Wideband Quantum-Dash-in-Well Superluminescent Diode at 1.6 μm

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***Abstract*—We demonstrate broadband superluminescent diode at $\sim$1.6-μm peak emission wavelength using InAs–InAlGaAs quantum-dash-in-well structure on InP substrate. The fabricated device exhibits the close-to-Gaussian emission with a bandwidth of up to 140 nm. The device produces a low spectrum ripple of 0.3 dB and an integrated power of 1.7 mW with the corresponding bandwith of 110 nm measured at 20 °C under 8 kA/cm^2.**

***Index Terms*—Optical coherent tomography, quantum-dash, quantum-dot (QD), superluminescent diode (SLD).**

THERE has been a growing interest in the broadband superluminescent diodes (SLDs) due to their wide applications in various optical fiber sensors, optical network testing and analysis, semiconductor wafer processing monitoring, optical networks, scientific instrumentation, spectroscopy, and biological imaging through optical coherent tomography technology [1]. SLDs as the broadband light source are very attractive as they are robust, compact, inexpensive, and capable of producing Gaussian spectrum with relatively high optical power, low spectral modulation, and short coherence length.

The continuous advancement in the semiconductor quantum-dot (QD) heterostructure as gain media has also led into the extensive exploration of its inhomogeneity nature to realize the broadband SLD on GaAs substrates. Using In(Ga)As-GaAs based QD structures on GaAs-substrate, broadband SLDs at emission wavelength between 1.0–1.3 μm have been demonstrated [2]–[7].

Device configurations such as facet-coating and tilted angle waveguide have been implemented to suppress the lasing action in the SLDs. This technique often produces significant optical feedback from the facets that results in a large spectral ripple. In addition, the tilted angle geometry gives an angled waveguide structure that will increase the complexity in the fiber pig-tailing process during the device packaging. To enable broad emission bandwidth, asymmetry quantum-well (QW) structure has been used in the active region [2]–[6]. SLDs utilizing this technique produce multiple-Gaussian spectrum, and significant photon reabsorption that reduces the device's emission efficiency. For high sensitive sensing, and high resolution imaging applications, these SLD device characteristics are undesirable.

Recently, long wavelength self-assembled InAs quantum nanostructures on InP substrate has generated a considerable interest as it produces an emission wavelength between 1.3–1.8 μm for the optical fiber communications [8]. The broadband emitter in this wavelength range is also highly important for wide range of applications in the atmospheric and planetary gases sensors such as H_2S, HCl, NH_3, C_2H_4, C_2H_2, C_2H_6, and C_6H_6. Furthermore, it will be suitable for various applications in optical telecommunications, highly sensitive fiber gyroscope, optical time domain reflectometers and wavelength division multiplexing systems [9].

Here, we report the demonstration of low-ripple, broadband 1.6-μm SLDs in InAs–InP quantum-dash-in-well (QDW) structure. In this device, the suppression of optical oscillation in the optical path is achieved via the integration of a photon absorber (PA) section. The QDW structure consisted of InAs dash embedded in InAlGaAs QW. The absorber configuration enables a high current injection into the device to simultaneously excite luminescence from both ground states (GS) and excited states (ES) of QDs, hence producing close-to-Gaussian emission spectrum of over 140-nm-wide bandwidth at wavelength peak at 1.6 μm.

The material was grown by molecular beam epitaxy on (100) oriented n-type S-doped InP substrate. The active QDW structure consists of four stacks of InAs dashes embedded in InAlGaAs QW. The waveguide core is based on a standard undoped separate confinement heterostructure of 160-nm $In_{0.52}Ga_{0.28}Al_{0.2}As$ lattice matched to InP substrate. Each of the five monolayers (MLs) thick InAs dash layer is embedded within a 7.6-nm-thick compressively strained $In_{0.64}Ga_{0.16}Al_{0.2}As$ QW and a 15-nm-thick tensile-strained $In_{0.50}Ga_{0.32}Al_{0.18}As$ barrier. The InAs quantum-dash layers, preferentially elongated along $[1\bar{1}0]$ direction [8], were grown 1 ML at a time, each separated by 5-s growth pauses. The island formation was monitored by reflection high-energy electron diffraction and the dash island was confirmed by the cross section transmission electron microscopy. The SLD structure was completed by an upper cladding $In_{0.52}Al_{0.48}As$ layer of 1700 nm and $In_{0.53}Ga_{0.47}As$ contact layer of 150 nm with Be doping of 2×10^{18} cm^{-3} and 2×10^{19} cm^{-3}, respectively.

