# Butt joint integrated extended cavity InAs/InP (100) quantum dot laser emitting around 1.55 μm

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The first Butt joint integrated extended cavity InAs/InP (100) quantum dot (QD) Fabry-Pérot laser emitting around 1.55 μm is demonstrated. Continuous wave lasing at room temperature on the QD ground state transition is achieved. The threshold current is comparable to that of all-active QD lasers. The Butt joint reflectivity for straight waveguides is below −40 dB.

*Introduction:* Monolithically integrated quantum dot (QD) lasers for photonic integrated devices and circuits have been demonstrated in the InAs/GaAs materials system by selective area and regrowth techniques [1, 2]. We demonstrate the first Butt joint active–passive integrated QD laser in the InAs/InP (100) materials system emitting in the technologically important 1.55 μm wavelength region for fibre-based optical telecommunication systems. The extended cavity Fabry-Pérot QD laser operates in continuous wave (CW) mode at room temperature (RT) on the QD ground state (GS) transition. The threshold current is only slightly larger compared to that of our all-active Fabry-Pérot QD lasers [3] and the Butt joint reflectivity is below −40 dB for straight waveguides.

*Device fabrication:* The integrated QD laser structure was grown by metal-organic vapour phase epitaxy (MOVPE) in a three-step process [4]. In the first epitaxy step, the active layer was grown on *n*-doped InP (100) substrate. It consists of a stack of five QD layers embedded in the centre of a 500 nm-thick $\lambda = 1250$ nm lattice-matched InGaAsP (Q1.25) layer. The average QD diameter, height, and density are 50 nm, 5.6 nm, and $2 \times 10^{10}$ cm$^{-2}$, and the Q1.25 separation layer is 40 nm thick. The emission wavelength of the three-monolayers (MLs) InAs QDs was tuned into the 1.55 μm wavelength region through insertion of ultrathin (1.3 MLs) GaAs interlayers underneath the QDs [5]. Then a *p*-doped 200 nm-thick InP layer was grown. Active mesa blocks were defined by photolithography using a 100 nm $SiN_x$ layer as etching mask. The mesa blocks are 30 μm wide and spaced apart by 250 μm with lengths varying from 200 to 2000 μm. The future passive areas were etched wet chemically 50 nm below the active layer, thus 560 nm were etched for regrowth. An overhang below the $SiN_x$ mask prevents the lateral overgrowth at the Butt joint. Then undoped Q1.25 and InP layers were regrown by selective area MOVPE using the same $SiN_x$ mask. The thicknesses of both layers are matched to the original thicknesses. The $SiN_x$ mask was removed and the 1.5 μm gradually *p*-doped InP top cladding and compositionally graded *p*-doped InGaAsP contact layer were grown. After growth, straight ridge waveguides with a width of 2 μm were fabricated by reactive-ion dry etching 100 nm into the Q1.25 layer. The structure was planarised by polyimide and Ti/Pt/Au contact layers were fabricated on the active region and the back side. The extended cavity laser under investigation consists of a 1450 μm-long active waveguide connected to one 800 μm-long passive waveguide, terminated by cleaved mirrors on both ends. A photograph of the device is shown in Fig. 1.

**Fig. 1** *Photograph of integrated extended cavity InAs/InP (100) QD laser*

Two current probes contact laser with 1450 μm-long active and 800 μm-long passive waveguides

*Results:* Fig. 2 shows the electroluminescence (EL) and lasing spectra taken from the as-cleaved facet as a function of current together with the total optical output power in the inset. Lasing occurs in CW mode at RT on the QD GS transition at 1.53 μm. Excited state (ES) EL evolves at shorter wavelength (1.50 μm) for increasing current owing to QD GS saturation. The threshold current of 231 mA is similar to that of our all-active Fabry-Pérot QD lasers with a comparable slope efficiency [3]. This confirms a low Butt joint loss, which has been previously evaluated to be 0.1–0.2 dB in passive–passive structures [4].

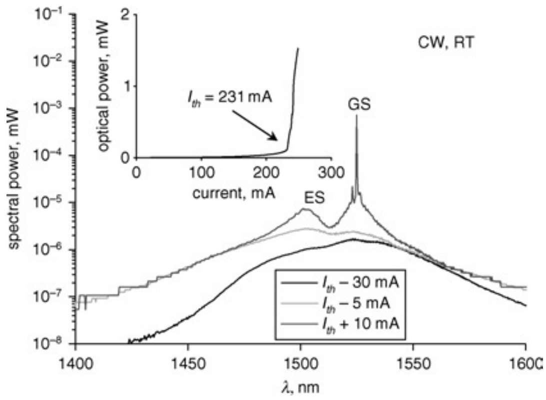


**Fig. 2** *Electroluminescence and lasing spectra against current taken in continuous wave (CW) mode at room temperature (RT)*

QD ground state (GS) and excited state (ES) transitions are indicated
Inset: total optical output power against current

