Modeling of Edge-Emitters and VCSELs and Comparison with Experiments

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Optical gain spectrum plays an important role on the operation characteristics of semiconductor lasers. In this talk, we will first present our theoretical model for strained InGaAsP and InAlGaAs quantum-well (QW) lasers [1]. Our theoretical model takes into account valence band-mixing and many-body effects. We compare our theoretical results with our experimental data using the Hakki-Paoli method by measuring the amplified spontaneous emission from edge-emitting semiconductor lasers. Shown in Fig. 1 are the measured net modal gain spectra (dashed curves) of a compressively strained InGaAsP QW laser for several injection currents up to the threshold. We also plot the theoretical optical gain spectra (solid curves) using a many-body gain model, which shows very good agreement with experiment. This comparison of theoretical and experimental gain spectra allows us to extract the carrier density, therefore, the differential gain parameter. We then perform high-speed modulation of these quantum-well lasers and extract the differential gain from the modulation bandwidth [2]. The squared relaxation frequency f_r^2 from the measured modulation response function is then plotted as a function of the photon density in Fig. 2 for three lasers (a –0.9% compressive strained InGaAsP QW laser, a -0.78% compressively strained InGaAlAs QW laser, and a lattice-matched InGaAlAs QW laser). The slopes of these curves are proportional to the differential gain and the reciprocal of the photon life time. The differential gain plays a central role in determining the fundamental frequency response of semiconductor lasers. The laser with a larger slope will reach a higher relaxation frequency faster for a given photon intensity which will give a higher intrinsic 3-dB modulation bandwidth. We show that the differential gain obtained from the dynamic response is very close to that measured from the static gain measured value near threshold [3]. Our theoretical model on the optical gain of strained QW lasers is an effective tool for designing high-modulation bandwidth, high-performance QW lasers.

Our gain model for the active quantum-well region is then used in an optical solver based on a numerical mode-matching method for vertical-cavity surface-emitting lasers (VCSELs). Our model provides important parameters such as the lasing wavelength, intensity profiles, and modal losses for VCSEL structures. We consider an ion-implanted index-guided VCSEL structure [4, 5]. We show that our model provides a very good agreement with the modally resolved light output vs. injection current for a multimode VCSEL structure. Combining the optical model with the rate equations, we can take into account the optical modal profiles, spatial hole burning caused by stimulated emission, and the optical gain spectrum. From the threshold analysis for the fundamental and the first higher-order modes, we can design single-mode high-power VCSELs.

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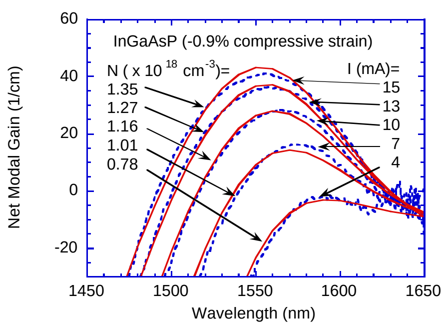

Fig. 1 The theoretical (solid curves) and measured (dashed curves) modal gain spectra for an $In_{1-x}Ga_xAs_yP_{1-y}$ QW laser with a –0.9% compressive strain in the wells.

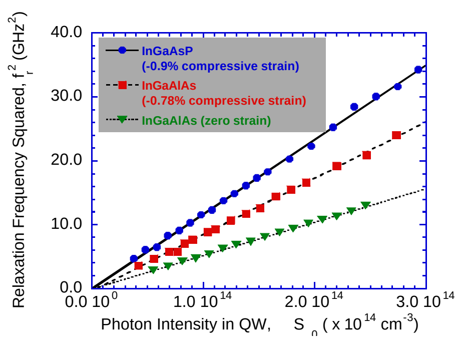

Fig. 2 The squared relaxation frequency vs. the photon intensity at 25°C. The lines are the least-square fit to the data to extract the slope or the differential gain.