Photoluminescence (PL) spectroscopy was performed at 77 K using 532-nm diode pumped solid-state laser as excitation source. As shown in Fig. 1, the GS emission of 1.52 μm was dominantly excited at excitation below 1.5 W/cm^2. The PL linewidth from the GS is 45 nm (24 meV) and 86 nm (42 meV) at 77 K and 300 K, respectively. Compared to the published data of InAs QD in InAlGaAs matrix [10], the narrow linewidth observed here can be attributed to the improved island inhomogeneity. The appearance of broadened spectra from the raise of ES indicates the presence of the QDW carrier confinement to form the quasi-continuous transitional band. No noticeable change of the peak position in quantized states is noticed as the excitation power increases. Up to five quantized states (labeled as GS, ES1–ES4, respectively) are identified under

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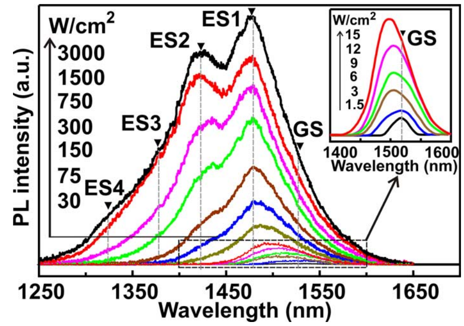

Fig. 1. State-filling PL spectra measured at 77 K under different excitation powers from 1.5 to 3000 W/cm^2 from QDW material revealing the ES at higher pumping level.

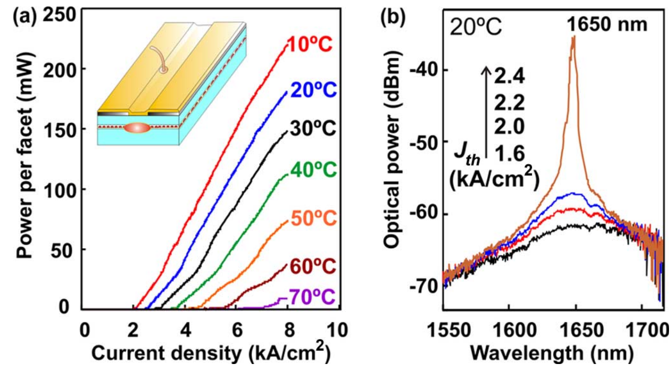

Fig. 2. (a) L–I characteristics of as-cleaved QDW laser with the dimension of $50 \times 1000\,\mu\text{m}^2$ under different current injection levels. (b) Wavelength emission around the threshold condition at 20 °C.

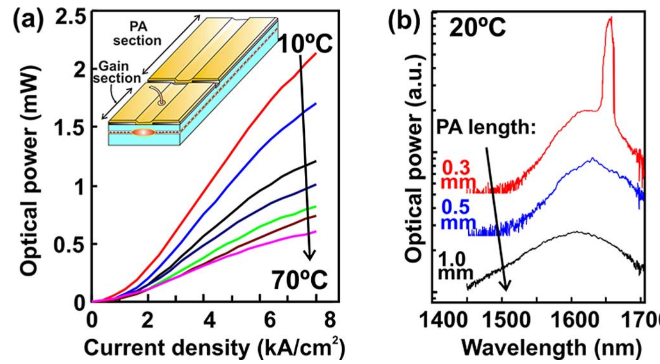

Fig. 3. (a) L–I characteristics from the QDW SLD at various temperatures. The inset gives the schematic structure of integrated 1-mm-long QDW SLD with 1-mm-long slab PA. (b) QDW SLD spectra from various PA lengths under constant injection current density of 8 kA/cm^2. The QDW SLD with 0.3-mm-long PA section exhibits the lasing action at $\sim 3 \times I_{\rm th}$ from the QDW laser with similar gain section.

high excitation density of 3000 W/cm^2 after deconvoluting into the multiple Gaussian curves. The energy separation of between the adjacent states varies from 22 to 37 meV.

