Modes discrimination analysis of coherently coupled AlInGaAs VCSEL array

Tomasz Czyszanowski, Jaroslaw Walczak, Maciej Dems, Robert P. Sarzala
Institute of Physics, Technical University of Lodz
Łódź, Poland
tomasz.czyszanowski@p.lodz.pl

Elodie Lamothe, Lukas Mutter
Laboratory of Physics of Nanostructures, Ecole Polytechnique Federal de Lausanne (EPFL)
Lausanne, Switzerland

Abstract—**We present analysis of AlInGaAs VCSEL array and analyze the influence of shallow etching, distance between the emitters and gain distribution on the modes discrimination. As a result we determine the optimal parameters assuring stable, single mode operation.**

Keywords: VCSEL array, laser coupling

I. INTRODUCTION

The efficient way to increase the emitted power by VCSEL is to combine several emitters into phase-locked array. Vertical geometry of device assures narrow linewidth by selection of single longitudinal standing wave being in the resonance with quantum wells. Sole mechanism contributing to the linewidth broadening originates in the existence of lateral modes of two kinds. First kind are modes of single emitters, second are the array supermodes formed of the same order of single-emitter modes. The key to narrow spectral linewidth is the control of the number of existing modes. First kind can be governed by the dimension of the single emitter or patterning of optical confinement, the control of the second kind of the modes is far more problematic.

This paper presents the optimization of the optical confinement and carrier injection aimed for single mode operation. The analyzed structure incorporates InAlGaAs quantum wells within InP cavity. The cavity is bounded by AlGaAs/GaAs DBRs. The tunnel junction is responsible for carrier funneling into the active region. The air-gap etched in the form of ring at the interface between cavity and top DBR is responsible for confinement of emitter modes. To rigorously simulate the physical phenomena taking place in the device we used multi-physical model, which comprises three-dimensional models of optical (Plane Wave Admittance Method) and thermal phenomena (Finite Element Method).

II. THE MODEL

The comprehensive three dimensional model used here to simulate the operation of AlInGaAs-based VCSEL array consists of vectorial optical approach based on the Plane Wave Admittance Method (PWAM) [1] and thermal model utilizing the finite element discretisation scheme [2]. In the optical mode, the interaction of electric and magnetic fields, described by the **E** and **H** vectors, with the matter is governed by the set of Maxwell equations. The set can be transformed to another one, which relates electric and magnetic fields parallel to the interfaces between layers of the structure. To describe the electromagnetic field as well as material parameters such as electric permittivity and magnetic permeability, we are using the orthonormal complete basis of exponential functions within plane perpendicular to the direction of light propagation. The basis functions have been defined as a product of two exponential functions (still satisfying orthonormality and completeness of the basis). The boundary conditions are assumed in the form of the absorbing Perfectly Matched Layers [2]. The amplitudes of **E** and **H** can be determined from the continuity conditions for the fields and its z-derivatives at the boundaries of the layers in a multi-layer structure. The continuity condition plays also the role of eigenequation for the optical modes. The characteristic equation is used to find out the complex modal wavelength of the emitted radiation, the imaginary part of which allows determination of the modal gain. More details of the model can be found in [1]. The method has proved already its exactness and efficiency in complex VCSEL devices [4,5].

III. THE RESULTS

This paper presents the optimization of the optical confinement and carrier injection aimed for single mode operation. The analyzed structure is AlInGaAs/InP tunnel junctions VCSEL array [6]. The tunnel junction is responsible for carrier funneling into the active region. To enhance single mode operation of the array shallow etching is assumed on the interface between top DBR and cavity. We investigated the following parameters to achieve strong modes discrimination: the depth of the etching, distance between single emitters and gain profile. The parameter, which determines the discrimination of the modes is difference of the imaginary part of the emitted wavelength (λ_{im}) of particular modes. λ_{im} corresponds to the modal gain and its positive value

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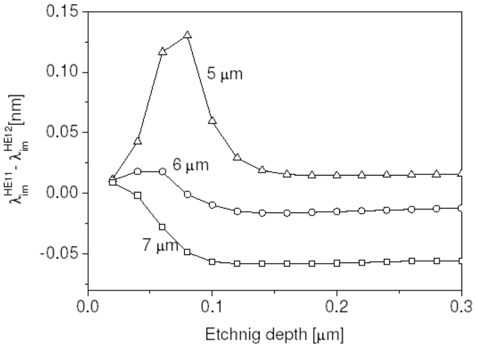

