Far-field patterns of Quantum Well, Quantum Dash, and Quantum Dot Laser Diodes

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Abstrac—**We perform measurements of far field pattern of various quantum-confined heterostructures namely quantum well (QW), quantum dash (Qdash), and quantum dot (Qdot) lasers to study the effect of different active gain mediums of semiconductor lasers on the optical beam quality and coupling efficiency. The beam pattern profile of the Qdash laser is similar to that of the QW laser (FWHM ~ 20°) while Qdot laser shows smaller divergence (FWHM ~ 5°) and retain its intensity profile of single lobe Gaussian-shape at current injection up to two and half times threshold current.**

I. Introduction

High power near-infrared laser diodes are attractive for many applications include the pumping source for Er-doped gain media for range measurement, flash lidar, and remote-sensing [1]. However, broad-area edge-emitters tend to exhibit self stabilized nonlinear modes and thus the issue of self-focusing will induce high-brightness unstable filaments, which destroys the spatial coherence of the beam and can lead to catastrophic optical damage (COD) at the laser facet [2]. Several methods to overcome this problem have been applied to produce narrow beam divergence to reduce the complexity and cost of an optical system, e.g. for direct coupling to a fiber. Broad area lasers challenges include filamentation and higher order transverse mode operation which destroys the spatial coherence i.e. focusing abilities of these devices [2]. However, the lack of studies on the effect of active gain medium on the spatial coherence properties may hinder a better understanding of the nature of far-field pattern formation from semiconductor lasers.

The technology of self-assembled quantum confined nanostructures such as dot and dash geometries has generated tremendous interest due to their near singular density of states, low threshold current densities, temperature insensitive characteristics, high modulation bandwidth, and small linewidth enhancement factor (α) relative to conventional QW lasers [3]. Numerical simulations indicate that filamentation for broad-area lasers with a stripe width > 50 µm occurs if α exceeds 0.5 [4]. Recent studies show that generally QW exhibits the largest α (typically more than 3), followed by Qdash (α~1 to 3) and Qdot (α<1) [5] [6]. In this paper, we perform the measurements and analysis of far field pattern from laser with different geometries of active gain medium such as InGaAs/InGaAsP QW, InA/InAlGaAs Qdash and InGaAs/GaAs Qdot of semiconductor lasers. The QW and Qdash lasers give light emission at long wavelength of ~1.55 µm and ~1.64 µm, respectively, while the Qdot lasers emit at the mid-range wavelength of ~1.18 µm.

II. Experiment

The lattice-matched InGaAs/InGaAsP QW laser structure was grown by metal organic chemical vapor deposition (MOCVD) on a Si-doped n-InP substrate. The structure is based on a standard separate confinement heterostructure (SCH) with two sets of multiple QWs. The upper SCH layers and the lower SCH layers are each 155nm-thick film of InGaAsP layer and an inner 600nm-thick film of doped InGaAsP. The undoped active region consists of two sets of multiple QWs with matching photoluminescence peaks: five 10nm $In_{0.446}Ga_{0.554}As$ wells with 20nm GaInAsP barriers and 6 (underlying) lattice matched 5.5nm $In_{0.47}Ga_{0.53}As$ wells with 12 nm GaInAsP barriers.

The InAs/InAlGaAs Qdash laser structure was grown by molecular beam epitaxy (MBE) on (100) oriented InP substrate. The active region consists of four sheets of 5 monolayer (ML) InAs dashes, each embedded within a 7.6 nm thick compressively strained $In_{0.64}Ga_{0.16}Al_{0.2}As$ QW and a 30 nm thick tensile strained $In_{0.50}Ga_{0.32}Al_{0.18}As$ barrier [7].

The InGaAs/GaAs Qdot sample was grown using a molecular beam epitaxy (MBE) system on Si-doped (100) GaAs substrates. A 1500 nm thick p-doped AlGaAs cladding and 200 nm GaAs contact layer were grown on top of the active Qdot layer. The Qdot layer is compromised of alternating monolayers (MLs) of InAs and GaAs at a ML each with a total thickness of ~ 10 ML. The Qdot active region consists of five stacks of Qdot layers buried with 40 nm thick GaAs space layers.