In addition to low absorption, a low Butt-joint reflectivity is essential for stable operation of photonic integrated devices and circuits. The Butt joint reflectivity is measured based on the analysis of sub-threshold emission spectra, which are recorded by an optical spectrum analyser (APEX AP2040) with a very high resolution of 0.16 pm [4]. By fitting the calculated sub-threshold mode structure to the recorded data, values of the reflectivity are extracted. Fig. 3 shows the Fourier transforms of the experimental and fitted emission spectra, which are shown in the inset. In addition to the dominant peak in the Fourier transform due to the extended cavity, small peaks are visible originating from the passive and active internal cavities formed by the cleaved mirrors and the Butt joint. The extracted Butt joint reflectivity is −42 dB ($6 \times 10^{-5}$). This is similar to the reflectivity of our Butt joints examined with bulk active region extended cavity lasers and can easily be reduced to below −50 dB using waveguides entering the Butt joint under an angle [6].

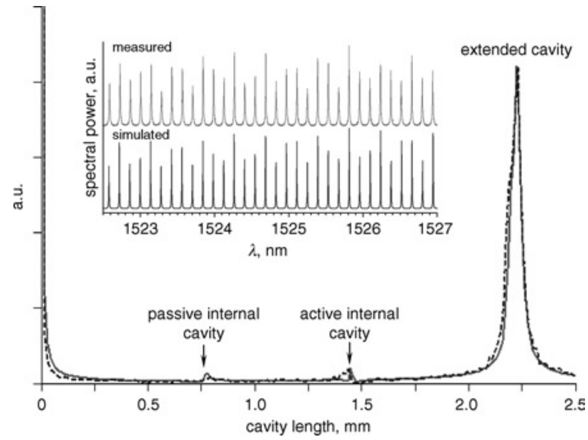


**Fig. 3** *Fourier transforms of experimental and fitted sub-threshold emission spectra, shown in inset*

*Conclusions:* We have demonstrated a Butt joint active–passive integrated extended cavity Fabry-Pérot laser based on InAs/InP (100) quantum dots (QDs) emitting around 1.55 μm. Continuous wave lasing at room temperature on the QD ground state transition was achieved. The threshold current was comparable to all-active Fabry-Pérot QD lasers. A Butt joint reflectivity <−40 dB for straight waveguides was determined. Hence, compatibility of our InAs/InP (100)

QD gain material with Butt joint active-passive integration is demonstrated paving the way for QD based photonic integrated devices and circuits operating in the technologically important 1.55 μm wavelength region for fibre-based optical telecommunication systems.


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**References**

1 Mokkapati, S., Tan, H.H., and Jagadish, C.: 'Integration of an InGaAs quantum-dot laser with a low-loss passive waveguide using selective-area epitaxy', *IEEE Photonics Technol. Lett.*, 2006, **18**, pp. 1648–1650

2 Yang, J., Bhattacharya, P., and Wu, Z.: 'Monolithic integration of InGaAs-GaAs quantum-dot laser and quantum-well electroabsorption modulator on silicon', *IEEE Photonics Technol. Lett.*, 2007, **19**, pp. 747–749

3 Anantathanasarn, S., Nötzel, R., van Veldhoven, P.J., van Otten, F.W.M., Barbarin, Y., Servanton, G., de Vries, T., Smalbrugge, E., Geluk, E.J., Eijkemans, T.J., Bente, E.A.J.M., Oei, Y.S., Smit, M.K., and Wolter, J.H.: 'Lasing of wavelength-tunable (1.55 μm region) InAs/InGaAsP/InP (100) quantum dots grown by metal organic vapor-phase epitaxy', *Appl. Phys. Lett.*, 2006, **89**, pp. 073115

4 Barbarin, Y., Bente, E.A.J.M., de Vries, T., den Besten, J.H., van Veldhoven, P.J., Sander-Jochem, M.J.H., Smalbrugge, E., van Otten, F.W.M., Geluk, E.J., Heck, M.J.R., Leijtens, X.J.M., van der Tol, J.G.M., Karouta, F., Oei, Y.S., Nötzel, R., and Smit, M.K.: 'Butt-joint interfaces in InP/InGaAsP waveguides with very low reflectivity and low loss'. Proc. IEEE/LEOS Symp. Benelux Chapter, 2005, pp. 89–92

5 Anantathanasarn, S., Nötzel, van Veldhoven, P.J., van Otten, F.W.M., Eijkemans, T.J., and Wolter, J.H.: 'Stacking and polarization control of wavelength-tunable (1.55-μm region) InAs/InGaAsP/InP (100) quantum dots', *Appl. Phys. Lett.*, 2006, **88**, pp. 063105

6 Barbarin, Y., Bente, E.A.J.M., Marquet, C., Leclère, E.J.S., Binsma, J.J.M., and Smit, M.K.: 'Measurement of Reflectivity of Butt-Joint Active-Passive Interfaces in Integrated Extended Cavity Lasers', *IEEE Photonics Technol. Lett.*, 2005, **17**, pp. 2265–2267