely, the semiconductor light sources active region material (i.e. the nanostructures) can also be made deliberately inhomogeneous through various techniques where different portions of the active region are associated with varying energy bandgaps and hence varying wavelengths. As a result, these different wavelength components add up collectively into a comprehensive gain profile and thus produce singular broadband emission covering a wide spectrum depending on the degree of inhomogeneity of the active region material structure. This material bandgap engineering concept has been readily applied to SLDs with improved emission bandwidth; however, the optical power remains a concern.

Recently, semiconductor broadband laser diodes (BLDs) have been demonstrated in the near-infrared region employing highly inhomogeneous active regions (i.e. broad gain active materials) [9, 10]. This technology is greatly favorable to the other approaches as it provides simultaneous achievement of high power and broad lasing emission bandwidth, hence high APSD, besides exhibiting a high degree of integrability with other optical components while attaining the features mentioned above of broadband semiconductor light sources, i.e. compact and cost-effective. Table 1 summarizes a comparison between LDs, SLDs, and BLDs in terms of operation, characteristics, and structure.

For the near-infrared region, two III-V semiconductor material systems are used in the growth of these structures, namely GaAs- and InP-based systems. Nonetheless, depending on the adopted material system and composition of the materials, the effective bandgap energy of these SLDs and BLDs can be tuned during the growth of the active region to cover a wide range from $\sim 1.1$ to $\sim 1.31$ μm (GaAs) and $\sim 1.5$ to $\sim 2.0$ μm (InP) wavelengths. In other words, almost six important optical telecom wavelength windows can be covered with these structures, namely O- to U-Bands (i.e. $\sim 1.26$–$1.36$ μm (O-Band), $\sim 1.36$–$1.46$ μm (E-Band), $\sim 1.46$–$1.53$ μm (S-Band), $\sim 1.53$–$1.565$ μm (C-Band), $\sim 1.565$–$1.625$ μm (L-Band), $\sim 1.625$–$1.675$ μm
Broadband Laser for Optical Telecommunication

Table 1 Summary of the difference between SLD, LD, and BLD in terms of their characteristics.

<table>
<thead>
<tr>
<th>Property</th>
<th>SLD</th>
<th>Narrowband LD</th>
<th>BLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light emission process</td>
<td>Amplified spontaneous emission</td>
<td>Stimulated emission</td>
<td>Stimulated emission</td>
</tr>
<tr>
<td>Optical bandwidth</td>
<td>Large</td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>Optical power</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>APD</td>
<td>Small</td>
<td>Large</td>
<td>Medium</td>
</tr>
<tr>
<td>Coherence length</td>
<td>Small</td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>Threshold current</td>
<td>—</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Optical feedback</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Device structure</td>
<td>Optical waveguide</td>
<td>Optical waveguide</td>
<td>Optical waveguide</td>
</tr>
</tbody>
</table>

(U-Band), as standardized by the International Telecommunication Union (ITU).

Naturally, semiconductor long-wavelength BLDs have become very attractive and garnered attention from the research and development community for implementation in several applications, mainly optical telecommunication, atmospheric monitoring, bio-medical imaging, metrology, etc. [11]. Figure 2 shows a summary of the applications of broadband light sources in the near-infrared region alongside their corresponding bandwidth coverage. Among the most important applications are medical diagnostic applications, particularly OCT, wherein SLDs and BLDs could accomplish high axial-resolution, signal quality, and depth of imaging as these characteristics are governed by the emission bandwidth and optical power of the employed light source [4,12].

On another front, the compactness and high optical power associated with BLDs qualify them as ideal light sources in different spectroscopy methodologies and applications viz. transmission, absorption, and luminescence used in molecular and material analysis and characterizations [13]. In particular, BLDs emitting in the range between 1100 and 1650 nm are viable compact portable in-situ multicomponent chemical sensors for a wide range of atmospheric and planetary gases, including CO, CO₂, CH₄, etc. [14, 15].

Furthermore, for applications of monitoring atmospheric pollution, light detection and ranging (LIDAR) and laser detection and ranging (LADAR) techniques have long been regularly utilized. In both methods, the light source’s wavelength is tuned to the absorption point of the specimens being analyzed that limits the measurement to one pollutant at a time. With that said, BLDs would potentially increase the efficiency of the pollution monitoring system by simultaneous multi-wavelength measurements while being cost-effective.

Another primary application of BLDs is high-precision optical metrology that necessitates broadband light sources in the near-infrared region. Said applications include optical instrumentation, optical time-domain reflectometry (OTDR) for optical fiber fault detection, and dense wavelength division multiplexed (DWDM) component characterization. In these applications, SLDs and BLDs are strong contenders to achieve a high degree of sensitivity and resolution in OTDR, in particular. Moreover, the high optical power of BLDs makes them very attractive sources in optical systems such as fiber gyroscope in addition to their broadband emission [16].

