Simulations and analysis of beam shaping in spatially modulated broad area edge-emitting devices

(Invited Paper)

Mindaugas Radziunas
Weierstrass Institute, Mohrenstrasse 39, 10117 Berlin, Germany. Email: Mindaugas.Radziunas@wias-berlin.de

***Abstract*—We apply a (1+2)-dimensional traveling wave model for simulations of broad-area semiconductor lasers and amplifiers. We discuss, how a periodic modulation of electrical contact in both spatial directions implies an angular filtering of the radiation.**

Edge emitting broad area semiconductor (BAS) lasers and amplifiers are robust, compact and highly efficient devices for generation of high power beams. However, the spatial and temporal quality of the emitted beams is usually rather low. Several approaches for the improvement of the spatial quality of the radiated optical beam have been proposed and implemented [1], [2], each, however, with its disadvantages.

Recently the shaping of the beam radiation by a 2-dimensional modulation of the semiconductor material was suggested [3], [4]. In the present work it is shown, how the (longitudinal and lateral) periodic structuring of the electrical contact with properly selected spatial periods (see Fig. 1) causes a significant spatial (angular) filtering of the beam.

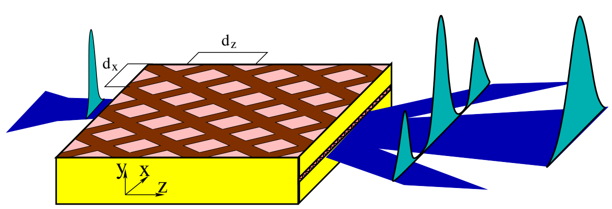

Fig. 1. Schematic representation of the periodically modulated optically injected broad area semiconductor amplifier.

Simulations and analysis of the diffractive propagation of the optical beam along the longitudinal axis of the BAS device were done using a full hierarchy of models. Once considering the dynamics of BAS *lasers*, the (2+1)-dimensional traveling wave (TW) model is applied [5]. It governs the spatio-temporal evolution of the complex slowly varying amplitudes of the counter-propagating optical fields and carrier density. The required computations in this case are performed by means of parallel solvers on parallel compute cluster at the Weierstrass Institute in Berlin.

For simulations of the field propagation and amplification in BAS *amplifiers*, the TW model can be simplified. First, one can assume an optical injection $\mu(x,t)$ through the front facet of the amplifier, neglect the facet reflectivities, and ignore the back-propagating field. The unidirectional propagation and amplification of the optical field $E(z,x,t)$ is defined by

$$\begin{aligned} &\frac{n_g}{c_0}\partial_t E = \left[-\partial_z - \frac{i}{2k_0 n_b}\partial_x^2 + \frac{g-\alpha-\mathcal{D}}{2} + i\tilde{n}\right]E, \\ &g = \frac{g'\ln(N/N_{\rm tr})}{1+\varepsilon|E|^2}, \quad \tilde{n} = k_0\sqrt{\sigma N}, \end{aligned} \tag{1}$$

where linear operator $\mathcal{D}$ gives a Lorentzian approximation of the material gain dispersion [6]. The field equations (1) are nonlinearly coupled to the diffusive rate equation for carrier density $N(z,x,t)$,

$$\partial_t N = D\partial_x^2 N + \frac{\bar{J}\zeta(z,x)}{qd} - R(N) - \frac{c_0}{n_g}\Re[E^*(g-\mathcal{D})E], \tag{2}$$

where $R(N)$ is carrier recombination, and $\zeta(z,x)$ represents laterally d_x- and longitudinally d_z-periodic electrical contact.

