2D Simulation of a Buried-Heterostructure Tunable Twin-Guide DFB Laser Diode

†L. Schneider, †A. Witzig, †M. Streiff, †M. Pfeiffer, †A. Bregy, ‡B. Schmidt, and †W. Fichtner
† Integrated Systems Laboratory, Swiss Federal Institute of Technology Zurich(ETHZ)
Gloriastrasse 35, CH-8092 Zürich, Switzerland
E-mail: lutz@iis.ee.ethz.ch
‡ Nortel Networks Optical Components, Binzstrasse 17, CH-8045 Zürich, Switzerland

Abstract— **A 2D simulation of an InGaAsP–InP buried-heterostructure tunable twin-guide (TTG) DFB laser diode is performed. The device structure is optimized with respect to maximal tuning range and output power. To minimize the current leakage around the active region, a p–n–p–n current blocking region is also modeled and its effect on the laser characteristics is discussed. Good agreement between simulation and measurements is obtained.**

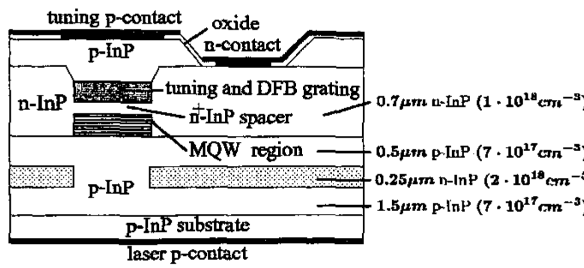

Fig. 1. Schematic cross-section of the buried-hetero–structure ridge TTG laser diode for 1.55μm wavelength emission [4].

I. INTRODUCTION

Tunable semiconductor lasers with single-mode emission wavelength in the 1.55–μm range play an important role in optical communications, measurement and sensing [1]. We present a comprehensive 2D simulation of an InGaAsP–InP buried-heterostructure tunable twin-guide (TTG) DFB laser diode. The TTG DFB laser represents a transversely-integrated structure and allows for continuous tuning ranges in the order of 10 nm. As illustrated in Fig. 1, the active InGaAsP region composed of 7 quantum wells is embedded in higher bandgap InP material. Furthermore, the ridge consists of another intrinsic InGaAsP region incorporating a distributed feedback (DFB) grating which guarantees longitudinal single-mode operation. The active and tuning regions are separated by a highly n-doped InP layer. As a consequence, the laser and tuning contacts can be independently biased. The structure allows for both electronic and thermal tuning depending on whether the tuning contact is operated under forward or reverse bias. Here, we consider only the former since it is generally preferred due to its faster tuning speed and better power efficiency. The electronic tuning mechanism is based on the change in refractive index due to carrier injection into the tuning region [2] which leads to a decrease in laser wavelength. The tuning region is optically coupled to the active region as described by the high confinement factors in both regions.

At increased laser currents and temperatures [3], common TTG laser diodes without blocking regions suffer from current leakage around the active region due to the wide p–n homojunction underneath the n-contact especially. This limitation can be overcome by introducing a p–n–p–n blocking region laterally aligned with the active region as shown in Fig. 1.

In this contribution, we investigate how the tunable twin-guide laser structure can be optimized with respect to maximal tuning range and output power and show that our simulations are in good agreement with measurements. To this end, the thickness of the tuning and spacer layers is varied. An analysis of the alignment between the active region and the current confinement structure reveals that only an exact alignment can boost device performance considerably.

II. SIMULATION MODEL

In our physics-based approach, we solve the fully coupled semiconductor drift-diffusion equations for electrons and holes, the photon rate equation and Helmholtz equation self-consistently [5]. The quantum wells are treated as scattering centers for the charge carriers. The carrier reservoir bound to quantum wells is connected to the continuum carriers via a carrier capture rate and escape rate equation. The optical gain and absorption model in the quantum well active region is based on Fermi's Golden Rule. The subbands in the quantum well are determined by solving the time-harmonic Schrödinger equation and a parabolic band approximation for the electrons, and the light and heavy holes [5].

For a standard Fabry-Perot laser the laser wavelength is determined by the maximum of the gain curve. To model the distributed feedback (DFB) grating incorporated into the tuning region, the laser is assumed to emit at the Bragg wavelength $\lambda_B = 2n_{eff}\Lambda$, where Λ is the period of the grating. The change in wavelength is caused by the effective modal index n_{eff}, which depends on the change in refractive index due to carrier injection and on the optical field distribution. The latter dependency requires that the optical field pattern be updated self-consistently.

