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Superluminescent diodes using quantum dots superlattice

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Abstract

We report a broadband superluminescence diode using InGaAs/GaAs self-assembled quantum dots structure grown by atomic layer molecular beam epitaxy. This two-section SLD consists of weakly guided-rib-waveguide gain section (4 μm wide) butt-connected to a broad-area photon absorber (50 μm wide) to minimize optical feedback and to suppress lasing action. The fabricated device produces a low ripple spectrum (<0.3 dB) with a spectral bandwidth of 135 nm at a peak wavelength of 1210 nm under continuous wave operation (20 °C) at 105 mA current injection.

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Keywords: A1. Quantum dot; B1. Superluminescent diodes; B2. III–V materials

1. Introduction

In recent years, there has been an increasing interest in broadband light sources for various commercial optical fiber sensor systems, chemical and gas sensors, highly sensitive optical gyroscopes, optical network fault analysis, semiconductor wafer processing monitoring, optical networks, spectroscopy, scientific instrumentation, and biomolecular imaging through optical coherent tomography (OCT) [1]. Particularly, the sensitivity, signal quality, and the axial spatial resolution of current bio-imaging and probing systems using OCT technology are primarily limited by the power and the bandwidth of the broadband light source. Generally, broadband light sources are obtained from four main sources: incandescent/halogen light sources, optically pumped crystal lasers, such as Ar-ion-pumped Ti:Al_2O_3 laser, optically pumped fiber-based amplified spontaneous emission (ASE) source, and semiconductor superluminescent diodes (SLDs) [2]. SLDs are very attractive for various photonic-based sensors as it is robust, compact, inexpensive, and capable of producing Gaussian spectrum with relatively high power, high efficiency, low spectrum modulation and short coherence length. Various technologies have been utilized to realize broad bandwidth SLDs using quantum-well (QW) platform. At the epitaxial engineering level, approaches such as (i) coupled SLDs [3], (ii) multiwidth QW [4], (iii) selective area epitaxy [5], and (iv) QW intermixing [6] have been used to further broaden the bandwidth of SLD. However, the spectral width of QW-based SLDs is limited by the bandgap tunablity of the QW system.

Recently, taking the advantage of highly inhomogeneity nature of self-assembled quantum-dot (QD) structures, broadband QD SLDs have been demonstrated [7]. Most of the reported SLDs incorporate titled angle and complex anti-reflection coating to suppress optical feedback, and to reduce the spectrum ripple. In this paper, we report the development of a broadband QD-based SLD that incorporate a photon absorber to suppress feedback oscillation.

2. Device design and fabrication

As schematically shown in Fig. 1, the SLD device consists of three sections that can individually be addressed by electrical pumping. Front- and rear-ribs are gain sections that produce a broad electroluminescence from QD assembly. The gain sections are 4 μm wide, ~1.5 μm deep, weakly guided rib waveguides. The rib width is chosen to provide a lateral single mode operation, which

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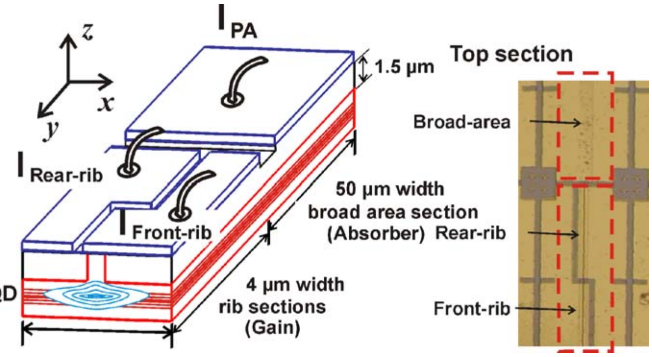

Fig. 1. The schematic diagram of the three-section QD SLD consisting of two gain sections in the form of 4 μm wide rib waveguide and a PA 5n the form of 50 μm wide broad area slab waveguide. The inset shows a top-view microscope image from the final three-section QD LSD device.