Once considering the stationary problem (injected beam is independent on time) and assuming that the optical field remains small along the amplifier, $|E| \ll 1$, one can get a further simplification of the TW model,

$$\partial_z E = \left[\frac{-i}{2k_0 n_b}\partial_{xx} + (1+i\alpha_H)a_m \sin(q_z z)\sin(q_x x)\right]E, \tag{3}$$

where $q_x = 2\pi/d_x$, $q_z = 2\pi/d_z$, whereas α_H and a_m are the linewidth enhancement factor and the harmonic modulation amplitude, both depending on the parameters of the TW model (1,2). By expanding the optical field into a few Bloch modes,

$$E(x,z) = e^{-ik_x x}\left(a_0 + a_{+1}e^{-iq_x x + iq_z z} + a_{-1}e^{iq_x x + iq_z z}\right),$$

one can reduce Eq. (3) to a system of ODEs,

$$\frac{d}{dz}\vec{a} = \frac{iq_x^2}{2k_0 n_b}\begin{pmatrix} \left(\frac{k_x}{q_x}\right)^2 & c & -c \\ c & \left(\frac{k_x}{q_x}+1\right)^2 - \mathcal{Q} & 0 \\ -c & 0 & \left(\frac{k_x}{q_x}-1\right)^2 - \mathcal{Q} \end{pmatrix}\vec{a}, \tag{4}$$

where $\vec{a} = (a_0, a_{+1}, a_{-1})^T$, $c = \frac{k_0 n_b(\alpha_H - i)a_m}{2q_x^2}$, and

$$\mathcal{Q} = \frac{2d_x^2 n_b}{d_z \lambda_0} = \frac{2k_0 n_b q_z}{q_x^2} \approx 1. \tag{5}$$

The solution of the linear system of ODEs (4) can be written as $\vec{a}(z) = \sum_{l=1}^{3}\vec{A}^{(l)}e^{-ik_z^{(l)}z}$, where $-ik_z^{(l)}$ and $\vec{A}^{(l)}$ are (k_x-dependent) complex eigenvalue and eigenvector of the related spectral problem, such that $\sum_{l=1}^{3}\vec{A}_0^{(l)}(k_x) = \mu(x,0)e^{ik_x x}$. Thus, $\Im m\, k_z^{(l)}(k_x)$ are the gain functions of the modes, fully defining the angular profile of the optical beam in long devices.

Upper row panels of Fig. 2 give a few examples of these gain functions. For $\mathcal{Q} \approx 1$ one of the modes possesses a

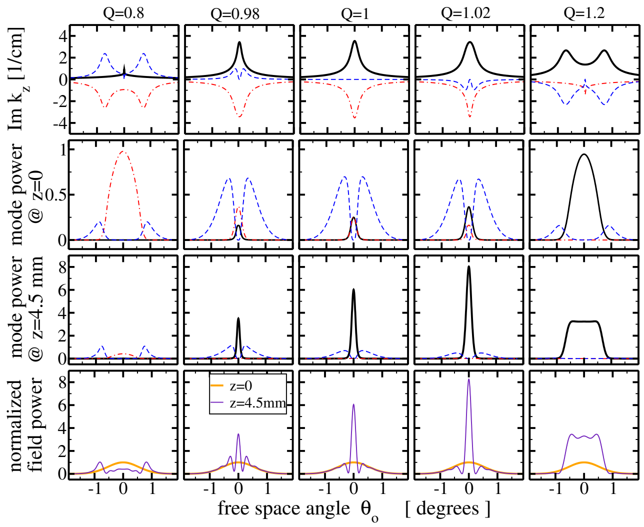

Fig. 2. Mode gain functions $\Im m\, k_z$ [1st row], their contributions at $z = 0$ [2nd row] and $z = 4.5\,\text{mm}$ [3rd row], and normalized total field intensity at $z = 0$ (thick) and $z = 4.5$ mm (thin) [4th row] for different $\mathcal{Q}$ [different columns] in dependence on radiation angle.