Nevertheless, the most useful and essential application of semiconductor light sources is optical telecommunication systems. Nowadays, the explosive consumer demand for bandwidth-hungry applications and...
ultra-high-definition applications such as, ultra-high-definition television (UHD-TV), voice-over-internet-protocol (VoIP), and internet of things (IoT) has pushed research and investigation for solutions and systems that can satisfy the market’s, industry’s, and consumer’s demand while being energy efficient (green communication) compact and cost-effective, in particular, in implementing wavelength division multiplexed (WDM) architectures. WDM technology provides simultaneous logical connectivity to multiple remote locations over a single point-to-multipoint optical fiber topology; in other words, a single shared medium can be used to transmit multiple channels simultaneously, enabling the realization of high channel capacities [17]. Figure 3a illustrates a conventional WDM optical communication system where $N$ ultra-narrow band semiconductor laser sources are used to provide $N$ wavelength channels (sub-carriers) on which $N$ information signals are transmitted over a single optical fiber/free space channel simultaneously after being multiplexed via an array waveguide grating (AWG) multiplexer. At the receiver end, these sub-carriers are demultiplexed and then sent to $N$ receivers that may be end-users or other sub-network. On the other hand, a single Fabry–Pérot (FP) BLD can potentially replace the $N$ narrow-band LDs by generating $N$ lasing longitudinal FP modes that can serve as $N$ wavelength channels or sub-carriers of the WDM system. Figure 3b shows a reduced WDM architecture where an AWG demultiplexer separates $N$ wavelengths channels from a single broadband lasing spectrum, where each channel can be modulated separately and then multiplexed, similar to the conventional WDM system. This could significantly reduce the cost and size by a factor of $N$
besides minimizing the power consumption and providing additional flexibility to the system.

2 Semiconductor Devices

Broadband semiconductor sources are classified into LDs and SLDs. In the following, a qualitative description of each of these devices is presented, which is crucial in understanding the broadband lasing technology.

2.1 Laser Diodes

The name Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation." Invented in 1962, the semiconductor lasers are constructed from a forward-biased p-n junction, which is made up of direct bandgap materials whose physical and atomic structure confers the possibility for efficient photon emission. Example of direct bandgap materials includes GaAs, InP, and their ternary and quaternary compounds. The lasing process relies on various radiation mechanisms happening in the active region of the device. The active region may be a depletion region formed because of band alignment of the p-type and n-type semiconductor material in the p-n homojunction device or could be a separate intrinsic region (active material) sandwiched between the n-type and p-type semiconductors, known as p-i-n structure, as shown in Figure 4a. Absorption or emission of radiation (light–matter interaction) occurs in an active region if a carrier transition between the conduction band (CB, $E_c$) and valence band (VB, $E_v$) energy levels ($E_c > E_v$) takes place, known as interband transition. If a carrier is excited to a higher energy level $E_v$, absorption of the photon takes place.
On the other hand, if a carrier is relaxed to a lower energy level \( E_v \), the emission of a photon takes place. In either case, the photon acquires energy \( \Delta E = E_g = E_c - E_v = h\nu \) (\( E_g \) is the bandgap energy, and \( \nu \) is the photon frequency). Moreover, lasing with a directional beam of light and small wavelength bandwidth is achieved due to the third process known as stimulated emission occurring in the active region. In this type of emission, a photon is emitted in this region of the semiconductor device by an impinging photon while acquiring its characteristics, i.e. the same direction, energy, phase, and polarization of the impinging photon.

In general, under the state of thermal equilibrium, the CB of the active region of the semiconductor material is almost empty, while electrons nearly occupy the VB. In this case, the rate of the absorption process is being balanced by the reverse radiative stimulated and spontaneous emission process, which, at the macroscopic level, can be viewed by Einstein’s relation:

\[
B_{cv}^{\text{stim}} + B_{cv}^{\text{sp}} = A_{\text{ab}}^{\text{vb}}
\]  

where \( B_{cv}^{\text{sp}} \) and \( B_{cv}^{\text{stim}} \) are the respective rates of spontaneous and stimulated emission and \( A_{\text{ab}}^{\text{vb}} \) is the absorption rate. Upon providing external energy in the form of a forward biasing (pumping) the semiconductor device, carriers, which are holes and the electrons, flow respectively through the \( p \)-type and \( n \)-type materials and start populating in the active region with electrons occupying the CB and holes accumulating in the VB, as shown in Figure 4a. Moreover, radiative-recombination of electron and holes leading to spontaneous emission of photons (i.e. generation of photons of random phase, polarization, and direction), as well as absorption of these generated photons (non-radiative recombination) by the active region due to scattering, material defects (crystal and dopant related imperfections), free carrier absorption, etc. simultaneously occurring in the system.

The spontaneous emission builds up the optical gain \( g \) in an optical wave in the active region, and this \( g \) increases as the number of electrons and holes injected across the junction increases. Since the spontaneous photons have random directions, a fraction of these photons propagate back and forth along the active region if assisted by a mirror cavity. These photons are responsible for starting the stimulated emission process in the system once the gain \( g \) increases and reaches the gain threshold \( g_{th} \) due to multiple reflections from the mirrors. In other words, when population inversion is achieved, which is the electron population \( (N_c) \) in CB, becoming greater than the hole population \( (N_v) \) in VB, a crucial condition to initiate stimulated emission that is accomplished by increasing pumping. This requirement can be written at the macroscopic level as:

\[
B_{cv}^{\text{stim}} N_c > A_{\text{ab}}^{\text{vb}} N_v
\]  

In general, the carrier population depends on the density of states (DOS) of the carriers in the respective bands that is a continuous
function of wavelength. Thanks to the band structure of the semiconductor crystal and the dispersion relation of the electrons and holes in the active region that enabled the inclusion of several energy levels. Hence the gain $g$ is a function of these energy levels, or in other words, dictated the emitted photons wavelength or energy, i.e. $g(\lambda)$, thus making a semiconductor laser distinct from other types of lasers.