Broad area lasers with 50-µm-wide oxide stripes were fabricated from the as-grown QW, Qdash, and Qdot samples. The as-cleaved faceted lasers were tested on the temperature controlled heat sink set at 15 ºC with an epitaxial p-side-up mounting configuration. Current injection was performed under pulsed operation at 0.2% duty cycle with 2 µs pulse width.

III. Results and discussion

The threshold current densities of the InGaAs/InGaAsP QW, InAs/InAlGaAs Qdash, and InGaAs/GaAs Qdot lasers are 1.5 kA/cm^2, 4 kA/cm^2, and 2.5 kA/cm^2, respectively. Fig. 1 to 3 shows the far-field profiles and Fig. 4 to 6 shows the lasing spectra of the three types of lasers at different current injections. The measurements are done in pulsed-current injection to avoid thermal effects and to produce smooth carrier profile. Henceforth, a smooth antiguide through the negative phase amplitude coupling of the semiconductor medium amplitude coupling of the semiconductor medium diffuses any local optical buildup and prevents the formation of filaments [8].

The electroluminescence spectra (EL) and far-field patterns illustrated in the figures are measured with the resolution of approximately 0.05 nm and 0.5º step, respectively. The EL of QW lasers (fig. 4) show that highly nonuniformity of the lowest order supermode present at even low injection (< 2 I_{th}). Consequently, carriers are unevenly depleted when this lateral mode is excited. At higher injection (> 2 I_{th}), gain saturation or spatial hole burning in a carrier concentration is expected to occur in semiconductor laser [9] where an increasing number of higher order lateral modes are excited as the power level escalates. This will result in broadened radiation patterns due to the slight displacement of single-lobed far-field pattern of each higher order lateral mode from that of the fundamental as noted in Fig. 1. However, Qdash shows the largest degree of deterioration in divergence (FWHM of 3.4° to 10.8°) with injection due to its unique property of self-assembled highly inhomogeneous broadening gain medium that tends to result in multimode oscillation [7], followed by Qdot (FWHM of 3.0º to 6.0º), which has improved homogeneity gain medium.

Nevertheless, both Qdash and Qdot exhibits a single-lobed far-field profile and show smaller beam divergence angle than QW (FWHM ~13º) regardless of the injection. In the QW laser, filamentation is present already at near threshold injection. With increasing output power, filamentation increases with more sharp peaks appearing in the beam profile. Side lobes start to emerge at higher drive current of ~4 I_{th}. This nearly twin-lobed far-field profile is evidence of a curved wavefront, which is a typical feature of gain-guided devices [10]. On the other hand, intrinsic filamentation suppression in Qdot lasers contributes to small divergence angle as compared to QW and Qdash lasers. Carriers injected into the Qdots are confined by lateral energy barriers as Qdots are disconnected laterally and are cladded by higher-bandgap materials [11].

Since Qdash is formed by elongated dots and our waveguide direction is perpendicular to the dash, the optical beam divergence of the Qdash is expected to be similar to that of the QW laser while reduced filamentation characteristics of Qdot will incur in Qdash. This can be evident by the observation of the substantial improvement in the far-field distributions of Qdash laser (fig. 2) as compared to the asymmetric far-field pattern of QW laser (fig. 1) with side lobes appearing even at low powers. Besides that, Qdash laser

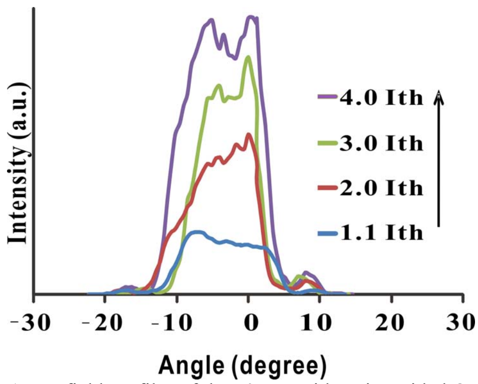

Fig. 1. Far field profiles of the 50-µm-wide gain-guided QW broad area laser with a cavity length of 0.5 mm at various current injections.

