NRC·CNRC

Quantum dot laser technology

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Background

The semiconductor laser is the workhorse of the telecommunications and data communications industry, used as the light source for transmitting data over optical fibre. These lasers have been traditionally based on indium phosphide (InP) materials, and in particular use quantum wells (QWs) as the gain medium. In 1982, predictions were made of improved performance for quantum dot-based lasers over their QW counterparts,[1] with promises of lower thresholds, temperature dependence and back-reflection sensitivity. This led to long-term studies looking at how to create such quantum dot (QD) structures, how to implement them in lasers and the comparison of their performance relative to QW lasers.

Since the mid 1990s, the National Research Council of Canada (NRC) has been heavily involved in developing quantum dots and dashes on both GaAs and InP substrates. In particular, applications in the 1.55 µm wavelength range have driven the growth of self-assembled InAs quantum dots on the InP-based platform. These QDs have been used to demonstrate lasers with performance advantages in high-speed data communications applications over QW lasers.

Description of the technology

Our QD lasers are based on conventional InP semiconductor lasers, which are ubiquitous in the optical telecommunications and data communications sectors. But in ours, the QW gain section has been replaced with QDs (see figure 1). This approach means that laser fabrication can be performed using all of the standard InP processing techniques available at the NRC, including grating fabrication and the creation of buried heterostructures.

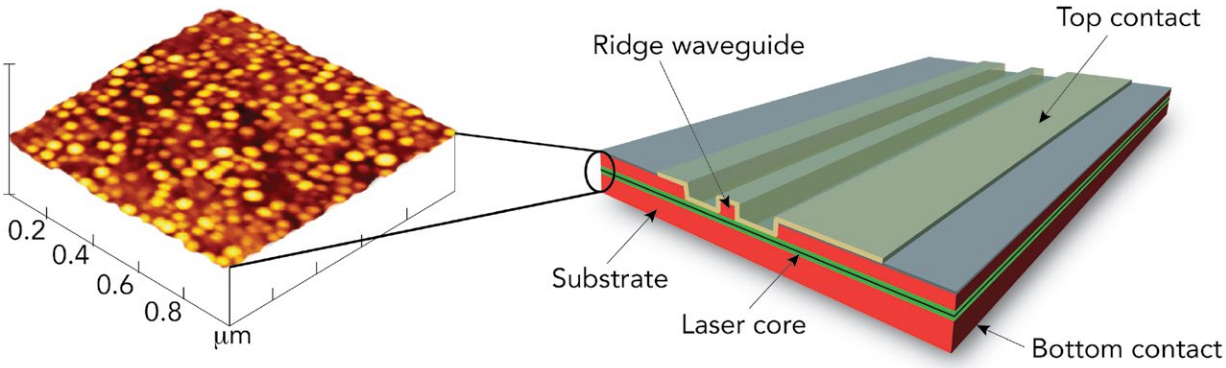

Figure 1 Schematic of a QD laser with a cutout showing typical quantum dots used in the laser core.

The InAs quantum dots are grown using a self-assembled Stranski–Krastanov growth process that has been optimized to allow precise control of the emission wavelength of each QD layer and minimize the broadening.[2] The physically discrete nature of each QD emitter creates an inhomogeneously broadened gain material that reduces the interaction between individual QDs through the charge carrier distribution. For certain applications, this property has demonstrated laser performance that is superior to that demonstrated with QW gain materials. These applications include high-speed data communications (including coherent modulation schemes) and radio over fibre (RoF).

Applications and advantages (compared with existing or commercialized technology)

Coherent communications

The demand for high-speed data communications continues to grow, requiring the development of more complex modulation schemes for higher speed and spectral efficiency while reducing costs. This puts high demands on the optical sources used to generate and carry the signals. The use of high spectral efficiency advanced coherent modulation schemes, such as multiple order quadrature amplitude modulation (QAM) for multiple simultaneous wavelength channels or the creation of a superchannel, requires many lasing wavelengths. Each wavelength channel must demonstrate both low relative intensity noise (RIN) and narrow linewidth (low phase noise). Combining multiple individual lasers becomes impractical for large channel counts and is infeasible when a fixed-mode spacing and a well-defined phase relationship are required between the lasing lines. A preferred approach is to use laser frequency combs to provide a source of evenly spaced narrow lasing lines with well-defined phase relationships between the lines. Conventional frequency comb sources, however, are typically complex to control, bulky, power hungry and expensive, making their deployment unattractive. The use of QD lasers can solve these issues.