Therefore, from the above discussion, three important entities are needed for lasing to occur in a system; population inversion (achieved by external pumping), amplifying medium (active region material), and an optical cavity or resonator (for reflecting the generated photons back and forth). These entities are easily configured in a single semiconductor LD on a chip, thus standing out over other gas lasers, solid-state lasers, etc. To understand the last two requirements further, consider Figure 4b that shows a typical resonator created by two parallel mirrors, commonly referred to as the FP cavity. This type of cavity formation is straightforward in a semiconductor laser of length $L$ by cleaving both the ends, thus forming crystal facets that act as partial mirrors with reflectively dictated by the refractive index step of the semiconductor material and air (usually $R_1 = R_2 = \sim 0.3–0.35$ for GaAs and InP based devices). During a single pass of the spontaneous photons, $g$ is generally small, but with multiple passes, $g$ increases substantially since with each pass, the stimulated photons are approximately doubled, thanks to increased radiative recombination rate that is maintained by increasing external pumping. This process is continued until gain threshold $g_{th}$ is reached, after compensating for the various losses occurring in the cavity (i.e. mirror loss $\alpha_m$ and internal material loss $\alpha_i$ as discussed above). Note that a semiconductor laser also behaves as an optical waveguide with the active region at the center of the core and the $p$-type and $n$-type regions forming the cladding layers. Hence, the generated photons inside the active region and those exiting out of the mirror are coupled to the lateral optical mode of the waveguide and are the usable laser beam. Hence, $g$ in the above discussion refers to the modal gain, i.e. an overlap of the optical mode with the active region since only this part of the active region takes part in the amplification process. Now, considering the photon decrement (i.e. loss) to be to $e^{-\alpha_i}$ and photon increment (i.e. gain) to be $e^g$, the threshold gain condition to sustain a lasing action in the round trip 2L of the cavity is given by:

$$g_{th} = \alpha_i + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) = \alpha_i + \alpha_m$$  (4)

Only discrete frequency/wavelengths would be resonant with the FP cavity, and each corresponding to a mode of oscillation often referred to as longitudinal mode. From the available cavity solutions, given by $\lambda_m = 2n_a L / m$, where $n_a$ is the refractive index of the active region and $m$ an integer, those who satisfy the above Equation (4) appear in the laser beam wavelength spectrum, whereas others are suppressed. This is qualitatively illustrated in Figure 5 for a typical narrowband lasing FP semiconductor LD with longitudinal mode spacing given by $\Delta \lambda = \lambda_m^2 / 2n_a L (\lambda_m$ being the peak wavelength). Moreover, the active material gain is a function of pumping current, and if $g < g_{th}$, then no lasing occurs. Therefore, a minimum pumping level is required to initiate lasing, which is known as threshold current $I_{th}$. Below this current value, the semiconductor laser would be in spontaneous emission mode and above this value, in simulated emission mode.

2.2 Superluminescent Diodes

SLD operation is similar to that of the LD, except the optical feedback mechanism is inhibited. Hence, the device experiences a single-pass optical amplification of the spontaneous emission photons along the device length $L$; hence, the name ASE semiconductor source is usually exercised. The emitted photons are coupled into the lateral optical mode of the waveguide, similar to the LD
Broadband Laser for Optical Telecommunication

3 Semiconductor Device Structure

3.1 Heterostructure

Remarkable progress in the performance of the semiconductor laser was achieved by the incorporation of double-heterojunction \( p-i-n \) in the device, as shown in Figure 4a. It consists of three different semiconductor sections with the bandgap of the middle semiconductor material (usually intrinsic) selected to be within the bandgap of the \( p \)-type and \( n \)-type semiconductor materials (could be same semiconductors with different doping concentrations as well). In other words, a smaller bandgap material is sandwiched between two large bandgap materials. This causes carrier confinement within the active region, as depicted in Figure 4a. Moreover, the structure naturally discussed above, and is collected from one or both the ends of the waveguide.

3.2 Quantum-confined Active Region

Further improvements to the optoelectronic properties of semiconductor laser were achieved by incorporating quantum-confined nanostructures in the active region of a \( p-i-n \) device structure, thus exploiting the quantum mechanical behavior of carriers. Thanks to the tremendous improvement in the material growth technologies such as molecular beam epitaxy (MBE) and metal-organic vapor phase epitaxy (MOVPE), which made the growth of high quality and ultra-thin layers (in the nanometer range) feasible. In the following, a brief description of various reported quantum-confined nanostructures is presented.

