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Quantum dot photonic devices for lightwave communication

Dieter Bimberg*, Matthias Kuntz, Matthias Laemmlin

Institut für Festkörperphysik and Center for NanoPhotonics, Technische Universität Berlin, Sekretariat PN 5-2, Hardenbergstr. 36, 10623 Berlin, Germany

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Abstract

For InAs–GaAs based Quantum Dot Lasers emitting at 1300 nm digital modulation showing an open eye pattern up to 12 Gb/s at room temperature is demonstrated, at 10 Gb/s the bit error rate is below 10^{-12} at -2 dBm receiver power. Cut-off frequencies up to 20 GHz are realised for lasers emitting at 1.1 μm. Passively mode-locked QD lasers generate optical pulses with repetition frequencies between 5 and 50 GHz, with a minimum Fourier limited pulse length of 3 ps. The uncorrelated jitter is below 1 ps. We use here deeply etched narrow ridge waveguide structures which show excellent performance similar to shallow mesa structures, but a circular far field at a ridge width of 1 μm, improving coupling efficiency into fibers. No beam filamentation of the fundamental mode, low α-factors and strongly reduced sensitivity to optical feedback is observed. QD lasers are thus superior to QW lasers for any system or network.

Quantum dot semiconductor optical amplifiers (QD SOAs) demonstrate gain recovery times of 120–140 fs, 4–7 times faster than bulk/QW SOAs, and a net gain larger than 0.4 dB/(mm×QD layer) providing us with novel types of booster amplifiers and Mach–Zehnder interferometers.

These breakthroughs became possible due to systematic development of self-organized growth technologies.

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Quantum dots (QDs) have appealed to physicists, chemists, and material engineers since many years to study carrier confinement effects [1,2]. If the motion of charge in a solid state is confined along some direction to a distance comparable to its de-Broglie wavelength, the energy spectrum along this direction becomes discrete [3]. If the motion of charge is confined in all three dimensions like in QDs, the energy spectrum becomes completely discrete and the density of states changes to a delta-function like form broadened to a Lorentzian by a temperature-dependent phase relaxation time [4].

Dingle and Henry realized in 1976, that the application of size quantization effects would be very beneficial for semiconductor laser applications and would improve laser performance [4]. For QD-lasers the anticipated advantages were largely extended tunability of the emission wavelength by the QD size and composition on a given substrate, decreased transparency current densities, increased material and differential gain, a large characteristic temperature T_0, i.e. independence of the threshold current on temperature and a decreased α-factor, which is responsible for the wavelength chirp under injection current modulation [5,6]. These early models were based on simplified assumptions and many scientists judged them as too unrealistic and doubted whether real QD-lasers could indeed deliver the predicted advantages [7].

Since the potential advantages of QD-lasers had been known since the mid 1980s, the most straightforward way to realise a QD-laser and to test the predictions was to pattern a QW-laser structure by using holographic or electron beam processes, etching and subsequent overgrowth. These technologies result in laterally ordered columnar shaped so called quantum-boxes. However, next to very delicate patterning and etching processes due to the latter, high densities of near surface defects are created in the active zone, which jeopardize laser performance. The best quantum-box laser realised in such a way demonstrated laser operation with a threshold current density of

* Corresponding author. Tel.: +49 30 314 22783; fax: +49 30 314 22569.

E-mail addresses: bimberg@physik.tu-berlin.de (D. Bimberg), kuntz@physik.tu-berlin.de (M. Kuntz), laemmlin@sol.physik.tu-berlin.de (M. Laemmlin).

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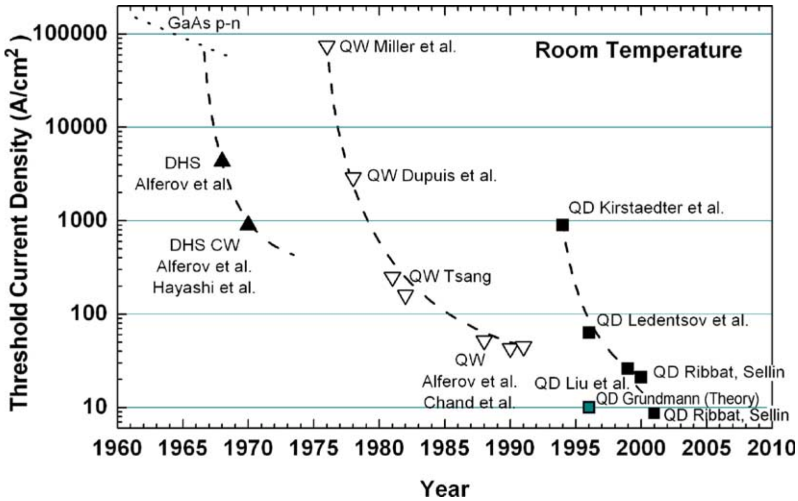