III. SIMULATION RESULTS

In the following, we investigate different aspects of device optimization with regards to tuning range and output power efficiency. Furthermore, the tuning dependence of the beam characteristics is discussed and one of the major obstacles for a wider tuning range is highlighted. We demonstrate how state-of-the-art device simulation can lead the way to a better laser design by analyzing both external and internal laser characteristics.

A. Tuning Range versus Output Power

Inherent to the TTG design is that the tuning range and the output power cannot be optimized independently. The tuning range can be extended by increasing the tuning layer thickness. This implies a reduction of the optical confinement factor of the active region, however, and ultimately limits the output power. Simulations of laser diodes with different thickness of tuning and n^+-InP spacer layers ranging from $0.15 - 0.3\mu m$ and $0.1 - 0.16\mu m$, respectively, have been performed. Two representative structures as specified in the parameter table below demonstrate this behavior. The results are shown in Figs. 2 and 3 and closely match measurements given in [6]. Laser diode no. 1 has a wide tuning range but the slope of the light output power is reduced whereas the opposite holds for laser diode no. 2.

B. Buried Current Blocking Region - Power Optimization

Crucial to good device performance is the confinement of the injection current to the active quantum well region. It should be noted that the slope efficiency for laser diode no.1 and no. 2 decreases for injection currents above 60 mA. It has been reported [4], [6], that the TTG laser diode suffers from current leakage through the p-n homojunction underneath the n-contact. As a remedy, a n–p–n current blocking region has been successfully incorporated into the TTG design [4], [6], as illustrated in Figs. 1 and 4. The maximum output power of the buried blocking region (BBR) TTG laser is increased by approximately 150% with almost constant slope efficiency of 0.18 W/A. The effect of current leakage (suppression) is clearly visible in the current flow plots of Fig. 4.

It has been observed that an exact lateral alignment between the active region and the current confinement structure is necessary to realize TTG laser diodes with improved performance [4]. Figure 7 shows the LI-curve for three different distances Δ from the ridge sidewall to the n-blocking region which indicate that tendency. For low current densities the slope efficiency is independent of Δ. At elevated current densities, however, the blocking structure becomes ineffective for $\Delta > 0$.

C. Further Discussion

Since the optical field pattern is updated self-consistently in our simulation methodology, the simulation reveals the response of the fundamental transverse mode pattern to the refractive index change induced by the injection of the electron and hole plasma into the tuning region. It can be seen from Fig. 5 that during tuning the transverse near field distribution is displaced from the tuning layer towards the active layer. Figure 6 shows the lateral and transverse far field pattern whose FWHM values between 38° and 40° are larger than for standard BH-lasers but are in very good agreement with measurements [6], [7].

A major limitation to the maximum tuning range is the heat generation in the tuning region which results in an increase of the laser wavelength and counteracts the intended negative wavelength shift caused by carrier injection. For improving the tuning efficiency it is necessary to obtain a maximum change of the charge carrier density with minimum tuning current. However, the nonlinear recombination law, especially Auger recombination, makes this difficult. In

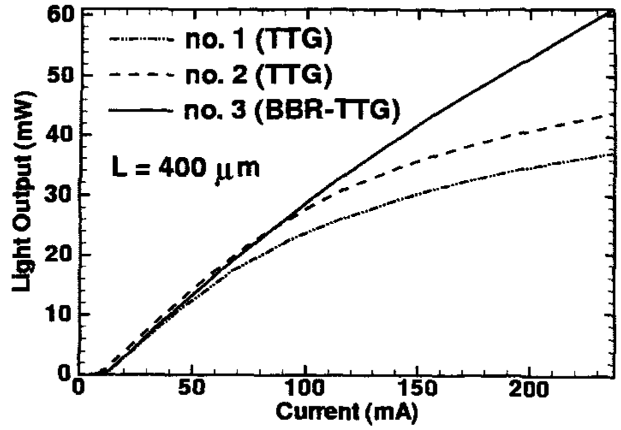

Fig. 2. Light output versus laser current characteristics of three different BH-TTG laser diodes for $1.55\mu m$ emission wavelength.