3.2.1 Quantum-Well

A quantum well (Qwell) is a thin layer capable of confining electrons and holes only in the spatial direction perpendicular to the surface of the layer while allowing free movement in other directions, i.e. two-dimensional (2D) system unlike the conventional bulk 3D system, as illustrated in Figure 6. This ultra-thin semiconductor layer is further embedded between two semiconductor layers called the quantum barrier layers. The semiconductor material for the middle layer is selected such that the electron available for conduction in this layer has lower energy (narrower bandgap) than the outer layers, thus forming an energy gap that can confine electrons, provides optical confinement as well due to the inverse relation between refractive index and bandgap of the material. This enables encompassing materials to act as waveguide cladding layers while the active region serves as part of the optical waveguide core. A proper bandgap engineering of individual material is exercised to achieve an efficient heterostructure (i.e. seamless flow of carriers into the active region) since bandgap alignment at the interface results in a discontinuity in the VB and CB edges known as band offsets and defines the electronic properties at the interface.
Figure 6 Illustration of bulk (a) and Qwell (b) semiconductors showing the typical bulk DOS (c) and the modification to the DOS because of carrier confinement in the z-direction (e). (d) Qwell energy band schematic showing the GS and ES1 energy levels due to quantization. Source: Adapted from M. Z. M. Khan, "Semiconductor Quantum Dash Broadband Emitters: Modeling and Experiments", PhD Dissertation, KAUST, 2013.

as shown in Figure 6a,b. Moreover, the thickness of the thin middle layer is in tens to hundreds of Angstroms (Å), i.e. in the order of de Broglie’s wavelength \( \lambda_B = h/\sqrt{2m^*E} \) (\( m^* \) and \( E \) correspond to the carrier effective mass, and it is kinetic energy). For instance, electrons in GaAs material exhibit \( \lambda_B \approx 5 \text{nm} \). Therefore, the electron in this layer experiences quantization effects in the perpendicular z-direction while it moves freely parallel to the layer (x- and y-directions), as illustrated in Figure 6d,e. The allowable energies in this potential well are discretized and the well-known parabolic dispersion relation for the bulk semiconductor material depicted in Figure 6c, changes in case of Qwell to:

\[
E_e = E_c + \frac{\hbar^2}{4\pi m^*} \left( \frac{n \pi}{d} \right)^2 + k_x^2 + k_y^2
\]

\[
E_h = E_v - \frac{\hbar^2}{4\pi m^*_h} \left( \frac{n \pi}{d} \right)^2 + k_x^2 + k_y^2
\]

Here \( n \) is the quantization number, \( k_i \) the wave vector in axis \( i \), \( d \) is the Qwell layer thickness and the indices \( e \) and \( h \) denote electrons and holes, respectively. This limited carrier motion in one direction also modifies the fundamental DOS property of the semiconductor Qwell layer material to a step-like function, as shown in Figure 6d,e. This infers that the DOS remains constant to specific energy and increases step-wise to the next higher energy sub-band within the CB or VB, i.e. in general, 2D-DOS,

\[
D_{2D}(E) : \sum_n U(E - E_n)
\]

where \( E_n \) is the allowed energy states in the confinement direction, and \( U(x) \) is a unit step function. Hence, confinement of carriers in the lowest energy level (GS) step-like DOS improves the radiative recombination in a Qwell compared to the bulk active region and significantly enhances the device performance, for instance, reduced \( I_{th} \).

Moreover, the majority of carriers are forced to recombine from a discretized energy level, thus narrowing the laser spectral linewidth tremendously.

Equation (5) also implies that the transition energy \( (E_0 = E_e - E_h) \) level for the electrons...
to recombine with holes in the potential well is now larger than the bandgap $E_g$ of the semiconductor Qwell material, as depicted in Figure 6d. Hence, the properties of Qwell, particularly the quantized energy levels, can be tailored by varying the barrier layer or the Qwell layer material composition, and the thickness. Stacking multiple Qwells (MQWs) consisting of different layers of alternating materials are also employed to alter the electrical and optical properties of the MQW system by varying the barrier thickness (i.e. either segregate or connect the Qwells). Moreover, MQW also improves the gain of the active region by increasing the material volume and are often employed in semiconductor lasers.

3.2.2 Quantum-wire and Quantum-dot
Quantum wire (Qwire) and quantum dot (Qdot) are narrow structures capable of confining electrons and holes in two and three spatial directions, i.e. one- and zero-dimensional system, respectively, as depicted in Figure 7. By employing photolithography or electron-beam lithography, one could imagine that Qwell can be patterned and etched to create Qwires, and cleaving the Qwires into tiny parts Qdots can be formed, albeit detrimental to the integrity of the semiconductor due to the inadvertent damage of semiconductor surfaces. In these low-dimensional systems, an increase in the charge carrier localization results in a change in the semiconductor material band structure with digitalize electronic states in two (Qwire) and three (Qdots) directions, as shown in Figure 7, with quasi delta-like and delta DOS, respectively, given by:

$$D_{1D}(E) = \sum_{n,m} \frac{1}{\sqrt{E - E_{n,m}}}$$ (7a)

$$D_{0D}(E) = \sum_{n,m,l} \delta(E - E_{n,m,l})$$ (7b)

where $E_{n,m}$ and $E_{n,m,l}$ are the discretized allowed energy levels in the confined directions in Qwire and Qdot, respectively. Since the DOS of an isolated ideal Qdot corresponds to a delta function, and no state exists between the delta-peaks, which is similar to atoms, Qdots are sometimes also referred to as artificial atoms [19].

