

Modeling of Vertical External Cavity Semiconductor Laser with MQW Resonant Structure

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Abstract— Numerical model is developed of a VECSEL with a resonant gain structure pumped by a fast electron beam. Optical modes properties for resonator formed by Bragg reflector, chip boundary and external mirror were studied. For above threshold operation carrier density in each of QWs obeys non-linear diffusion equation. A new iteration procedure for round-trip operator evaluation was developed, which provides linear growth of computation time with a size of MQW.

I. INTRODUCTION

The concept of a vertical-cavity resonant periodic gain surface-emitting laser was suggested in papers [1-3]. The key idea of this design is to create an optimal overlap between the periodic gain medium and the standing wave optical field of the lasing mode. If the period is multiple of half-wavelength the longitudinal confinement factor can be up to twice as large as that for MQW design with chaotic positions of QWs. The upper limit is achieved provided the QWs are located at antinodes of modal wave field.

Typically, VECSELs are optically pumped by diode lasers [4]. Electron beam pumping can be implemented, too. Usage of the electron beam is a promising way to extend the laser spectral range into shorter wavelength region [5]. Theoretical modeling of devices with both types of pumping can be unified by introducing of an effective pump current density [6, 7].

Characteristics of the laser output beam when operated on the fundamental mode are calculated by Fox-Li iterations. Results of numerical simulations well agree with experimental data for a VECSEL at $\lambda=640$ nm pumped by a short-pulse electron beam [7]. An approach to diagnose fundamental mode stability is developed. A new version of the bi-directional beam propagating method is developed based on round trip propagation operator [8]. Evaluation of this operator is made by 2x2 T-matrix method applied to Fourier components of wave field in combination with Arnoldi algorithm [9] allowing for calculation of a set of high-Q

optical modes.

II. MODEL

Characteristics of the fundamental mode operated above threshold were found from solution to Helmholtz equation. The Fox-Li iterations, in contrast to standard case, were organized as follows: inner iteration cycle includes iterations at the fixed value of wave-vector to convergence of mode profile; the external iterative cycle encloses the inner cycle. Iterations were performed by changing the wave vector magnitude until it converges to some value, which was identified as an eigenvalue of the fundamental mode. The refractive index value incorporates non-linear component, Rg , g is the gain coefficient, R is line enhancement factor.

The gain coefficient distribution within each QW was found from diffusion equation for carrier density, N_l , in the l -th QW:

$$\frac{D}{r} \frac{\partial}{\partial r} \left(r \frac{\partial N_l}{\partial r} \right) - \frac{N_l}{\tau_{nr}} - B N_l^2 - \frac{|U_0|^2 N_{tr} g}{\tau_{nr} g_0} = -F \cdot I \cdot f(r),$$

where for the material constants the values are taken as in [7]:

$B = 3.5 \cdot 10^{-10} \text{ cm}^3 \text{ s}^{-1}$ is the nonlinearity coefficient,

$D = 0.5 \text{ cm}^2 \text{ s}^{-1}$ is the diffusion coefficient, $\tau_{nr} = 1 \text{ ns}$ is the

recombination time, N_{tr} is the transparency carrier density,

corresponding with the e-beam current density

$j_{tr} = 2.35 \text{ A} \cdot \text{cm}^{-2}$, $F \cdot I \cdot f(r)$ is the pumping intensity with

radial profile $f(r) = 1 / (1 + r^4 / r_0^4)$, r_0 is the radius of e-beam,

I is the e-beam current, F is proportionality factor. The

dependencies of the gain and the refractive index in l -th QW on the carrier density are approximated with functions

$g_l = g_0 \ln(\chi(N_l / N_{tr}))$ and $n_l = n_0 - R(g_l - g_{\min}) / (2k_0)$,

with $R = 2.5$, $g_{\min} = 1000 \text{ cm}^{-1}$, $g_0 = 3400 \text{ cm}^{-1}$,

$\chi(Y) = \alpha + (1 - \alpha) Y^{1/(1-\alpha)}$ if $Y < 1$, $\chi(Y) = Y$ if $Y \geq 1$,

$\alpha = \exp(g_{\min} / g_0)$. Zero boundary conditions are imposed on

N_l at the lateral boundary placed at sufficiently large distance from the axis.