Mode-locking a semiconductor laser is an attractive way to produce a frequency comb but usually requires multi-section devices and very precise control of the operating conditions in order to maintain the high-quality comb required for coherent communication applications. The unique properties of the QD gain material allows these lasers to readily mode-lock using a very simple, easily controlled single-section Fabry–Perot laser cavity.[3] There is no requirement for separate saturable absorbers or multiple electrical contacts, and the range of operating conditions (e.g. drive current, temperature) where good mode-locking occurs is large. All of the modes are mutually phase-locked, making them ideal for coherent communication.

Operation of the laser creates many lasing lines, e.g. 56 at a 28.4 GHz mode spacing, as shown in panel (c) of figure 2. Each of these lasing lines has verified low RIN and low linewidth,[4] making them ideal for data communication over optical fibre at wavelengths around 1.55 µm. We have demonstrated data rates up to 220 Gb/s for an individual line using dual polarization 16-QAM at a base modulation rate of 28 GHz. This provides an aggregate data rate of 12.5 Tb/s for the whole lasing spectrum[5] and has been demonstrated for both back-to-back (B2B) and over 100 km of standard single-mode fibre (SSMF). This finding highlights the viability of the QD lasers as a low-cost optical source for large-scale networks.[5,6]

Figure 2 shows the schematic and actual implementation of a mode-locked QD laser that has been locked to a fixed 25 GHz frequency grid.

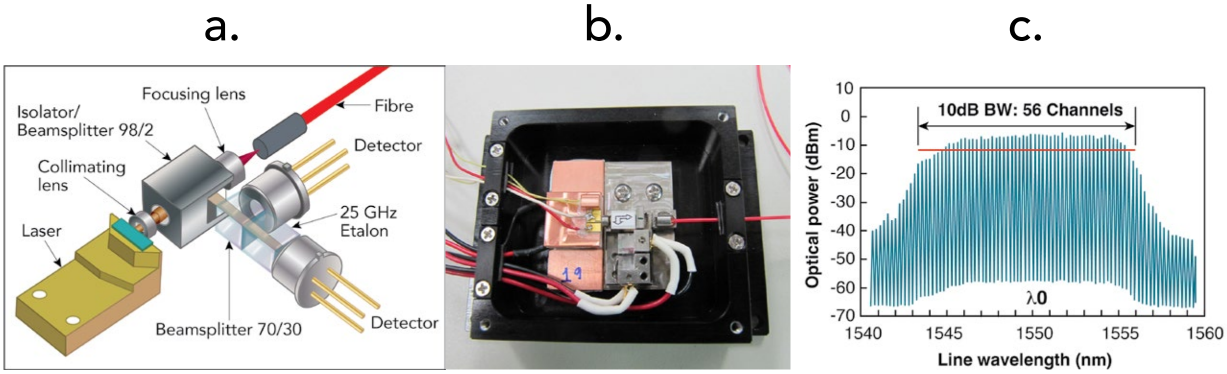

Figure 2 (a) Optical design schematic (b) Optical fibre pigtailed subassembly of a QD laser locked to a fixed wavelength grid (c) Typical lasing spectrum for a QD laser

Radio over fibre

The demand for broadband high-speed wireless connectivity with low latency and reliability has been driving 5G and beyond wireless communications, with usage scenarios that specify high-speed broadband services with peak data rates of tens of Gb/s. To achieve such ultra-high-speed broadband and low latency services, high carrier frequencies in the millimeter wave (mmW) bands (30 GHz to 300 GHz) are of great interest. However, generating mmW signals with traditional electronic methods becomes increasingly difficult as the frequency increases, and the transmission of those signals over long distances is a real challenge. Consequently, in the optical domain, broad-bandwidth, simple, efficient and cost-effective photonic millimeter-wave-over fibre (mmWoF) solutions are considered viable alternatives for mmW signal generation, processing, control and distribution for application in broadband wireless access networks. The generation of mmW signals can be addressed using optical techniques based on the heterodyne beating of two optical signals, spaced at the desired mmW frequency where digital or analog data are encoded onto either one or both optical signals.