Fig. 1. Threshold current density of diode lasers.

7.5 kA/cm^2 at low temperatures (77 K) in pulsed operation [8]. The early theoretical models [5,6] were based on assumptions like:

- lattice matched heterostructures;
- infinite barriers;
- one confined electron and hole level;
- bimolecular e-h-recombination;
- equilibrium carrier distribution.

In the beginning of the 1990s it was realised, that universal self-organisation on surfaces in lattice mismatched heteroepitaxial growth which can be used to form high densities of homogenous QDs [9,10]. Such QDs form today the basis of novel generations of optoelectronic devices like edge and surface emitting lasers, amplifiers…, in particular for lightwave communication and have a large potential for future quantum communication systems. First such QD lasers based on self-organised growth were created by us in 1993 [11]. None of the early theoretical assumptions applies to these QDs. New, realistic models of quantum dot lasers [1,12,13] close to reality are based on:

- strained heterostructures;
- finite barriers;
- many electron and hole levels;
- monomolecular (excitonic) recombination;
- non-equilibrium carrier distribution.

Our predictions like a decreased α-factor and wavelength chirp [14], have been demonstrated now on actual devices. In particular the use of GaAs-based QDs in diode lasers and amplifiers at data- and telecom-wavelengths has been demonstrated today to yield a large number of decisive advantages for lightwave communication systems, both from point of view of performance and of cost. Amongst them are:

- Lasing wavelengths in the 1.3 μm spectral range, both for edge and surface emitters using GaAs substrates being commercially available at 6 in. diameter. An emission wavelength of 1.5 μm of the edge emitting lasers with reasonable threshold current density of the order of 1 kA/cm^2 [15].
- Transparency current density of 40 A/cm^2, 5 W output power for 100 μm stripe, 300 mW for 7 μm stripe edge emitters and large T_0-values of 260 K up to 70 °C at 1.3 μm [15].
- Very low transparency current density (<6 A/cm^2 per QD sheet, see Fig. 1) and internal losses (~ 1.5 cm^{-1}), high internal quantum efficiency of 98% for a triple sheet QD-laser at 1.15 μm. 12 W output power, equivalent to a power density of 18.2 MW/cm^2, for a 6-fold MOCVD grown stack (see Fig. 2). In lifetime tests at 1.0, 1.5 W and 50 °C heat sink temperature no aging of these lasers within 3000 h could be observed [16,17].

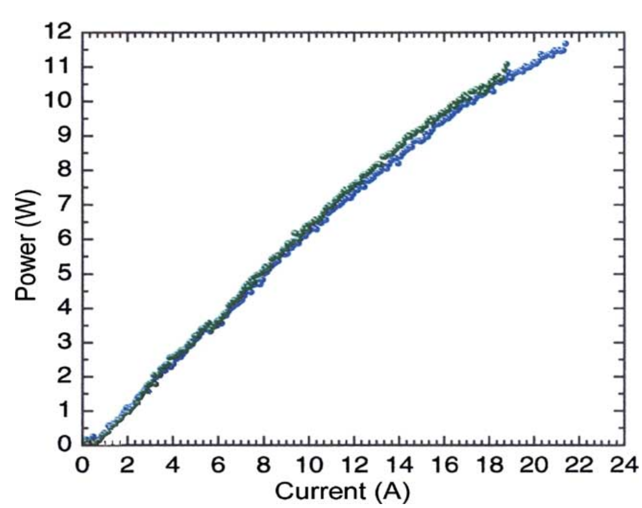

Fig. 2. Maximum output power of 12 W from a QD laser diode (limited by COD) measured quasi-cw, duty cycle 1:4.