The QDW SLD device consists of two sections: the gain section of 50-μm-wide oxide stripe waveguide and the PA section in the form of slab waveguide. The PA is effectively a one-dimensional planar waveguide structure, confining light only in the growth direction. This section is employed to minimize the lasing action and optical feedback from the rear facet [7]. As the optical feedback from the rear facet is negligible, a flat and low ripple spectrum is expected.

The QDW SLD device was fabricated following the standard two-section broad area laser fabrication processes with the inter-electrode separation defined by removing the highly doped contact layer using selective chemical etching. The nonfacet coated SLDs at different PA lengths $L_{\rm PA}$ were tested under pulsed current at 5-μs pulsewidth and a duty cycle of 0.1%. During the measurement, only the gain section was pumped while the PA section was left unpumped. For comparison, 50-μm-wide oxide stripe gain guided lasers were also fabricated on the same wafer and characterized to study the lasing behavior around and above the threshold of QDW material.

Fig. 2(a) shows the light–current (L–I) characteristics of 1-mm-long cavity QDW laser at various measurement temperature. The electroluminescence below the threshold condition exhibits a broad spontaneous emission width. At 10 °C, the laser gives a threshold current ($I_{\rm th}$) of 1 A, which corresponds to the threshold current density ($J_{\rm th}$) of 2 kA/cm^2. The maximum output power per facet is 220 mW. Fig. 2(b) depicts the wavelength emission of QDW laser around the threshold condition. The lasing wavelength of $\sim$1.64 μm is similar to the emission peak of the amplified spontaneous emission spectra indicating the GS has sufficient gain to support the lasing action [Fig. 1(b)]. The lasing emission from GS level has been measured from the 1-mm-long device up to 80 °C.

Fig. 3(a) depicts the typical L–I characteristics with superlinear behavior from the 50-μm broad area QDW SLDs. These devices have 1-mm-long gain section and 1-mm-long PA section. With the presence of the PA section, the lasing action can be effectively suppressed up to a current density of 8 kA/cm^2. Optical power exceeding 2 mW has been measured at 8 kA/cm^2 at 10 °C. Under $J = 8$ kA/cm^2 injection, the optical output power decreases with increasing temperature of operation from 10 °C to 70 °C associated with the reduction in the QDW recombination efficiency. This temperature-sensitive operation is caused by the close energy spacing between GS and ES1 in our QDW structure. Note that the QDW active region used in this experiment is undoped, hence only a limited number of holes available for recombination. With the p-doped active region, the thermal property of the QDW emitter is expected to improve accordingly [11].

Fig. 3(b) summarizes the effect of different PA lengths to the SLD emission at $J = 8$ kA/cm^2. Despite the high injection level up to 8 kA/cm^2, the Fabry–Pérot oscillation from SLDs with 0.5- and 1-mm-long PA lengths can be effectively restrained. Under similar injection condition, the SLD with shorter PA of 0.5 mm exhibits a narrower spectral bandwidth. However, the lasing action cannot be suppressed for devices with 0.3-mm PA length. This fact corresponds to the transparent condition in the PA section under the high photon excitation across the waveguide from the active section.

Fig. 4(a) and (b) denotes the SLD spectra and the bandwidth summary for SLDs with 1-mm-long PA section under different injection levels and measurement temperatures. The bandwidth evolution indicates the systematic filling of overlapping quantized states, which shifts the overall spectra towards a shorter wavelength regime. The appearance of large oscillating noise at beyond 1680 nm is associated with the low detection sensitivity of our spectrum analyzer. At $J < 2$ kA/cm^2 (not shown