We have addressed the photonic generation of mmW signals using two approaches enabled by the use of QD laser technology:

1. QD comb laser

To create a high purity mmW carrier, the two optical signals used to generate the beat signal should have the same intensity and a well-defined phase relationship. These characteristics are found in a mode-locked laser such as the QD device described in the section on coherent communications, above. Because the laser is mode-locked, there is a well-defined phase relationship between the different lasing lines, which means the beating of any two individual lines produces a pure tone with a linewidth of the order of only 5 kHz. By choosing an appropriate pair of lines a mmW beat signal can be generated from tens of GHz to THz.

This scheme can be used to generate the optical source for a mmWoF network[7] where one or both of the laser lines are modulated to carry the data. We have demonstrated a 16 Gb/s radio-over-fibre–based optical heterodyne RF wireless signal delivery at 25 GHz with a total of 25 km of fibre link and a 2 metre wireless link.[7,8]

2. QD dual wavelength distributed feedback laser

A common approach to generating the mmW beat signal is to use 2 separate lasers operating at 2 different wavelengths. The disadvantage of this scheme is that, without complex control systems, the two lasers can drift relative to each other, introducing noise in the mmW signal generated. To address this issue, we generate both wavelengths in a single laser cavity, which minimizes relative drift between the two lasing lines and is made possible through the use of the QD gain medium. This results in high optical power per mode and high spectral purity with low relative intensity and low-phase noise. Importantly, this makes the device comparatively simple and compact. As a result, the QD dual-wavelength laser has the advantage of reducing system complexity and cost, showing the potential to offer a simple and low-cost solution for 5G optical heterodyne mmWoF systems.

The dual-wavelength laser is an InP-based p-n blocked buried-heterostructure distributed feedback (BH DFB) structure using QD gain material. A novel synthesized aperiodic diffraction grating layer was designed to provide the distributed feedback such that two longitudinal modes would lase simultaneously. Particular attention was paid to obtaining almost identical threshold gain for both desired modes. Examples of lasing spectra are shown in figure 3, which demonstrates two different wavelength separations, 47 GHz and 230 GHz.

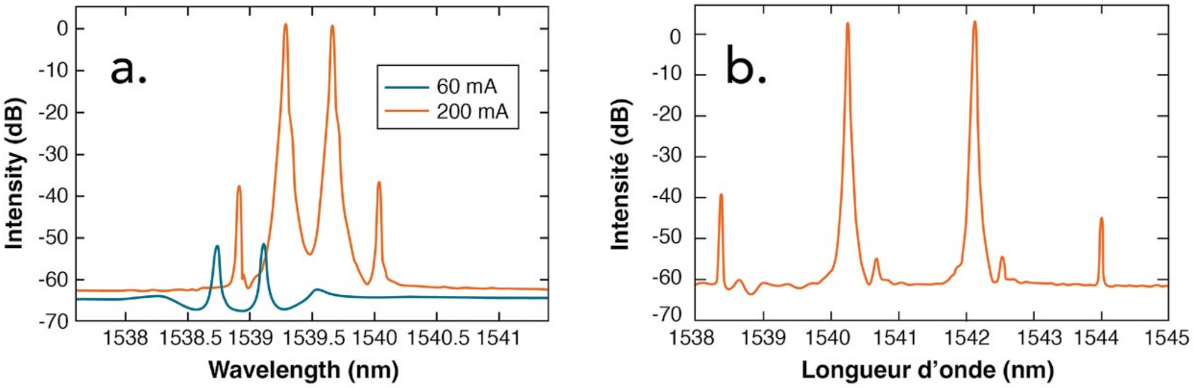

Figure 3 (a) Dual wavelength DFB lasing spectra with 47 GHz mode spacing and (b) 230 GHz mode spacing.

Using the dual wavelength QD laser with a 47 GHz mode spacing, we demonstrated real-time broadband multi-Gb/s mmW signal generation and wireless transmission at the frequency band of 47 GHz based on analog radio-over-fibre (AroF) fronthaul. One laser mode was encoded using 6-Gbaud multi-level quadrature amplitude modulation (M-QAM) (16-/32-/64-QAM) baseband data signals; the other lasing mode was used as an optical local oscillator for optical-heterodyne remote up-conversion to a mmW carrier of 47.2 GHz. Consequently, optical baseband modulated data signals with data capacity up to 36 Gb/s (6-Gbaud × 64-QAM) were transmitted through back-to-back (B2B) and 50 km of standard single-mode fibre (SSMF) before the mmW carrier was optically synthesized remotely for free space wireless data transmission and detection over a 9 metre air gap.[9]

Other potential applications and advantages of QD gain materials

There are many other potential applications where QD gain material could have advantages over conventional QW material.

