## **Quantum Dot Lasers. Commercial Challenges and Opportunities**

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## 1. Introduction

In recent years great attention has been attracted to Quantum Dot (QD) lasers and the prospects for their commercialization because idealized QD devices were theoretically predicted to outperform their quantum well counterparts. In particular, reduced threshold current and temperature independent characteristics were expected. However complex energy band diagram, inhomogeneous broadening as well as other numerous factors significantly affected characteristics of actual QD lasers and the realization of the advantages has required years of technology development, heterostructure engineering, and device optimization. The major breakthrough took place when industrial molecular beam epitaxy (MBE) machines were used to grow quantum dots. Remarkably, in addition to the improvement of basic device performance QD lasers show fundamentally new unique properties such as low relative intensity noise of individual modes. In this paper we report on QD lasers developed by Innolume including the products and also discuss future applications of our novel comb laser for short-reach optical interconnects.

# 2. InAs/GaAs QD Lasers for Telecom, Medical and Industrial Applications.

High performance QD diode lasers developed by Innolume cover a unique wavelength range of 1064 -1320nm. The lasers show high output power of 16 W for a broad area 200 µm wide devices and >700 mW for single mode lasers at room temperature in continuous wave (CW) mode. Temperature independent performance is demonstrated from -20° to 90°C in devices with p-type modulation doped active region. Experimentally derived 40°C lifetime is more than 10°h. Thus, QDs enable highpower, high-brightness lasers for new medical and industrial applications, from selective fat heating (1210 nm) to inexpensive, long-lived 1064 nm diodes replacing old Nd:YAG solid state lasers.

Due to low threshold current density, low temperature sensitivity and low sensitivity to optical feedback directly modulated uncooled QD DFB lasers operating at 10 Gbit/s [1] are very promising for cost-effective telecom applications in the entire 1.3  $\mu$ m band as required for short and medium distance metropolitan networks.

### 3. Comb Laser for Optical Interconnects.

In addition to the improvement of basic device performance QD lasers show fundamentally new unique properties: individual modes of a Fabry-Perot QD laser exhibits very low noise. Ten longitudinal modes of a QD laser emitting near 1265 nm were sifted out using a tunable filter and each of them was independently tested. Relatively intensity noise of a mode was 0.22% in the 0.001-10GHz frequency range. Each mode after spectral filtering was modulated at 10Gb/s by a  $2^{31}$ -1 pseudorandom binary non-return-to-zero sequence using external modulator. A bit error rate less than  $10^{-13}$  was measured for an individual mode [2]. Thus, individual modes of Fabry-Perot QD lasers can be used as independent optical channels for Dense Wavelength Division Multiplexing (DWDM). More recently we have demonstrated a comb-laser with more than fifty error-free channels (Fig.1) each having relative intensity noise less then 0.1% [3]. Output power was approximately 1 mW per channel.



Fig. 1 Comb spectrum of an InAs/GaAs QD laser. Squares show RIN for each mode.

Comb laser amplification can be done using an integrated laser plus amplifier or a discrete Semiconductor Optical Amplifier (SOA). One use is to increase the power per channel in denser combs. Other uses include compensation for comb de-multiplexing loss, as well as insertion and coupling losses in the system, and, of course, to extend transmitter reach. The active medium for the SOA used here is a 15 layer, MBE-grown, InAs/GaAs QD waveguide structure. Remarkably, the comb's spectral shape is maintained after amplification. To quantify spectrum amplification, output was measured at different comb intensities. Figure 2 is the measured gain versus output power of the SOA at different pump levels (200mA; 300mA; 400mA), assuming a best estimate of 20% optical coupling efficiency. As high as 27dB unsaturated gain has

been demonstrated and 3dB saturation output power is around 30mW at 400mA pump current. The ASE level at 400mA pump current is 8.4 mW without injection.

The RIN spectrum of each channel before and after the SOA was measured by coupling SOA output into an RF analyzer through a tunable Fabry-Perot filter.



Fig. 2 The SOA amplification factor as a function of the comb laser's total output power.

At low injection levels, ASE creates additional noise that can generate transmission errors. Therefore, ASE influence was examined and a result shown in Fig. 3. RIN of the one mode was measured over a range of SOA output power, regulated by input power at the same 400 mA SOA pumping current. Total RIN of the mode was obtained by integrating the spectrum from 1 MHz to 10 GHz. As expected, RIN decreased with increasing output power because the relative part of the ASE is reduced. The spectra converge when output power is greater than 60 mW, which corresponds to 1 mW input power (18 dB gain). Total RIN in the range 0.03-0.04% is the same as before amplification which is well acceptable for 10 Gb/s error-free transmission.



Fig. 3. 1262.5 nm channel RIN noise spectrum at different ASE levels. SOA output power and total (integrated) RIN for each are in the legend.

Today's WDM optical network based on DFB arrays on InP, or perhaps bonded to silicon in the future, have several drawbacks. It requires a large number of wavelength specific light sources and thus the inventory and field installation can become very complex, and unmanageable in large-scale deployment for access. A better alternative, particularly for what will eventually become commodity signaling systems, is a single diode QD comb laser that can provide multiple channels each corresponding to a longitudinal mode from the laser cavity (Fig.4). This approach reduces requirements for the precision of lasing wavelengths because a channel separation is naturally predetermined by only one parameter which is a resonator length. In this case, all channels can be stabilized and tracked simultaneously.



Fig. 4. Future high-bandwidth WDM transmitter based on QD comb laser.

#### 4. Conclusions

Present 1064 - 1320nm InAs/GaAs edge-emitting QD lasers show excellent performance and are expected to eventually replace conventional InP-based QW lasers for majority of applications. The novel comb lasers enable economical WDM, which is extremely promising for short-reach optical interconnects between and within computers. The comb lasers will target deployment in systems delivering data rates of at least 1 Tbit/s, because this will be the likely tipping point for transition from electrical to optical interconnects.

#### References

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