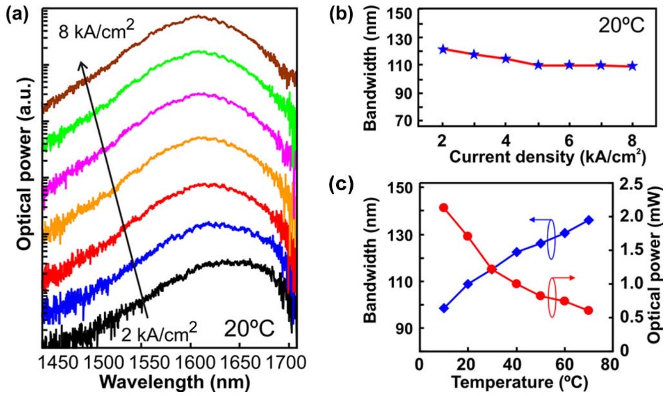

Fig. 4. (a) Broadband spectra from QDW SLD (1-mm-long gain section with 1-mm-long PA section) at different current injections from 2–8 kA/cm^2 measured at 20 °C. The summary of the bandwidth as functions of (b) current density measured at 20 °C and (c) the temperature at a $J = 8$ kA/cm^2.

here), the SLD emission from GS is dominant related to the inhomogeneous broadening of dashes. The carriers at higher current density cause the saturation of GS level at 1.65 μm. The excitation of first ES begins at $J = 2$ kA/cm^2. The dominant emission from the first ES peaked at $\sim$1.61 μm is observed as indicated from the systematic reduction in spectral width at $J > 2$ kA/cm^2. This dominant peak from the first ES agrees well with the earlier PL measurement in Fig. 1(a) under optical density of 25 W/cm^2. This is associated to the higher optimum gain on the ES due to the higher angular momentum degeneracy [12]. At $J = 5$ kA/cm^2 and higher, the bandwidth stays almost unchanged, while the integrated power increases. The intensity related to certain quantized states saturates very fast and carriers start to occupy the higher quantized levels at high injection level. The observation of the close-to-Gaussian emission form these devices are originated from the uniformly broadened gain spectra from the QDW structure with close energy spacing. This shows an advantage over InGaAs–InP QW SLD with a comparable bandwidth but exhibits a small hump in the shorter wavelength region [13].

A similar signature of bandwidth evolution versus temperature is observed from devices operated at high temperatures. A maximum bandwidth of over 140 nm has been achieved under $J = 8$ kA/cm^2 (limited by the maximum current available in our current source) at 10 °C. The integrated optical power under this condition is exceeding 0.5 mW. This corresponds to a coherence length $L_c = \lambda^2/\Delta\lambda$ of 18.5 μm, where λ is the central wavelength and $\Delta\lambda$ is the spectral bandwidth. The thin film coating can be applied onto SLD facets to increase the optical power and to minimize the ripple.

We measured the spectrum ripple of QDW SLD operated at 20 °C under $J = 8$ kA/cm^2 coupled with a nonfacet coated multimode fiber to the spectrum analyzer (with 0.1-nm resolution). The corresponding bandwidth and optical power are 110 nm and 1.7 mW, respectively. The spectrum ripple is $\sim$0.3 dB over 10-nm span from the emission peak. The value is comparable to QD SLDs on GaAs substrate with tilted angle configuration [2]–[6]. This yields the spectral modulation of 4% (defined here as $(P_{\max} - P_{\min})/(P_{\max} + P_{\min})$ over 10-nm span from the wavelength peak, where $P_{\max}$ and $P_{\min}$ are the maximum and the minimum optical power obtained from analyzer, respectively).

Although the result was obtained from broad area devices under pulsed current operation, further optimization of the growth condition and wafer structure design should improve the device performance and enable continuous-wave operation at room temperature. The adaptation of ridge waveguide structure with an expense of longer device length will and an integrated semiconductor optical amplifier should allow the coupling of light emission from the device to a single-mode fiber with respectable efficiency.

In summary, we have demonstrated SLD with integrated PA slab as lasing suppression section in InAs–InAlGaAs QDW structure. At an injection of 8 kA/cm^2, the as-cleaved SLD device produces >140-nm bandwidth and close-to-Gaussian emission spectrum. An optical power >2 mW with a spectral ripple of 0.3 dB have been measured. The low ripple observed from the device is attributed to effective PA section to suppress optical oscillation in the waveguide.

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