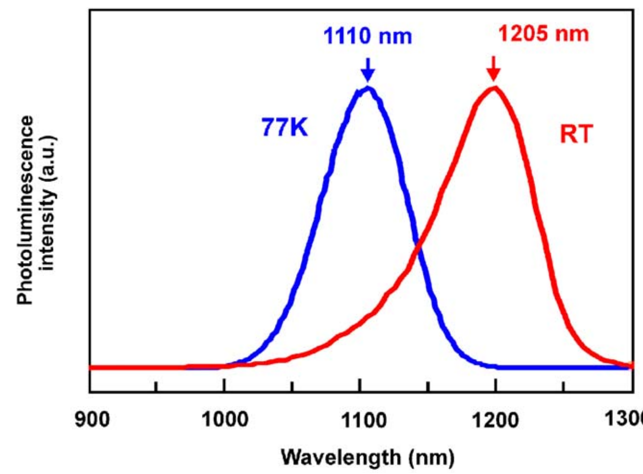

Fig. 2. Photoluminescence spectra of InGaAs–GaAs QDs measured at RT and 77 K using 532 nm laser as excitation source.

provides a high optical power coupling to the single mode fiber. The front-rib can be employed as either the emitter to enhance output power, or as an optical amplifier when electrically pumped to transparency. By electrically addressing the individual sections, the emission power can be continuously tuned, whereas the luminescence bandwidth can be tuned in step. The photon absorber (PA) is butt-coupled and monolithically integrated to rear-rib in the form of 50 μm wide broad area slab-guide to increase the absorption efficiency, hence enhancing the suppression of lasing action. As the effective refractive index at PA is only 10^{-4} higher than rear-rib, the reflection at the rear-rib/PA interface is almost negligible ($\sim 2.2 \times 10^{-8}$). Effectively, this absorber is a one-dimensional planar waveguide structure confining light in the growth direction. Upon entering the rear-rib/PA interface, photons will be dispersed in lateral direction, and absorbed in the active region of PA.

The SLDs were fabricated using a five-stack self-assembled InGaAs/GaAs dot structure grown by atomic layer epitaxy technique on Si-doped (1 0 0)-oriented GaAs substrates, embedded between two 20 GaAs/AlGaAs superlattice layers. A 1500 nm thick $Al_{0.3}Ga_{0.7}As$ lower cladding layer was first grown, which was followed by a superlattice of 20 pairs of 2 nm $Al_{0.3}Ga_{0.7}As$ and 2 nm GaAs. Five InGaAs dot layers were then consecutively grown, with each dot layer comprising of five pairs of alternating InAs and GaAs monolayers. Under a constant arsenic flux, growth was interrupted after each monolayer in order to stabilize the surface. Forty nanometers thick GaAs spacers were inserted between the dot layers. Finally, a superlattice of 20 pairs of 2 nm $Al_{0.3}Ga_{0.7}As$ and 2 nm GaAs, a 1500 nm thick $Al_{0.3}Ga_{0.7}As$ upper cladding layer, and a 200 nm thick GaAs contact layer were grown. The photoluminescence (PL) spectrum at room temperature (RT) shows the peak at 1205 nm with a broad spectrum linewidth of ~58 nm as can be seen in Fig. 2. This broad luminescence is attributed to the inhomogeneity nature of self-formed QD related to the size and compositional fluctuation.

The SLD fabrication was carried out using standard ridge waveguide laser fabrication steps including the rib-waveguide formation requiring chemical etching, dielectric insulation and window opening, p-type metal evaporation, substrate thinning, n-type metal evaporation and the metal alloying. After cleaving, the non-facet coated SLD device was tested under continuous wave (CW) current injection on the temperature-controlled heat sink.