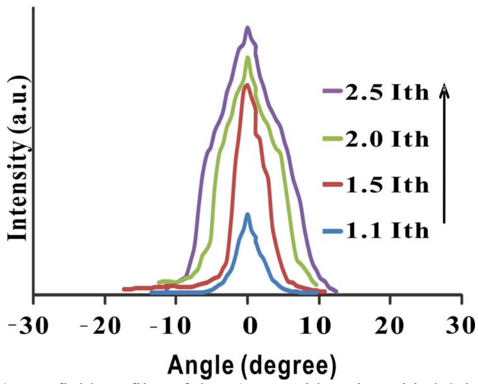

Fig. 2. Far field profiles of the 50-µm-wide gain-guided Qdash broad area laser with a cavity length of 0.5 mm at various current injections.

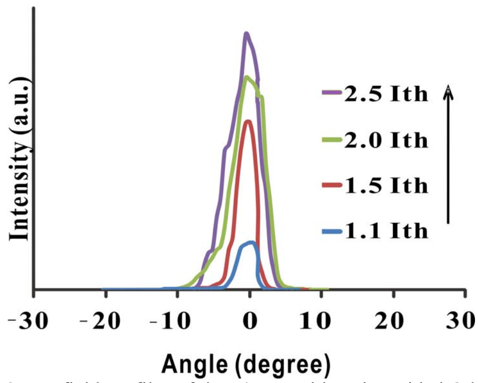

Fig. 3. Far field profiles of the 50-µm-wide gain-guided Qdot broad area laser with a cavity length of 1.0 mm at various current injections.

demonstrating the similar behaviors of far-field patterns as the enhanced current spreading QW laser [12] indirectly shows enhanced lateral current spreading in Qdash nanostructure without any special design of epitaxial layers.

IV. Conclusion

In summary, Qdash laser shows similar beam divergence at high injection but improvement in filamentation as compared to QW laser due to the nature of lateral carrier diffusion, which lead to the issue of self-focusing and thus the different degrees of filamentation. Quantum dot has better optical beam quality due to the three dimensional confinement of carriers. However, the largest degree of broadening radiation pattern with increasing injection in Qdash structure followed by Qdot and QW in sequence indicates that improvement of inhomogeneity self-assembled active gain medium is needed especially for applications in free space communication

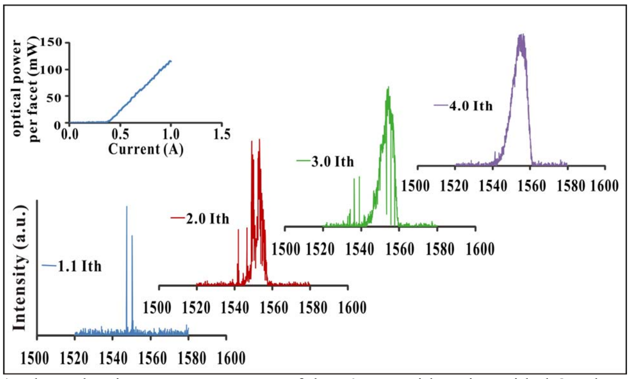

Fig. 4. Electroluminescence spectrum of the 50-µm-wide gain-guided QW broad area laser with a cavity length of 0.5 mm at various current injections. The inset shows a light-current curve of laser under pulse operation at 15°C.

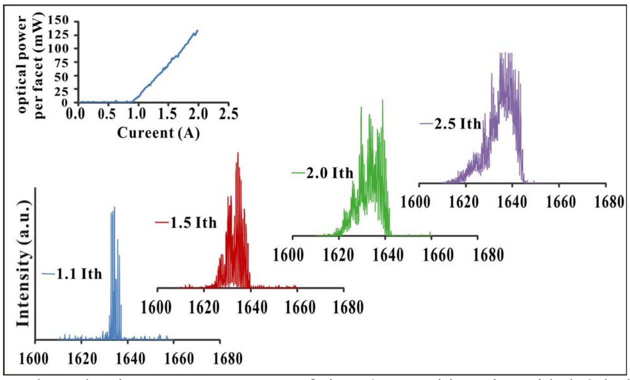

Fig. 5. Electroluminescence spectrum of the 50-µm-wide gain-guided Qdash broad area laser with a cavity length of 0.5 mm at various current injections. The inset shows a light-current curve of laser under pulse operation at 15°C.