The most common approach to grow Qwires/Qdots is the strained epitaxial growth known as the Stranski–Krastanov (SK) method. In this technique, a thin layer of semiconductor material (InAs) consisting of an intentionally larger lattice constant (atomic spacing) is grown over a smaller lattice constant material (GaAs/InP substrate), which will create a resulting strain due to difference in lattice constants that could be in the range of several percents (4–7% for InAs/GaAs and InAs/InP). In an attempt to reduce the resultant strain energy between the bonds and under favorable conditions, the thin top layer spontaneously self assembles into two- or three-dimensional islands, which are Qwire and Qdots, respectively. Afterward, the growth of lattice-matched material over these Qdots/Qwires completes the confinement potential, and the lattice constant adapts to the overgrowing material for the subsequent growth of other layers.
Figure 8: An illustration of self-assembled Qwires (a), Qdots (b), and Qdashes (c) through the atomic force microscopy images. Source: (a) Luis Javier Martínez, Benito Alén, Ivan Prieto, David Fuster, Luisa González, Yolanda González, María Luisa Dotor, and Pablo Altor Postigo, “Room temperature continuous wave operation in a photonic crystal microcavity laser with a single layer of InAs/InP self-assembled quantum wires,” Opt. Express 17, 14993–15000 (2009); (b) D. Zhou et al., “Study of the characteristics of 1.55 μm quantum dash/dot semiconductor lasers on InP substrate,” Applied Physics Letters, vol. 93, p. 161104, 2008; (c) MZM Khan, PhD dissertation, KAUST 2013.

A proper strain engineering approach is required to grow either Qwires or Qdots, whose sample planar view is shown in Figure 8, which is obtained through atomic force microscopy (AFM) [20, 21]. As seen, the naturally occurring shape and size fluctuation of self-assembled Qdots/Qwires is visible in Figure 8, which exhibits small material volume and may saturate the system gain at high pumping. Therefore, in general, multiple stacks of Qdot/Qwire layers are utilized to improve the modal gain $g$ of Qdot/Qwire based semiconductor broadband devices.

### 3.2.3 Quantum-dash

Quantum dashes (Qdashes) are asymmetric and elongated 2D nanostructures, resembling a combination of Qdots and Qwires, as depicted in Figure 8. The dimensions, i.e. width, height, and length, are generally in the range of $\sim 10–20$ nm, $\sim 1–4$ nm, and $\sim 30$ to hundreds of nm, respectively. When the SK growth technique is applied with thin InAs material layer on the InP platform, elongated nanostructures that are asymmetric dot-like and wire-like are formed instead of pure 3D Qdot islands, and this new-class of the nanostructure is referred as Qdashes, as shown in Figure 8. The formation of this new Qdash structure is attributed to the complex growth kinetics and anisotropic surface strain that dominates, causing InAs material to form elongated nanostructure instead of 3D dot islands. As such, unlike zero-dimensional confinement of carriers in Qdot structure, only two directions are confined, leaving the elongation direction unconfined, thus limiting the Qdash’s carrier confinement. Such a quasi-zero dimensional DOS system is shown to acquire the electrical and optical properties of Qwires. This low-dimensional nanostructure attracted the scientific community much because of its emission in the near-infrared region and covering the optical fiber communication wavelengths. Also, these nano-islands exhibits higher gain than Qdots due to the large material volume, a result of inherited intermediate properties between Qwells and Qdots. These niche features offered by Qdashes have been exploited to realize various semiconductor devices, including broadband lasers and SLDs [16, 22].

### 3.3 Unique Active Region Characteristics for Broadband Applications

The self-organized SK growth is a random process that results in each Qdot/Qdash transition energy state to differ based on size, shape, and composition. This statistical process could only be controlled with macroscopic parameters like substrate temperature, growth rate, V/III ratio, etc. As this causes a variation in confinement potential of each Qdot or Qdash, the corresponding delta-function or quasi-zero-dimensional DOS is no longer valid, and the concept of the ensemble is usually employed. The groups or ensembles of Qdot or Qdash are represented by a single confined transition state. Hence, all these different confined states of each Qdot or Qdash ensemble are encompassed with an inhomogeneously broadened Gaussian curve, as shown in Figure 9, assuming a single $E_0$ GS energy level of dot/dash ensemble. Moreover, in Qdot/Qdash, the gain is spatially distributed,
and hence, recombination occurs within them at fixed dot/dash positions. Although these nanostructures are spatially isolated, their carrier dynamics allow them to interact, which is discussed in the subsequent section. The Gaussian envelope width $\Gamma_{inh}$ indicates the interband transition energy spread of the dot/dash ensembles and qualitatively dictates the gain profile of the active region material. As shown in Figure 9a, optimization of SK growth process could lead to a narrow gain profile, indicating nearly uniform Qdot/Qdash size and the closer the DOS to the ideal case of delta/quasi-delta function, hence would result in narrowband lasing emission if employed as active gain material in semiconductor lasers, depicted in Figure 5. On the other front, a normal growth process results in dispersive GS energy transitions due to dissimilar Qdot/Qdash size active region. This results in a broad gain profile, as depicted in Figure 9b, and is an essential requirement for the realization of broadband lasers. In the following, more insight into achieving broad gain active material and the carrier dynamics governing this new-class of material are discussed.