3. Results and discussions

Fig. 3(a) delineates the typical voltage–current and light–current characteristics of the non-facet-coated QD SLDs operated at 20 °C under a CW operation. The cavity lengths rear-ribs and PA are 350 and 500 μm, respectively. The Front-rib section of the devices highlighted in this paper, are either 270 or 600 μm. The front- and rear-rib were simultaneously injected while the PA section is grounded. The power saturates beyond the current injection of 105 mA due to the thermal effect. This yields to a maximum power of 25 μW. The efficiency of the emitter is relative low due to the relative low density of QD in the active region. The photocurrent characteristics were obtained by reverse biasing the PA and rear-rib sections at different voltage biases as displayed in Fig. 3(b). This permits the broad area section to be used as a photocurrent monitor. However, due to the imperfection in current isolation of the individual section, large leakage current has been observed from the rear-rib and PA when these two sections are under reverse bias.

The SLD spectra were measured with a position adjusted bare fiber detector connected to an optical spectral analyzer. As the injected current at both ribs varies, the peak wavelength does not change significantly (<2 nm) while the bandwidth is notably tunable from 71 to 91 nm. We further observed the broadened bandwidth when compared with the same device with a similar injection level on the front-rib section only, while the rear-rib and

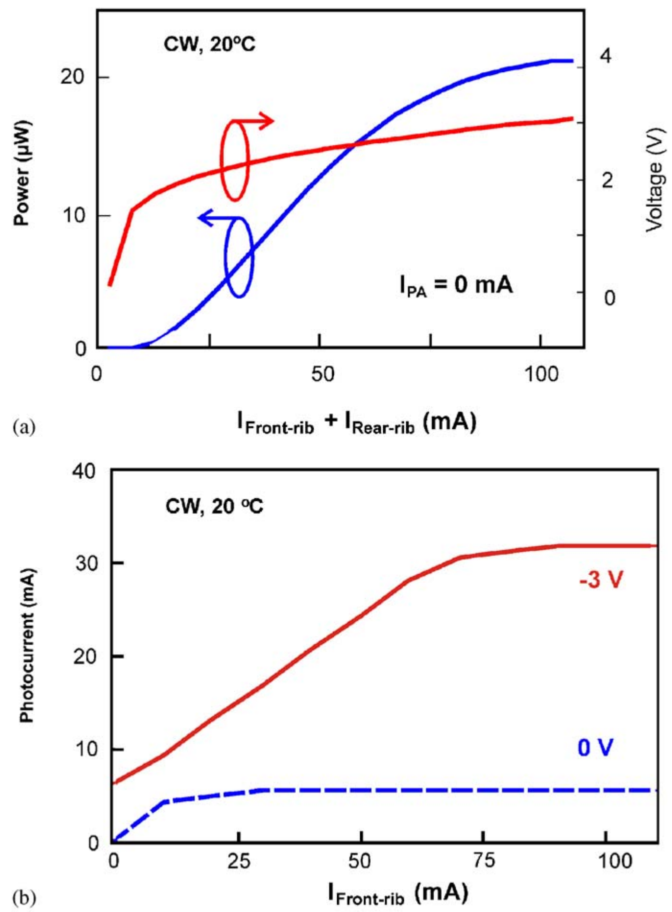

Fig. 3. (a) The light–current and voltage–current characteristics from the fabricated QD SLD measured under CW mode and at a temperature of 20 °C. The current was injected to both the front- and rear-ribs, while PA is grounded ($V_{PA} = 0$ V). (b) The photocurrent characteristics obtained by reverse biasing PA and rear-rib sections at 0 and −3 V.