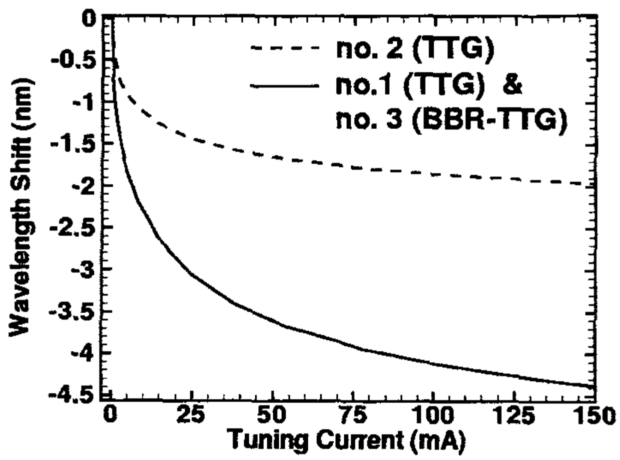

Fig. 3. Electronic tuning characteristics under forward bias of TTG laser no.1,2 and BBR-TTG laser no.3 .

Fig. 8, Auger recombination is shown along a vertical cut through the ridge for very low and high tuning currents. It is evident that the tuning region experiences a dramatic increase in Auger recombination. To overcome this limitation, a type II superlattice to separate electrons and holes spatially from each other has been proposed [8].

Laser Simulation Parameters

Laser Diode	no. 1	no. 2	no. 3
Tuning Region Thickness$[\mu m]$	0.3	0.15	0.3
n^+-InP Spacer Thickness$[\mu m]$	0.1	0.16	0.1
BBR Technology	no	no	yes
Tuning Range (Forward Bias) $[nm]$	4.5	1.5	4.5

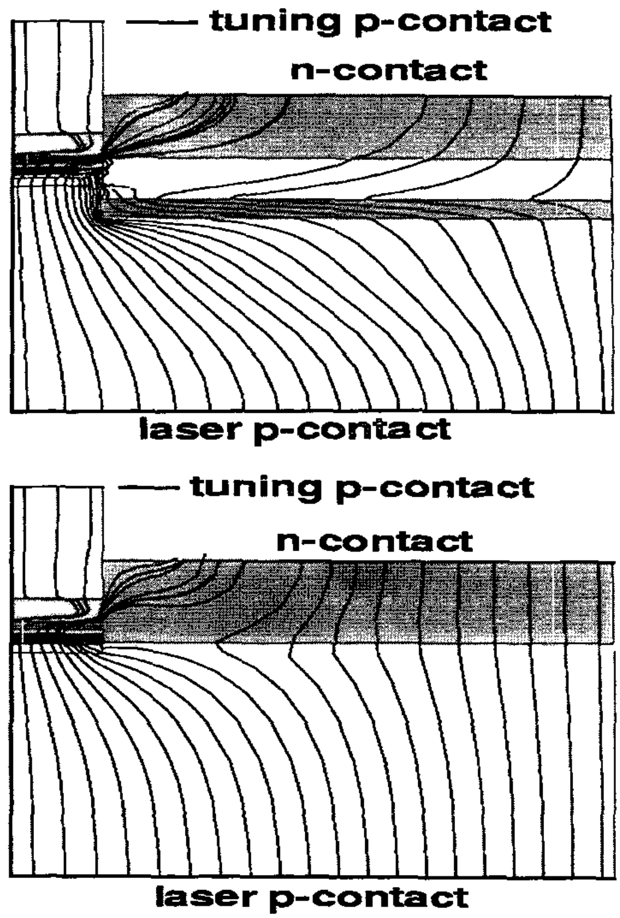

Fig. 4. Comparison of the current density vector flow between TTG laser diode no.1 (bottom) and BBR-TTG laser diode no.3 (top) at bias condition $I_{Laser} = 150mA$. The streamtraces of the current density vector field illustrate the effect of the current blocking region. For the BBR-TTG structure (top) the current flow is mainly directed into the active region while it is split into two equally weighted branches for the TTG laser diode no.1 (bottom). Note, the plot of the BBR-TTG laser on the top shows the resulting current crowding around the blocking region.

IV. CONCLUSION

In conclusion, a 2D simulation of a buried-heterostructure continuously tunable TTG DFB laser diode has been performed in order to optimize the device structure with respect to tuning range and light output power. The importance of the exact lateral alignment of the current blocking region and the limitation to the tuning efficiency due to Auger recombination has been demonstrated. Overall, several different representative structures have been discussed and the results closely reproduce experimental characteristics.