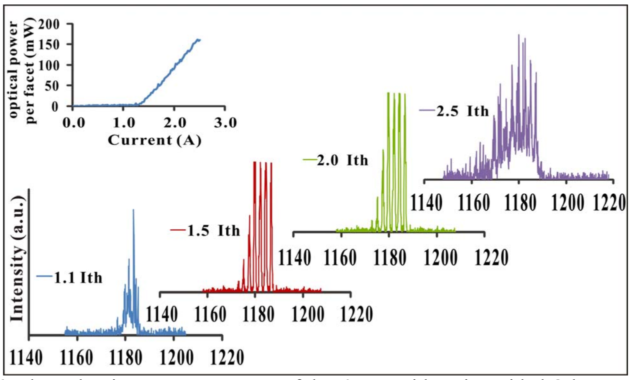

Fig. 6. Electroluminescence spectrum of the50-µm-wide gain-guided Qdot broad area laser with a cavity length of 1.0 mm at various current injections. The inset shows a light-current curve of laser under pulse operation at 15°C.

REFERENCES

[1] S. D. Setzler, K. J. Snell, T. M. Pollak, P. A. Budni, Y. E. Young, and E. P. Chicklis, ”5-W repetitively Q-switched Er:LuAG laser resonantly pumped by an erbium fiber laser”, *Opt. Lett.,* vol. 28, pp. 1787-1789, October 2003

[2] J. R. O’Callaghan, J. Houlihan, V. Voignier, G. Huyet, J. G. McInerney, B. Corbett, and P. A. O’Brien, “ Focusing properties of high brightness gain tailored broad-area semiconductor lasers”, *IEEE Photon. Technol. Lett.*, vol. 14, pp. 9-11, January 2002

[3] D. Bimberg, M. Grundman, and N. N. Ledentsov, *Quantum Dot Heterostructures*, Wiley, Chichester, pp. 281-294, 1999.

[4] J. R. Marciante and Govind P. Agrawal, “Nonlinear mechanisms of filamentation in broad-area semiconductor lasers,” *IEEE J. Quantum Electron.,* vol 32, no. 4, pp. 590-596, April 1996

[5] S. Schneider, P. Borri, W. Langbein, U. Woggon, R. L. Sellin, D. Ouyang, and D. Bimberg, ”Linewidth Enhancement Factor in InGaAs Quantum-Dot Amplifiers,” *IEEE J. Quantum Electron.,* vol. 40, no. 10, pp 1423-1429, Oct. 2004

[6] K. Kikuchi, M. Amano, *C.* E. Zah and *T.* P. Lee, ”Measurement of Differential Gain and Linewidth Enhancement Factor of 1.5-pm Strained Quantum-Well Active Layers,” *IEEE J. Quantum Electron.,* vol. 30 no. 2, pp. 571-573, February 1994.

[7] H. S. Djie, C. E. Dimas, and B. S. Ooi, “Wideband quantum-dash-in-well superluminescent diode at 1.6 µm”, *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1747-1749, August 2006.

[8] J. R. O. Callaghan, John Houlihan, Vincent Voignier, Guan H. Wu, Eamonn O’Neill and John G. McInerney et al, “Spatial coherence and thermal lensing in broad-area semiconductor lasers,” *IEEE J. Quantum Electron.,* vol. 40 no. 1, pp. 1-9, January 2004

[9] Kuo Liang and Shyh Wang, ”Spatial hole burning problems in evanescently coupled semiconductor laser arrays,” *Appl. Phys. Lett.*, vol. 47, pp. 555-557, September 1985.

[10] J. R. Marcianteet and Govind P. Agrawal, ”Controlling filamentation in broad-area semiconductor lasers,” *Appl. Phys. Lett.*, vol. 69, pp. 593-595, May 1985.

[11] Ch. Ribbatet, R. L. Sellin, I. Kaiander, F. Hopfer, N. N. Ledentsov, and D. Bimberg et al, ”Complete suppression of filamentation and superior beam quality,” *Appl. Phys. Lett.*, vol. 82, pp. 952-954, February 2003.

[12] P. A. O’Brien et al, ”Broad area semiconductor lasers with improved near and far fields using enhanced current spreading,” *IEEE Electronic. Lett*, vol 34, no 20, pp. 1943-1944, October 1998