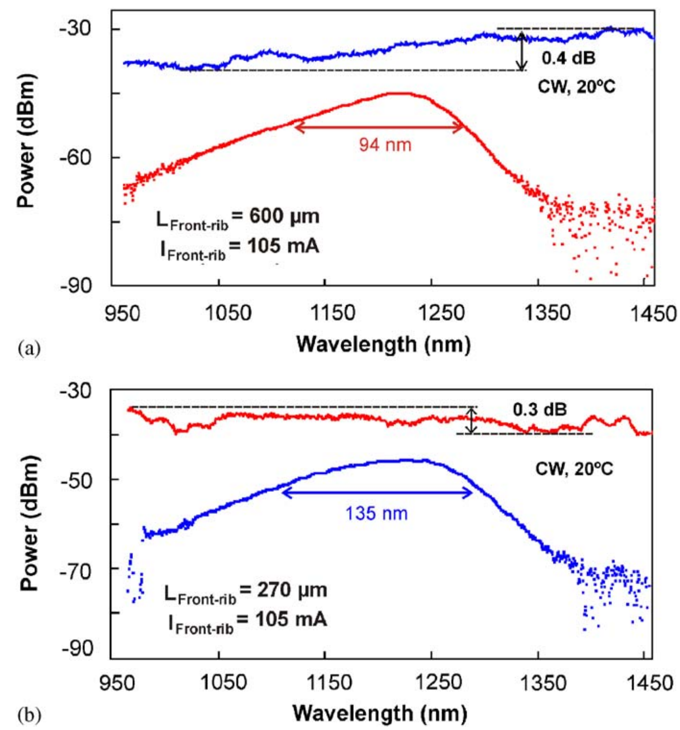

Fig. 4. The emission spectra from QD SLDs at an injected current of 105 mA to front-rib section ($I_{front-rib} = 105$ mA) with different active cavity lengths: (a) $L_{front-rib} = 270\,\mu m$ and (b) $L_{front-rib} = 600\,\mu m$. The length of rear-rib and PA are similar for both devices ($L_{rear-rib} = 350\,\mu m$ and $L_{PA} = 500\,\mu m$). Both rear-rib and PA are grounded.

PA sections are grounded ($V_{rear-rib} = V_{PA} = 0$ V). The bandwidth broadens with increasing injection current density due to the band filling effect. When the optical confinement and the cavity length decreases and injection current remains fixed, bandwidth increases as well due to the increase in current density.

Fig. 4(a) depicts the Gaussian-like emission spectrum and spectral ripple of QD SLD at 105 mA injection at front-rib, while the rear-rib and PA are grounded. The QD SLD has the spectral bandwidth of 94 nm with low ripple below 0.4 dB, which measured within 10 nm span at the wavelength peak of 1210 nm. The calculated spectral modulation is 4.5%, which the spectral modulation here is defined as $(P_{max} - P_{min})/(P_{max} + P_{min})$ over 10 nm in 0.01 increments of wavelength. This low ripple suggests that optical feedback is effectively suppressed by PA section.

Fig. 4(b) displays the measured spectrum from the QD SLD with a shorter cavity length at the front-rib section. Compared with the previous one, the device only has 270 μm long front-rib. The measured power from both devices is ~20 μW using an integrating sphere. The spectral bandwidth of 135 nm has been obtained from this short device at the same current injection (105 mA) at the front-rib section, while both the 350 μm long rear-rib and 500 μm long PA are grounded. The corresponding ripple and spectral modulation are 0.3 dB and 3%, respectively. The corresponding coherence length of QD SLD with short front-rib cavity is 10.8 μm. These performances are comparable with the long cavity QD SLD with the discrepancy from the measurement errors and uncertainties. The broadened bandwidth is attributed to the band filling effect to QD gain media at the higher current density on the rib section. To our knowledge, the fabricated SLD here has the broadest spectral width utilizing the QD active media, even if compared with the achieved bandwidth using the chirped configuration in QDs as gain media [7].

4. Conclusions

In summary, we have demonstrated the InGaAs/GaAs QD SLD that incorporates the broad area slab waveguide as an effective photon absorber. A Gaussian-shaped spectral emission with a bandwidth of up to 135 nm has been obtained with a low spectral modulation of 3% from QD SLD. Optical power at tens of microwatt regime has been measured due to low gain nature of the semiconductor QD material. The results demonstrate broadband superluminescent technology utilizing multiple-functional area of QD material achieving the low-ripple broad spectrum.

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