Simulation and analysis of $1.55\mu m$ quantum dot lasers designed for ultra-narrow spectral linewidth

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***Abstract*—Quantum dots (QDs) are well known as active materials with remarkable properties such as high differential gain, very low linewidth enhancement factor and low threshold current density. Using a comprehensive in-house developed laser simulator based on the traveling wave method, we investigate the limitations in terms of spectral purity of quantum dot based distributed feedback lasers (DFB) for use in high bit rate optical communications. Even though quantum dot based edge emitting lasers have demonstrated linewidths below the standard quantum well and bulk lasers, by optimization of the resonant cavity we further reduce the linewidth to below 20KHz while studying the resulting operating conditions.**

I. Introduction

With the evolution of optical communication systems the reduction of spectral linewidth has become one of the major concerns in high bit rate and long haul optical connections. To accommodate the ever increasing demand for higher bit rates, as a cost-effective solution the higher-order optical modulations can be used on the existing infrastructure, which inevitably requires higher standards for the spectral purity of the signal emitters [1]. With the introduction of quantum wells and quantum dots as active materials in semiconductor lasers, significant improvements have been made in terms of spectral purity of emitted light by reduction of the threshold current density and the linewidth enhancement factor (LEF) [2].

In this paper we investigate the limits of spectral purity of the quantum dot based semiconductor lasers by applying a novel design of the resonant cavity [3], experimentally tested with quantum well lasers. We start by briefly describing the employed numerical time-domain laser model based on the traveling wave method [4], which we apply on standard quantum dot edge emitting DFB laser design and an optimized resonant cavity design resulting in the reduction of spectral linewidth by one order of magnitude. Using a comprehensive spatially-resolved laser model allows for insight into operating conditions of the resulting design as we conclude with the discussion of factors that make the superior performance of the optimized design possible.

II. The Quantum Dot Laser Model

The dynamic laser model employed here consists of three distinct modules: the quantum dot gain model, the multi-section traveling wave simulator and the spatially resolved small-signal postprocessing module. The gain model is used to solve the quantum dot heterojunction problem and extract the dispersions of carrier dependent gain and refractive index, the traveling wave simulator to evolve the laser problem in

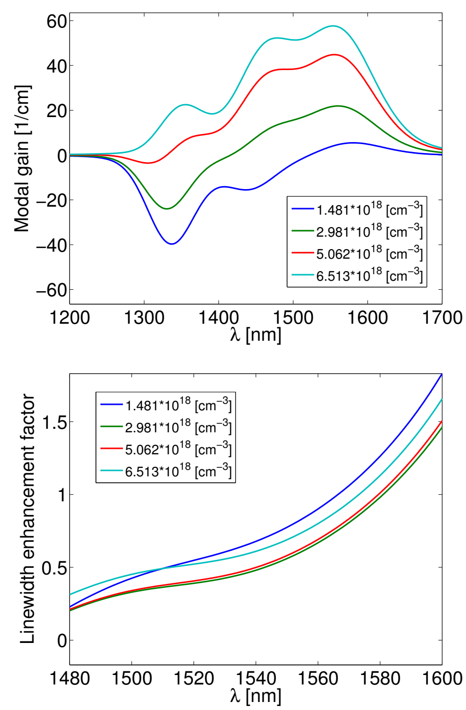

Fig. 1. Calculated dispersion of modal gain and linewidth enhancement factor of a $1.55\mu m$ multiple QD-layer epi-structure

time and postprocessing module, developed after the work of B. Tromborg et al. [5], to extract the spectral linewidth.

The gain model assumes a simplified quantum disk geometry for the quantum dots [6]. This allows us to solve the quantum confinement problem semi-analytically for the eigenenergies of the conduction and valence band. The quasi Fermi levels are calculated for a given set of injection currents and finally the gain and refractive index dispersion extracted on a finite wavelength span.

Despite the adopted approximations, after calibrating the gain model with experimental results [7], the dispersion calculation produces realistic gain and linewidth enhancement factor curves, see Fig. 1. The linewidth enhancement factor without the contribution of wetting layer, is estimated to ~ 0.6 at the ground state, which is in accordance with experimental values below threshold [8]. Moreover, to complement the gain model in high injection regime we include the plasma effects of the wetting layer via a simple rate equation model [9].