The external spherical mirror has the curvature radius 3 cm

and reflection coefficient 0.985. Calculations have been performed for various sizes of this mirror and for variable distance of this mirror from the output facet of the heterostructure, which contains 25 QWs.

III. RESULTS AND DISCUSSION

Figs. 1 and 2 show calculated output power and beam divergence at the half intensity level as functions of the distance to the external mirror at e-beam radius 25 μm .

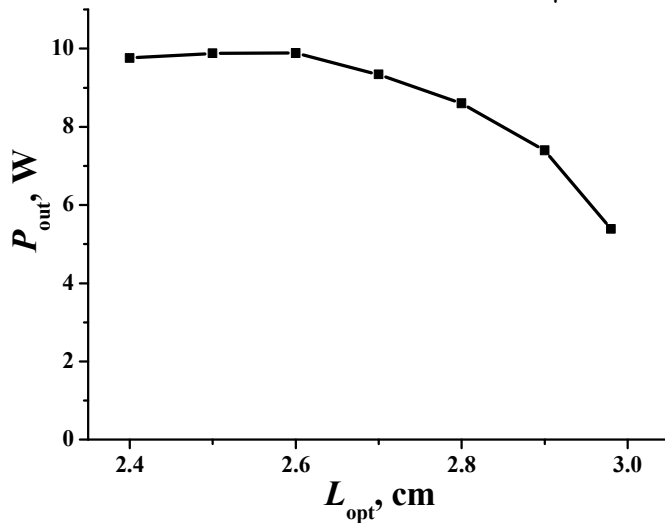


Fig. 1. Output power as a function of distance to the external mirror with size $\varnothing = 0.4 \text{ mm}$; $I_{eff} = 400 \text{ mA}$ $r_0 = 25 \mu\text{m}$.

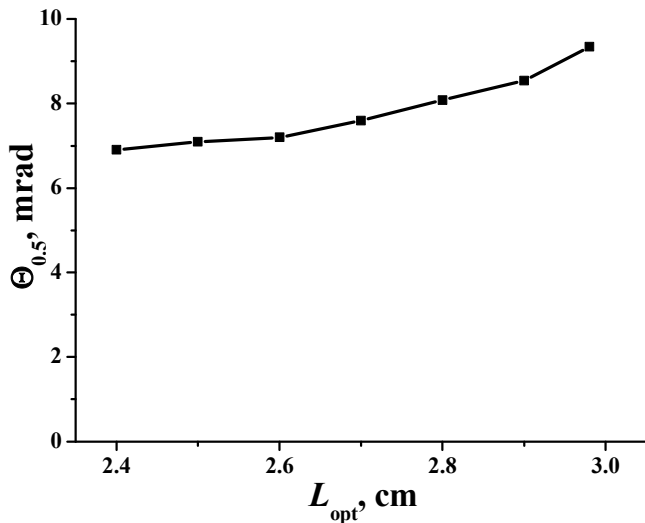


Fig. 1. Half power beam divergence as a function of distance to the external mirror with size $\varnothing = 0.2 \text{ mm}$; $r_0 = 25 \mu\text{m}$.

The output power has a maximum at a distance about 2.5 cm, while the beam divergence monotonously grows with increasing of distance between the output facet and the mirror. Appearance of the maximum in the laser power corresponds with variation of the laser beam radius within the structure. Dependence of the output power on the distance to the mirror is explained in terms of overlap factor between gain and laser beam. The maximum of power is achieved when this overlap factor is maximal. Our simulations demonstrate that transverse pattern of the fundamental mode is sensitive to nonlinear

index profile. As a result, mode patterns may remarkably deviate from pattern of classic Gaussian.

Numerical code developed allows us to calculate a large set of optical modes in the structure with fixed gain and nonlinear index distributions. A number of optical modes are calculated simultaneously with help of Arnoldi algorithm and iterations to find two iteration parameters: mode decay rate and wave vector magnitude. Parameters of structure design and of the e-beam pump are found, which provide stability of the fundamental mode at a high pump rate. Discrimination between modes with specified spatial and longitudinal indices is determined by two factors: 1) loss caused by diffraction on the mirror edge; 2) gain/loss balance quantified by magnitudes of the transverse and longitudinal overlap factors. Parameters of the MQW structure as well as of the external mirror and its location should be selected carefully to provide high efficiency and stability of the VECSEL.

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