High Performance Superluminescent Diode with InAs Quantum-Dashes and Chirped AlGaInAs Barriers Active Region

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Abstract: The demonstration of high power, ultra-low ripple superluminescent diode using multiple quantum-dash-in-a-well layers with variable barrier thickness is reported. The device exhibits >20 mW power, <0.3dB ripple, and >80 nm 3dB bandwidth at ~1.55 μm.

Broadband superluminescent diode (SLD) are attractive light source of choice because of its low cost, compact, and robust features, with wide applications in optical coherence tomography, fiber optic gyroscope and sensors, wavelength division multiplexing and subcarrier optical transmission systems [1]. Therefore, there has been growing interest to exploit the inhomogeneous nature of matured self-assembled quantum-dots (Qdot) as the gain media to realize broadband SLD on GaAs substrates in the wavelength range of 1-1.3 μm [2,3]. Recently, InAs quantum-dash (Qdash) structure grown on InP has also shown considerable interest in broadband emitter applications because of their wavelength span of ground state transition between 1.4 and 2.0 μm, particularly attractive for low-loss optical fiber communication and gas sensing applications. In our recent work, we demonstrated the first Qdash based SLD with maximum of 2 mW output power and ~ 110 nm emission bandwidth [4,5] centered at ~1.6 μm. Our thrust to improve the device performance lead to the exploration of chirped Qdash structure wherein the InGaAlAs barrier layer thickness is varied among the Qdash stacks. With this device structure, we achieved output power as high as > 20 mW which is the record value reported from the Qdash nano-structure based SLD. Our seamlessly integrated pump-absorber device configuration enables a high current injection and amplified spontaneous emissions from intentionally dispersive size dashes, and hence producing broad emission > 80 nm under pulsed operation and exhibiting ultra low ripple < 0.3 dB SLD at central wavelength of 1.55 μm.

The self-organized InAs/InP Qdash device chirp laser structure (QCLS) was grown by molecular beam epitaxy on (100) oriented, S-doped n-type InP substrate. The waveguide core comprises undoped quantum-dash-in-asymmetric-well active region with 4 alternating stacks of 1.3 *nm* thick compressively strained $In_{0.64}Ga_{0.16}Al_{0.2}As$ well layer, a 5 ML thick InAs dash layer, and a 6.3 *nm* thick compressively strained $In_{0.64}Ga_{0.16}Al_{0.2}As$ well layer. Each quantum-dash-in-asymmetrical-well stack is separated by varying thickness (10 *nm*, 10 *nm*, 15 *nm*, and 20 *nm*) tensile-strained $In_{0.50}Ga_{0.32}Al_{0.18}As$ top barriers, on a single $In_{0.50}Ga_{0.32}Al_{0.18}As$ 25 *nm* thick lower barrier. More details of the structure can be found elsewhere [4]. In the 20 *μm* wide broad area SLD, the partial suppression of Fabry-Perot resonances in the optical path is achieved via the integration of photon-absorber (PA) section to a1 mm long pump section. The device was mounted on a brass heat sink using a thermo-electric cooler operated at 20°C.

Fig. 1(a) and (b) corresponds to the [011] and [0-11] cross-sectional transmission electron microscope (TEM) micrographs of the QCLS sample and the atomic force microscopy (AFM) image of the Qdashes showing highly dispersive dash sizes. Utilizing TEM images, a statistical average dash (bright truncated pyramids) heights of ~ 3 *nm* (top), ~ 2.8 *nm,* ~ 2.7 *nm,* and ~ 2.5 *nm* (bottom), are obtained, suggesting enhanced dispersion in the size of the dash thus leading to enhanced inhomogeneous broadening of the active region. A conduction band energy model is shown in Fig. 1(c) for better illustration. Photoluminescence (PL) spectroscopy at 77 K using 1064 *nm* diode pumped solid-state laser on the dash sample reveal ground state (GS) emission of ~1.54 *μm* at low excitation. The PL peak wavelength blue shifts and the spectra gradually broaden with increasing excitation. At high excitation of 3000 W/cm^2, a peak wavelength at ~ 1.46 *nm* and broad spectra with ~150 *nm* full-width at half-maximum (FWHM) is achieved as shown in Fig. 2. This enormously large broadening of the PL spectra is a collective contribution from different multiple transition states appearing from the extended inhomogeneous broadening among the dispersive average height dash layers, in addition to the localized or in-plane inhomogeneity.