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Following the the solution of the heterojunction problem, the gain model is fitted into the traveling wave laser model, via a set of parallel infinite impulse response filters. The traveling wave simulation is used to sweep the injection current which produces axial profiles of carrier density, photon density, modal gain etc., which are ultimately used to extract the spectral linewidth using the small-signal analysis [5].

III. Results and Discussion

A. Standard QD-DFB laser design

As a reference design, we simulate first a standard edge emitting DFB laser with uniform coupling coefficient of $\kappa = 20cm^{-1}$, and $\lambda/4$ phase shift at left facet to ensure single mode operation. For the active medium we use multiple QD-layer epi-structure as in Fig. 1, while internal losses are set to $\alpha = 11cm^{-1}$, as estimated experimentally [7].

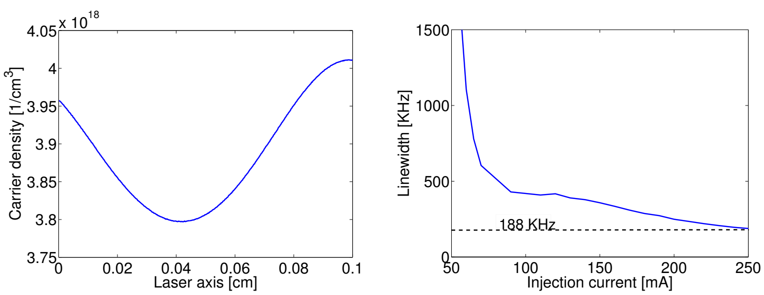

Fig. 2. Carrier density profile and spectral linewidth of the standard DFB laser with cleaved facets and $\lambda/4$ phase shift at left facet

As expected, the high performance active material yields very low linewidth with a minimum of $188KHz$ at injection current of $250mA$, Fig. 2, while the high number of active layers minimizes the plasma effects of the wetting layer and maintains the low linewidth enhancement factor [8].

B. Optimized Resonant Cavity

Following the basic guidelines of the experimentally tested design [3], we devise a new high-coherence resonant cavity consisting of three sections, two passive distributed Bragg reflector (DBR) mirrors on the outer side and a short strongly coupled DFB section in the middle, with varying coupling coefficient $\kappa = 35cm^{-1}, 110cm^{-1}, 35cm^{-1}$, respectively. The linewidth calculation for this design yields a value of below $20KHz$ at $250mA$, Fig. 3. This has been demonstrated experimentally recently in [3].

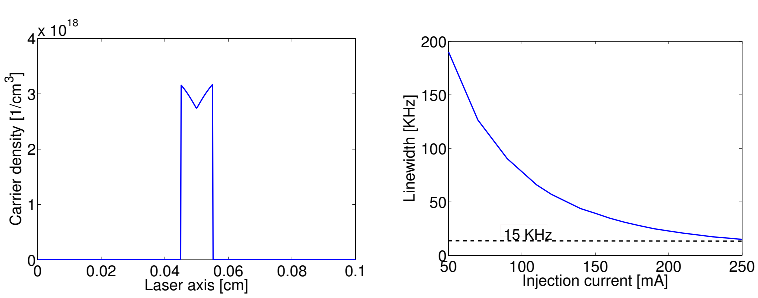

Fig. 3. Carrier density profile and spectral linewidth of the optimized laser with anti-reflection facets and $\lambda/4$ phase shift at the center of resonant cavity

To reduce the threshold carrier density and the spontaneous emission noise we reduce the internal losses to $\alpha = 2cm^{-1}$, for the active central section while keeping the gain model the same. This can be achieved by improved transversal mode engineering.

IV. Conclusion

The spectral linewidth is reduced by factor of 13 compared to standard DFB design, which following from Schawlow-Townes linewidth equation, Eq. 1, can be explained as follows:

$$\Delta\nu = \frac{\Gamma R'_{sp}}{4\pi N_p}(1 + {\alpha_H}^2) \quad (1)$$

The optimization of three major factors contributing to spectral linewidth, linewidth enhancement factor, α_H, spontaneous emission coupled into the laser mode, R'_{sp}, and photon density, N_p, does result in very narrow linewidth. Spontaneous emission coupled into the laser mode is reduced by the passive DBR sections. The photon density in the cavity is maximized by using a short cavity with high quality factor. The linewidth enhancement factor is reduced by the high quality factor cavity and low internal optical losses. The output power of the optimized design was found to be moderate which can be still alleviated by optical amplifiers, making such design applicable to long haul optical networks.

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