3.3.1 Broad Gain Active Materials

The naturally occurring inhomogeneous broadening of the active region offered by Qdot/Qdash nanostructures, which is not possible with a Qwell active region, has recently attracted the scientific community and has been an exciting topic of research nowadays for broadband applications. As illustrated in Figure 9b, different dot/dash ensembles with different heights leads to a variation of the potential well and hence alters the electron-hole GS transition energy, thus creating broadband of GS transition energies for carrier radiative recombination. Moreover, a broad and flat-top gain from Qdot/Qdash active materials could also be achieved with comparable DOS of each electron-hole transition state, through bandgap engineering, which is crucial to realize a broadband semiconductor laser. This is qualitatively discussed using Qdot-based active material using two approaches and is applicable for the Qdash system as well. In the first approach, a collective broad and nearly flat gain profile is obtained from a composite three-stack Qdot system by using the natural in-plane inhomogeneity of a Qdot layer while employing identical growth conditions to all stacks. Here, the system relies on the natural Qdot size dispersion across the stacks, as shown in Figure 9b for a single GS Qdot system. The other approach is based on employing nonidentical growth

![Figure 9](image-url)
conditions to each Qdot stack, thereby attaining different Qdot size fluctuations, as illustrated in Figure 10 for a three-stack configuration with GS and excited state 1 (ES1) transition energies.

The first approach is quite straightforward; however, it usually is limited to a moderately wide gain profile, while the second technique is quite appealing as ultra-broad and flat-top gain profile can be achieved. In this case, the intentional inhomogeneous broadening across the stacks can be accomplished by chirping the active region, i.e. by varying the strain during the growth of each Qdot stack by varying the barrier/capping layer thickness/composition, or by modifying the Qdot material composition itself, or both. Developing broad gain active materials from both chirped and un-chirped (natural broadening of the gain profile) methods has been the area of exciting and active research for realizing broadband devices, such as semiconductor optical amplifiers (SOAs), modulators, and lasers.

### 3.3.2 Carrier Dynamics

Different processes can capture carriers in a self-organized Qdash/Qdot active region as the possible recombination transition energy states are spread over a band of wavelengths. Moreover, the overlap of energy states of different Qdot/Qdash ensembles increases the number of available states of a particular energy transition. These features, in addition to the Qdot or Qdash properties,
**Figure 11** The possible carrier emission processes under forward bias (applied electric field $F$). (a) Thermal activation and phonon-assisted tunneling, and (b) tunneling and optical activation. These processes are shown for an electron escape from a confined state in Qdash into the conduction band. Source: M. Z. M. Khan, "Semiconductor Quantum Dash Broadband Emitters: Modeling and Experiments," 2013; M. P. Geller, "Investigation of carrier dynamics in self-organized quantum dots for memory devices," PhD, TU-Berlin, 2007.

complicate the carrier dynamics in the highly inhomogeneous active region. Carriers can escape from a Qdot/Qdash by possibly four mechanisms viz. thermal activation, tunneling, phonon-assisted tunneling, and optical activation. These processes are schematically sketched in Figure 11 for a simple electron escape from a dot confined state $E_0$ and $E_1$ into the top of the barrier, in the CB [17, 23]. This can readily be extended to a carrier escape from one dot/dash group to another dot/dash ensemble by either one process or a combination of processes depending on the average dot/dash size (i.e. the mean electron-hole transition energy). In addition, these processes also affect the carrier emission mechanism among the dots within a Qdot ensemble, thus making the emission process interpretation rather tricky. These processes are summarized below:

3.3.2.1 **Thermal Activation** In this process, by acquiring thermal activation energy $E_A$ or $E_A + E_B$, an electron can escape from the Qdash/Qdot deep confined state ($E_0$) to shallow ($E_1$) confined state, or to the top of the barrier in the CB, as shown in Figure 11a.

3.3.2.2 **Tunneling** This is an established quantum mechanical effect which allows carriers of Qdash/Qdot confined state ($E_0$) to tunnel through barriers to the top of the barrier present in the CB (see Figure 11b). Under forward bias conditions, the potential barrier is tilted or lowered, thus enhancing the tunneling rate since the tunneling time is inversely proportional to the barrier thickness. Moreover, tunneling of carriers among adjacent stacks is also feasible in a multi-stack Qdash/Qdot active region if the barrier thickness is small, without reaching the top of the barrier, in the CB. In this case, the electrons/holes residing in a Qdash/Qdot energy state of a particular stack can purely tunnel through the barrier into a similar confined energy state of other Qdash/Qdot ensemble belonging to the adjacent stack.

3.3.2.3 **Phonon-assisted Tunneling** This process combines pure tunneling and thermal activation processes, as illustrated in Figure 11a. Under forward bias, from the deep confined energy state $E_0$ of Qdash/Qdot ensemble, the carriers can first thermally activate to acquire higher confined energy state $E_1$ of the dot/dash ensemble and later tunnel through the barrier either into the top barrier within the CB or into the adjacent stack Qdash/Qdot ensemble.