Fig. 3(a) shows the emission spectrum of the fabricated QCLS SLD device at different current, and the change in the emission bandwidth (FWHM) with increasing injection current density, at 0.5 μs pulse width with 0.2% duty cycle. The bandwidth progressively increases with current injection (see Fig. 3(b)). For injection current density > 5 kA/cm^2 a linear increase in the bandwidth might indicate progressive collective emission from different size dashes in our quantum-dash-in-well structure. The *L-I* characteristics of this device are shown in Fig. 3(c). An output power as high as > 20 *mW* is achieved at > 20 kA/cm^2 without apparent roll-over being observed, with a bandwidth of > 80 nm. To our knowledge, this is the largest power measured from Qdash nano-structure SLD ever reported. It is to be noted that power and bandwidth improvement could be further achieved by using longer tapered

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or multi-section devices [1, 2] and post growth bandgap engineering (for instance, intermixing technique) [6]. In addition to high power, our device exhibits extremely low gain ripple (< 0.3 dB) within 10 *nm* span from the central wavelength which makes it attractive for the optical coherent tomography applications. The theoretical coherence length of our structure calculated by (central wavelength^2/bandwidth) is ~ 28 μm and the average spectral power density (output power/bandwidth) is ~ 0.25 *mW/nm*.

In conclusion, a small footprint, simple configuration, high performance chirped barrier layer thickness Qdash SLD is realized, with > 80 nm emission bandwidth. This is the first demonstration of high power and ultra low ripple SLD from Qdash nano-structures.

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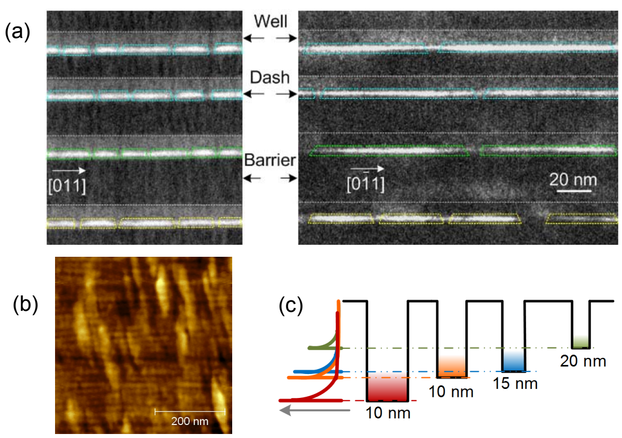

Fig.1 [0-11] and [011] cross-sectional TEM micrographs, (b) AFM image of the Qdashes, and (c) conduction band energy model of the chirped Qdash laser structure

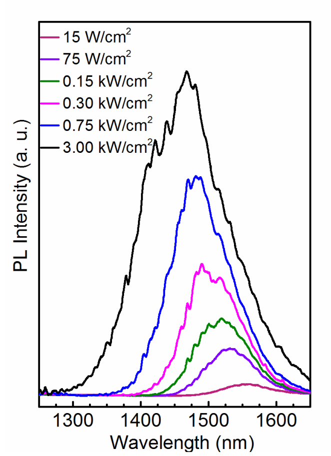

Fig. 2 77 K PL emission spectra from chirped Qdash laser structure at various excitation power densities.

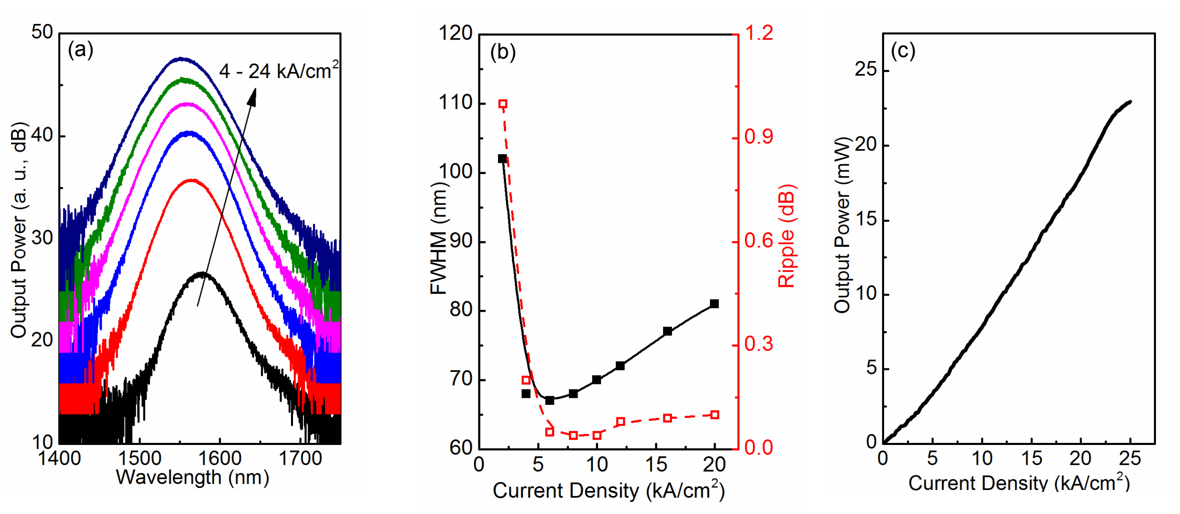

Fig. 3 (a) Emission spectra at various pumping current density values (current density step 4 kA/cm^2), (b) emission bandwidth and ripple as a function of injection current density, and (c) *L-I* characteristics, of the QCLS Qdash SLD under pulsed operation (0.5 µs pulse width and 0.2% duty cycle). The solid (dash) lines in (b) are guide to the eye.