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High-performance 1.52 μm InAs/InP quantum dot distributed feedback laser

Z.G. Lu, P.J. Poole, J.R. Liu, P.J. Barrios, Z.J. Jiao, G. Pakulski, D. Poitras, D. Goodchild, B. Rioux and A.J. SpringThorpe

A high performance ridge-waveguide InAs/InP quantum dot distributed feedback laser around 1.52 μm with a cavity length of 1 mm and a stripe width of 3 μm is demonstrated. In continuous-wave operation singlemode output power was up to 18.5 mW and its sidemode suppression ratio was greater than 62 dB. The relative intensity noise was measured to be less than -154 dB/Hz from 10 MHz to 10 GHz, and the optical linewidth smaller than 150 kHz when the injection current was 200 mA at room temperature of 18°C.

Introduction: The concept of quantum dots (QDs) was proposed by Arakawa and Sakaki in 1982 for application to semiconductor lasers with the theoretical prediction of having much better performance as compared with conventional bulk and quantum well (QW) semiconductor lasers [1]. More specifically, QD lasers have been theoretically predicted to show outstanding characteristics such as temperature insensitivity and ultra-narrow optical linewidth [1, 2]. Utilising those unique properties of QDs, temperature-insensitive 1.3 μm InAs/GaAs QD distributed feedback (DFB) lasers with laterally loss- or index-coupled gratings have been demonstrated [3]. To reach the important 1.55 μm wavelength range for optical fibre communications, considerable effort has been expended in the growth and fabrication of InAs/InP-based QD gain material, where we have successfully demonstrated QD multiwavelength lasers (QD-MWLs) [4], and femtosecond (fs) pulse generation from passive C- and L-band QD modelocked lasers (QD-MLLs) [5, 6]. As yet there are only a very limited number of reports on singlemode InAs/InP QD DFB lasers operated at 1.55 μm and the reported output powers were less than 10 mW [7, 8]. In this Letter, we report the successful development of a high-performance singlemode 1.52 μm InAs/InP QD DFB laser with an output power of 18.5 mW, a sidemode suppression ratio (SMSR) of larger than 62 dB and an optical linewidth of less than 150 kHz.

Design, growth and fabrication: The InAs/InP QD DFB gain material used in this study was grown by chemical beam epitaxy (CBE) on a (100) oriented n -type InP substrate. The undoped active region of the laser consisted of five stacked layers of InAs QDs with 30 nm $\text{In}_{0.816}\text{Ga}_{0.184}\text{As}_{0.392}\text{P}_{0.608}$ (1.15Q) barriers. The QDs were tuned to operate in the desirable operation wavelength range by using a QD double cap growth procedure and a GaP sublayer. Growing the dots on a thin GaP layer allows a high dot density to be obtained and improved layer uniformity when stacking multiple layers of dots, providing maximum gain. This active layer was embedded in a 350 nm-thick 1.15Q waveguiding core, providing both carrier and optical confinement. An average dot density of approximately $4 \times 10^{10} \text{ cm}^{-2}$ per layer was obtained according to atomic force microscopy (AFM) measurements on uncapped stacked dot samples. Following the growth of the QD active core the wafer was removed to pattern the grating region. This was performed using an HeCd laser to holographically expose the pattern, followed by chemical etching.

Fig. 1 shows a selectively etched cross-sectional scanning electron microscope (SEM) image of the completed laser structure showing the five-layer QD core and the floating grating. Before overgrowth the grating pitch was confirmed using the HeCd laser on the optical bench by finding the difference between the Littrow angle and the angle of normal reflection. The grating period used was 236 nm, giving an operating wavelength of 1520.6 nm. Following the patterning of the grating the p -type contact layers were regrown using metal-organic chemical vapour deposition (MOCVD). The wafer was photoluminescence (PL) mapped before and after regrowth by MOCVD and no change was observed in the PL emission wavelength, indicating the high material quality of both growth steps. Single lateral mode ridge waveguide lasers were then fabricated with a stripe width of 3 μm and a cavity length of 1 mm. One of the cleaved facets was coated with a high reflectivity coating of 62%, the other with a 2% antireflection coating. All measurements were made with the laser driven using a DC current source and temperature stabilised on a heatsink.