3.3.2.4 **Optical Activation** Carriers can escape from the confined state $E_0$ of a Qdot/Qdash by optical activation (interband absorption) if photons of sufficient energy are generated within the active region, or irradiated externally, as depicted in Figure 11b. The former mechanism usually happens under electrical injection, which plays a vital role since broad gain materials are subject to this type of emission process. The source of photons can be the high-energy photons emitted from a dot/dash ensemble with shallow confining potential, which in turn activates the carriers of deep confined state in Qdots of Qdashes. This is a sort of carrier feeding mechanism via optical pumping.
4 Broadband Semiconductor Lasers

Acquiring the basic knowledge of semiconductor laser and the broad gain active materials, the concept of achieving broad interband lasing action is illustrated in Figure 12. In this case, increasing the external pumping to compensate for all the internal ($\alpha_i$) as well as mirror ($\alpha_m$) losses in the FP cavity with a broad gain medium is achieved by simultaneous radiative recombination of carriers from several dissimilar energy levels. Once the threshold is reached, lasing action could be accomplished consisting of different energy photons that are coupled to several longitudinal modes of the FP cavity, thereby broadening the lasing spectrum, as illustrated in Figure 12. Of course, the threshold current $I_{th}$ for the broadband semiconductor lasers is expected to be higher than the typical narrowband lasers owing to increased $\alpha_i$. In this case, $\alpha_i$ includes the inherent material losses as well as losses due to intense photon re-absorption occurring in the system because of complex carrier dynamics, as briefly discussed in the previous section.

In literature, demonstration of broadband lasing from a semiconductor laser was first reported in mid-infrared 6–8 $\mu$m wavelength region employing a quantum cascade configuration. In this case, lasing actions from different energy levels within the CB (inter sub-band transitions) is demonstrated rather than typical interband transitions. The reader is referred to references 14 for more details and further reading on quantum cascade lasers. Broadband lasing from interband transitions has been demonstrated on Qdot, Qdash, and very recently on Qwell platforms in the near-infrared region covering 1.0–1.7 $\mu$m and at room temperature operation, unlike quantum cascade laser that operated at below room temperature [24–30]. Since this new class of broadband stimulated emission spectrum is exhibited by a semiconductor laser, the name broadband lasers came into existence.

Figure 12 Schematic representation of (a) the gain profile of a broadband semiconductor laser. Longitudinal modes (b) of the FP cavity, including the semiconductor active gain region. (c) Resulting lasing spectrum with several FP modes as they reached the threshold gain condition simultaneously. This corresponds to a broad stimulated emission bandwidth.

Figure 13 shows a schematic of the spectral coverage of different quantum-confined nanostructure-based active regions on GaAs- and InP- material platforms. The emission of $\sim$1300 and $\sim$1550 nm, which are covered mostly by InGaAsP/InP Qwells and InGaAsP/InP and InGaAlAs/InP Qdots and Qdashes, are crucial for applications in optical communications and Qwell based semiconductor lasers are widely applied for short- and long-haul optical fiber communications. InAs/GaAs Qdots were the first choice to realize semiconductor lasers owing to available mature GaAs material technology, thanks to GaAs – Qwell lasers that propelled this technology in the early 1970s for optical communications. High-performance narrow-linewidth lasers, as well as the new wave of broadband lasing technology, were first demonstrated on InAs/GaAs Qdot lasers in $\sim$1100–1300 nm region. The next logical step was to realize these Qdots on InP-platform for long-haul optical communications. However, instead of
Broadband Laser for Optical Telecommunication

17

Visible 850 nm 1000 nm 1300 nm 1590 nm 2000 nm

Figure 13 Schematic describing the spectral coverage by the different quantum-confined active materials on GaAs- and InP-platforms. Source: Adapted from Z. Zhang, R. Hogg, X. Lv, and Z. Wang, “Self-assembled quantum-dot superluminescent light-emitting diodes,” Advances in Optics and Photonics, vol. 2, no. 2, pp. 201–228, 2010.

dots, InAs/InP Qdash lasers on InP platform were achieved in the early 2000s, due to the growth kinetic discussed in the previous sections. Since then, significant efforts on optimizing the growth process were in full swing until recently laser with InAs Qdots on InGaAlAs- and InGaAsP-InP were successfully demonstrated.

Alternatively, several research groups took advantage of the inherent inhomogeneous broadening of the Qdot/Qdash active region and developed ultra-broadband lasers emitting in ∼1140–1650 nm band, covering the essential wavelength regions of 1550 nm C-band optical communication. Moreover, very recently, broadband laser on GaAs – Qwells was also reported with high power, thanks to the precise design and growth of the active region that enabled proper distribution of carriers across the Qwells, thereby exhibiting broad lasing spectrum. In the following, a brief discussion of Qdot [24, 27], Qdash [22, 25, 26, 28], and Qwell [29, 30] broadband laser, shown in Figures 14 and 15 are presented.

4.1 Quantum-dot Broadband Lasers

Broad interband InAs Qdot lasers on GaAs platform was reported in 2007 that exploits the inherent dot size dispersion during dot growth in a multi-stack active region structure with four layers of Qdots separated by barrier and spacer layers. By employing the first approach of natural inhomogeneous broadening of the active region, a lasing −3 dB bandwidth of ∼22 nm was reported at ∼1160 nm with optical power in hundreds of mW at room temperature. The inhomogeneity in the optical transitions of the GS and ES1 of the dots caused broad and continuous dissimilar energy levels from which carriers recombine to emit stimulated photons of various wavelengths.

Moreover, intentionally broadening of the active region inhomogeneity to further enhance the lasing spectrum is also demonstrated on InAs/GaAs chirped active region design. In this design, the InGaAs capping (i.e. covering) layer of Qdots is varied in a three-stack Qdot system before growing the barrier layer, to introduce additional broadening of the optical transitions. This complex growth kinetics usually decrease (increase) the dot size (particularly height) on increasing (decreasing) the capping layer thickness. A broadened emission in the O-band wavelength region with a record −3 dB lasing bandwidth of ∼75 nm and ∼10 mW nm⁻¹ APSD is achieved, as shown in Figure 14a. The lasing initially starts from the GS emission that is situated at smaller dot optical transition energy. With the continuous increase in electrical pumping, the emission from GS broadens with the onset of lasing from ES1, and later both the energy states broaden with a relatively flat-top lasing spectrum. This suggests a broad and flat-top gain bandwidth spectrum exhibited by the composite Qdot active material, similar to the one discussed in Figure 10.