- Frequency combs have been utilized for spectroscopic sensing and metrology
- The large inhomogeneously broadened gain bandwidth available with QDs makes them ideal for amplifier applications
- Predictions of lower back reflection sensitivity could reduce requirements for optical isolators
- The discrete nature of the QDs means that they exhibit improved radiation hardness, a possible advantage for use in space applications.

Examples of typical specifications for QD lasers

Specification	Unit	Coherent comb laser	Dual WL DFB laser[7]
Threshold current	mA	40	70
Power at 300 mA	mW	32	21
Mode spacing	GHz	25 (range 10-100)	47.2 (+/-1)
6 dB bandwidth	nm	12	
Single-mode RIN	dB/Hz	–132	–158
Single-mode optical linewidth	MHz	0.6 to 1.5	0.015
Operating temperature range	°C	15 to 85	15 to 85

Prototyping and manufacturing

The NRC's Canadian Photonics Fabrication Centre (CPFC) is a state-of-the-art III-V, InP pureplay foundry located in Ottawa, Canada. The CPFC offers a range of fabrication services, from prototyping, through to full-scale volume manufacturing. The CPFC's facility is equipped with the latest tools and equipment for processing photonic devices and photonic integrated circuits. The CPFC offers a range of services:

- **Foundry services**:
  - Epitaxial growth (molecular organometallic chemical vapor deposition, MOCVD)
  - Molecular beam epitaxy (MBE)
  - Chemical beam epitaxy (CBE)
  - Plasma-enhanced chemical vapour deposition (PECVD)
  - Projection and electron-beam lithography, metallization, plasma etching and back-end processing
- **Design and modelling**: For devices and circuits to improve yield and performance
- **Test and characterization**: Testing for optical and electronic devices, surface and materials analysis

The NRC's patent and process IP portfolio of QD technologies demonstrates the NRC's ability to innovate and enable best-in-class and disruptive technologies. The CPFC has been fabricating QD-based lasers at 1550 nm commercially for over a decade.

For those interested in developing quantum dot lasers and other advanced optoelectronic devices, the CPFC allows clients to retain their design IP while leveraging a process-related IP toolbox capable of supporting high-reliability, high-yielding process blocks needed for leading-edge designs—including buried heterostructures (BHET) lasers and multi-regrowth DFB lasers, electro-absorption modulated lasers (EML), avalanche photodetectors (APD) and focal plane arrays (FPA) photodetectors, semiconductor optical amplifiers (SOA) and gain chips, and the interconnects and waveguides to build photonic integrated circuits. The CPFC has a team of commercially facing experts that work closely with customers throughout the device fabrication process to develop customized solutions that meet their specific needs and requirements.

Opportunity details

Licence available

Granted patents

- Zhenguo Lu, Jiaren Liu, Sylvain Raymond, Philip Poole, Pedro Barrios and Daniel Poitras. Quantum dot based semiconductor waveguide devices. US patent number. 7769062-B2 (August 3, 2010).
- Jiaren Liu, Zhenguo Lu, Sylvain Raymond, Philip Poole, Pedro Barrios and Daniel Poitras. Multi-band multiwavelength quantum dot mode-locked lasers. US patent number 7991023-B2 (August 2, 2011).
- Zhenguo Lu, Jiaren Liu, Philip Poole, Chunying Song and Shoude Chang. Stable linewidth narrowing of a coherent comb laser. US patent numbers 10707647-B2 and 10707648-B28 (July 7, 2020).

Other US patent applications

- Mohamed Rahim, Greg Pakulski, Philip Poole and Zhenguo Lu. Synthesized aperiodic gratings and method of manufacture. US patent publication number 20220221715 (submitted on April 30, 2020).
- Khan Zeb, Zhenguo Lu, Jiaren Liu and Xiupu Zhang. Methods and apparatus for high capacity spectrally efficient MIMO and optical beamforming enabled photonic millimeter-wave over fiber (mmWoF) transceiver systems based on quantum dot multi-wavelength lasers with wavelength division multiplexing and space division multiplexing. US patent application (submitted on July 20, 2022).
- Youxin Mao, Zhenguo Lu, Jiaren Liu, Khan Zeb, Guocheng Liu and Philip Poole. Multi-input and multi-output photonics analog-to-digital microwave down-conversion and digital-to-analog up-conversion methods and systems. US patent application (submitted on February 23, 2023).

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