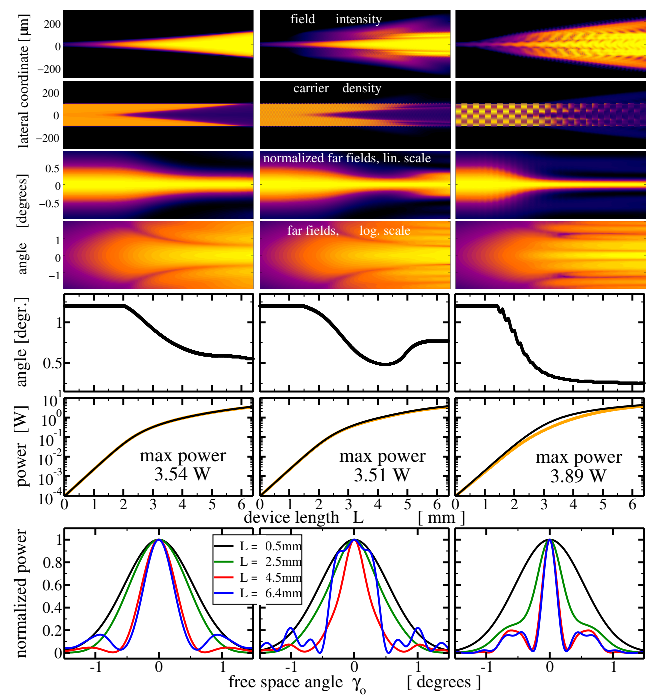

Fig. 3. Beam propagation in non-modulated (left), modulated with $(d_x, d_z) = (4, 100)\,\mu$m (middle), and $(d_x, d_z) = (8, 400)\,\mu$m (right) BAS amplifiers according to Eqs. (1,2). Injected beam intensity was 0.1 mW, factor $\mathcal{Q} = 1.04$. 1st-4th rows: mappings of the field intensity, the carrier distribution, normalized and non-normalized FF recorded and computed for different longitudinal positions (different lengths) of the amplifier. 5th and 6th rows: FWHM of the central FF lobe and the field intensity at corresponding longitudinal position. 7th row: central part of the FF at four different longitudinal positions.

well pronounced narrow gain peak around the central emission angle, and, according to the discussion above, one can expect a significant spatial filtering of the emitted beam. For the amplifiers of moderate length, however, the final profile of the far-fields (FF) [lower row] strongly depends on the initial contributions of all modes [second row]. Thus, according to this figure, the best angular filtering of the beam can be expected for the factor $\mathcal{Q}$ which is slightly higher than 1.

Finally, the simulations of the beam propagation and amplification in non-modulated and two different modulated BAS amplifiers using the TW model (1,2) were performed: see Fig. 3. The intensity of the injected beam is small, so that the exponential growth of the field intensity takes place for $z \leq 2.5\,\text{mm}$ (see 6th row panels). For $z > 4\,\text{mm}$, the beam intensity becomes rather high and saturates the gain (see depletion of carrier densities in the second row panels), which, consequently, leads to the saturation of the field intensity itself. The spatial distribution of the carriers, gain and index functions at large z in modulated BAS devices still show well recognizable modulation periods d_x and d_z. The modulation amplitudes, however, are no more uniform in space, what implies deviations from the linear theory results. Nevertheless, a significant beam amplification and shaping in modulated BAS devices is still present: see 3rd and 5th row panels within the second column for $L \approx 4\mu$m, and the third column for $L > 3\mu$m. For the devices with the fine modulation period (second column) the beam shaping effect is, however, small. It is due to the carrier diffusion, which diminish the modulation of the gain and index functions. A more optimistic situation is in the case of the BAS amplifiers with larger modulation periods (right column). The FF compression is significantly enhanced, whereas the field emission intensity is also slightly increased.

To conclude, it is predicted that a spatial modulation of the bias current in BAS amplifiers with a length on the order of a few millimeters can lead to a substantial improvement of the spatial structure of the amplified beam. Beyond what is here presented, this new technique could be implemented to improve the spatial quality of emission of BAS lasers.

Acknowledgment

The author would like to thank the support of EU FP7 ITN PROPHET, Grant No. 264687.

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