Fig. 1 Cross-sectional scanning electron microscope image of completed laser structure showing five-layer QD core and floating grating

Fig. 2 L - I - V curves of ridge-waveguide InAs/InP QD DFB laser operating in continuous-wave at room temperature of 18°C

Fig. 3 Lasing spectrum of singlemode InAs/InP QD DFB laser with injection current 200 mA at room temperature of 18°C

Inset: Corresponding RIN values against frequency

Fig. 4 Optical linewidth of InAs/InP QD DFB laser measured with RF spectrum analyser using delayed self-heterodyne interferometer with injection current 200 mA at room temperature of 18°C

Experimental results and discussion: Fig. 2 gives the L - I - V curves of our developed InAs/InP QD DFB laser at the room temperature of 18°C. The threshold current was 48 mA and the series resistance was 1.3 Ω . The external differential quantum efficiency was about 31% and the output power was up to 18.5 mW for an injection current of 200 mA. Singlemode lasing operation was successfully observed up to 90°C. The SMSR value of the QD DFB laser was greater than 62 dB, as shown in Fig. 3, when the injection current was 200 mA. To investigate its system performance, we have measured its relative intensity noise (RIN) and the optical linewidth, which describe the instability in the power level and its phase noise behaviour, respectively. By using an Agilent N4371A RIN measurement system, the inset in Fig. 3 shows that the RIN values of our developed InAs/InP QD DFB laser were in the range from -154 to -162 dB/Hz when the injection current was 200 mA at a room temperature of 18°C. The optical linewidth was measured with a delayed self-heterodyne interferometer (Advantest Q73321), which had an acoustic-optic modulator (AOM)

operating at 150 MHz and a 5 km delay optical fibre yielding a frequency resolution of 20 kHz. Fig. 4 shows that its 3 dB spectral bandwidth was less than 300 kHz detected with an RF spectrum analyser (Advantest R3361A), the resolution bandwidth (RBW), video bandwidth (VBW) and sweep time (SWP) of which were set at 30 kHz, 100 Hz and 0.7 s, respectively. Here we assume that the spectrum of our QD DFB laser is Lorentzian; the 3 dB bandwidth in the spectral analyser would be twice of the real 3 dB spectral linewidth [9], so the optical linewidth of the InAs/InP QD DFB laser was estimated to be smaller than 150 kHz. Using the exact same experimental setup, we had measured the linewidths of several commercial QW DFB lasers in our labs, the values of which were in the range 2–20 MHz. We believe that the main reasons for the smaller linewidth of our QD DFB laser compared to the measured linewidth of commercial QW DFB lasers are that our QD gain materials have much smaller linewidth enhancement factor α and carrier-induced refractive index change owing to its delta-function-like density of states giving rise to a symmetric gain spectrum [10]. Such ultra-low RIN values and extremely narrow linewidth from our developed InAs/InP QD DFB lasers, compared to typical QW DFB lasers, should lead to excellent phase noise and time–jitter characteristics in high-speed directly modulated laser applications. Our developed InAs/InP QD DFB lasers have great potential to be an outstanding source for coherent optical fibre communications, fibre-optic sensing and spectroscopy (e.g. LIDAR) applications.

Conclusions: We have fabricated and demonstrated CW singlemode InAs/InP QD DFB lasers operated around 1.52 μm . Our experimental results clearly confirm that InAs/InP QD DFB lasers show great promise for use as high-performance, low-timing-jitter, low phase and amplitude noise light sources for WDM telecommunication systems, coherent optical communications and sensing applications around 1.55 μm .

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One or more of the Figures in this Letter are available in colour online.

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