4.2 Quantum-dash Broadband Lasers

InAs/InP Qdash lasers became a hot topic of research owing to the active materials niche features and emitting in the telecommunication wavelength band. In 2007, broadband lasing from four stacks InAs Qdash with InGaAlAs barrier layers, on InP-platform was demonstrated with the natural inhomogeneous broadening of the GS since a clear indication of excited states lasing has not been observed yet and still debatable. A lasing bandwidth of ~22 nm in L-band and ~41 nm in C-band are reported, as depicted in Figure 15a, with APSD of ~7 and ~15 mW nm\(^{-1}\), respectively. Moreover, an enhanced emission bandwidth of ~50 nm is achieved by chirping the active region of a four stack Qdash by varying the barrier layer thickness, thus deliberately broadening as well as offsetting the average GS emission of each Qdash stack ensemble [31]. Figure 15b shows the lasing spectra of the chirped active region InAs/InP Qdash laser at two different pumpings above the threshold, a representative of simultaneous emission from all dissimilar dash optical transitions.

4.3 Quantum-well Broadband Lasers

The development of broadband lasing emission from GaAs/InGaAs Qwell lasers took a while after the demonstration of Qdot/Qdash lasers. In general, MQW active region with asymmetric Qwells is employed to obtain a wide gain profile. In this system, Qwells of different thickness, corresponding to varying GS energy states, are grown, thus broadening the available GS transition energies and hence the gain profile. However, asymmetric MQW active region is found to suffer from strong nonuniform carrier distribution and carrier leakage under stimulated emission, thus impeding their exploitation for broad laser applications. In short, carriers moving into MQW active region are mostly...
trapped in the first Qwell potential that they experience, with few carriers transporting to other Qwells and resulting in their relatively less carrier trapping. This highly nonuniform carrier distribution across the active region, together with carrier leaking (escape from the potential well by thermal or optical activation) at high pumping, narrows down the threshold gain profile of the active region instead of broadening. Lately, in 2014, this issue was addressed by introducing tunnel injection between two Qwells in the MWQ active region that assists in populating all the Qwells evenly, thereby reducing the nonuniformity of the carrier distribution across the active region [29, 30]. Moreover, by deliberately dispersing the GS and ES energy transitions, in addition to tunneling phenomenon, in InGaAs/GaAs MQW system, a broad spectral bandwidth of \( \sim 38 \) and \( \sim 51 \) nm are reported. The emission bandwidth covers \( \sim 1040-1090 \) nm wavelength region, as shown in Figure 14, with APSD \( \sim 1.2 \) and \( \sim 15 \) mW nm\(^{-1}\), respectively.

5 Applications in Optical Communications

In this section, a brief overview of the deployment of this new class of broadband
Broadband Laser for Optical Telecommunication

LD in optical communication is presented. The reader is referred to references 32–34 for more details. Since the wavelength of interest is $\sim 1550$ nm, an InAs/InP Qdash laser is the ideal candidate and hence has been utilized to firstly extract more than 40 channels (or longitudinal FP modes where each mode serves as a sub-carrier channel) from its broadband stimulated emission spectrum with $>20$ nm bandwidth, as shown in Figure 16a. These channels (i.e. FP modes) are separated using wavelength selective switch or interleavers that works mainly as a demultiplexer, which is shown in Figure 3. After separating the FP modes, each sub-carrier is then externally modulated with an 18 Gbaud 16 quadrature amplitude modulated (QAM) digital signal, corresponding to a data rate of 72 Gb s$^{-1}$. These 40 sub-carriers are then multiplexed and transmitted through 75 km single-mode optical fiber and later coherently detected by a modulation analyzer equipment. Successful transmission of 13 channels reaching a bit error rate below 7% forward error correction limit of $3 \times 10^{-3}$, a standard in optical communications, is demonstrated in Figure 16b. Later, successful transmission of up to 28.2 Gb s$^{-1} \times 160$ channels, corresponding to an aggregate data capacity of 4.5 Tb s$^{-1}$, is also reported on a 3 km fiber. These demonstrations show the potential of broadband semiconductor lasers in addressing the green communication requirements of future optical networks while being compact and cost-effective.

6 Summary

Broadband semiconductor lasers are comprehensively studied, starting from a conventional laser operation to the advancements in the laser device designs. In particular, quantum-confined nanostructure-based active region starting from Qdots to Qdashes and finally to Qwells show promise as active gain material for broadband applications. Stand out from them are InAs/InP Qdash laser exhibiting niche characteristics of wide wavelength tunability from C- to U-band wavelength region. Their potential deployment as an energy-efficient laser source in WDM optical communication is summarized. Ongoing research and development activities indicate that in the future, this new class of laser device might take center stage, thus providing viable next-generation laser source for powering green information and communication technology.
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22 \textit{Broadband Laser for Optical Telecommunication}


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