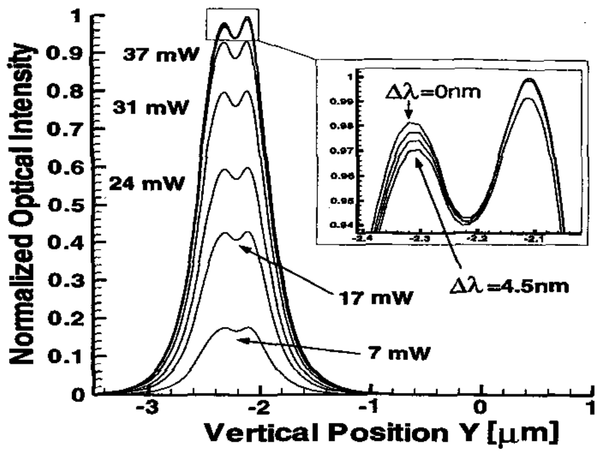

Fig. 5. Transverse optical near field distribution for BBR-TTG laser diode no.3 at different laser and tuning biasing conditions. The inset shows the displacement of the field distribution from the tuning towards the active layer during tuning.

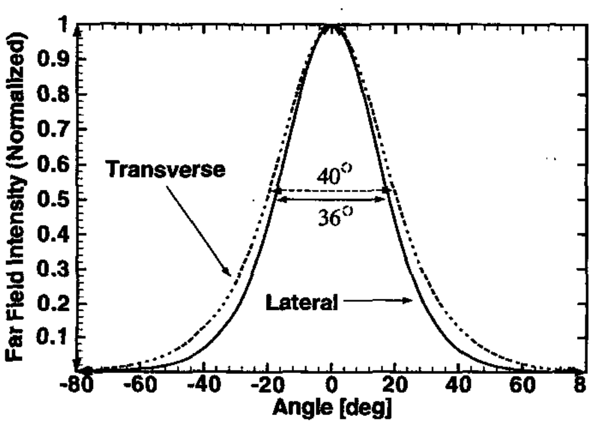

Fig. 6. Transverse optical far field distribution for BBR-TTG laser diode no.3 at maximum light output power.

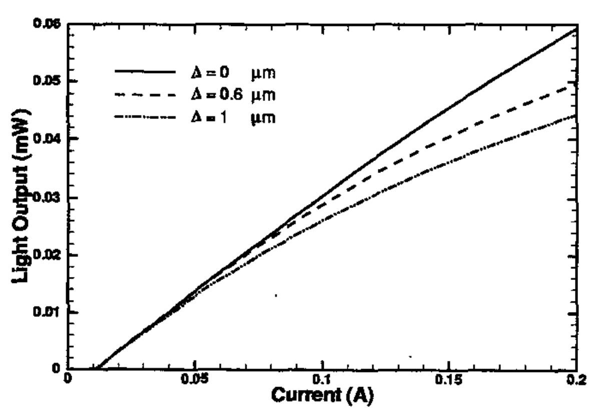

Fig. 7. Dependence of the light output power on the displacement Δ of the n-blocking region from the ridge sidewall.

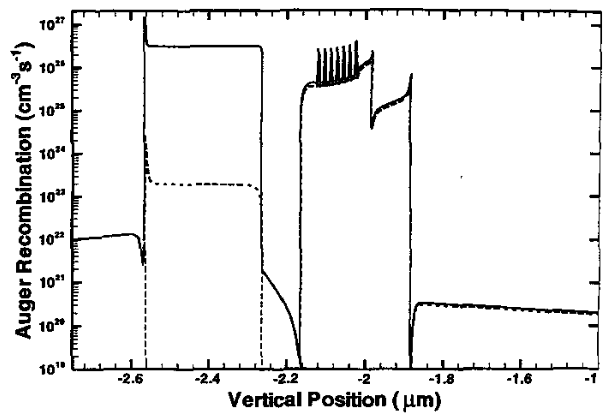

Fig. 8. Auger recombination along a vertical cut through the ridge for tuning currents $I_t = 1mA$ (dotted curve) and $I_t = 100mA$ (solid curve). The graph shows a zoom into the tuning (left) and active (right) regions.

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