Figure 1. Difference of imaginary parts of emitted wavelength of HE$_{11}$ amd HE$_{21}$ modes versus etching depth. Curves have been ploted for three different tunnel junction apertures (5 μm, 6 μm, 7 μm)

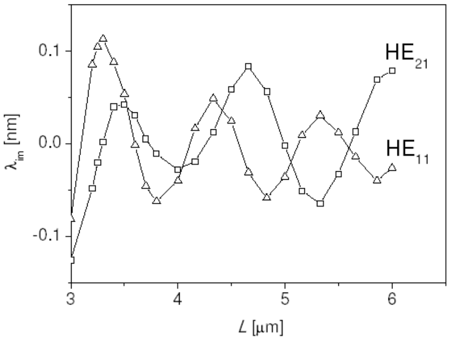

Figure 4. Imaginary part of emitted wavelength of HE$_{11}$ and HE$_{21}$ modes as a function of the distance between the centers of tunnel junctions

determines, which mode is lasing under particular conditions. Fig. 1 illustrates the difference of λ_{im} between two the lowest order modes as a function of etching depth. The strongest modes discrimination is assured by 5 μm optical aperture which is 1 μm smaller than the tunnel junction aperture. The optimal etching depth ranges from 0.05 μm to 0.1 μm. Such etching depth relates simultaneously to efficient confinement of the fundamental mode and scattering of first order mode. The design with 0.1 μm etching depth was used to determine the optimal distance between two emitters, which will assure lateral resonance of in-phase HE$_{11}$ mode and discriminate competitive out-of-phase HE$_{21}$. Fig. 2 shows that L = 5.2 μm assures such situation. Finally, the gain distribution was investigated in a three emitter array as an additional factor contributing to the modes discrimination. Some of the cavity modes of the three emitter array are plotted in Fig. 3. In the analysis the sum of Gaussian distributions has been taken to reproduce the optimal gain distribution. Fig. 4 shows the difference between $\varepsilon_{0,2}$ mode and all others with respect to λ_{im} as a function of full width at half maximum of the gain distribution (σ). σ assuring the strongest modes discrimination equals 1.8 μm and gives assumptions for optimization of tunnel junction conductivity.

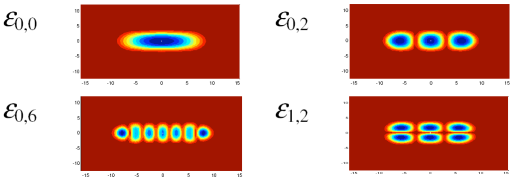

Figure 2. Distribution of the intensity of chosen array modes in the plane of active region

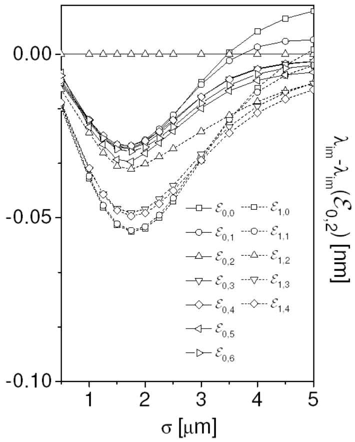

Figure 3. Imaginary parts of emitted wavelength of array modes with respect to lim of e0,2 mode as a function of full width at half maximum of the gain distribution

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REFERENCES

[1] M. Dems, R. Kotynski, and K. Panajotov “Plane Wave Admittance Method – a novel approach for determining the electromagnetic modes in photonic structures,” Opt. Express, vol. 13, pp. 3196-3207, 2005

[2] R. P. Sarzała and W. Nakwaski, “Optimisation of the 1.3-μm GaAs-based oxide-confined (GaIn)(NAs) vertical-cavity surface-emitting lasers for their low-threshold room-temperature operation,” J. Phys: Cond. Matter, vol. 16, pp. S3121 – S3140, 2004

[3] C.-P. Yu, H.-C. Chang, “Yee-mesh-based finite difference eigenmode solver with PML absorbing boundary conditions for optical waveguides and photonic crystal fibers”, Opt. Express, vol. 12, pp. 6165 -6177, 2004.

[4] M. Dems, I.-S. Chung, P. Nyakas, S. Bischoff, K. Panajotov “Numerical Methods for modeling Photonic-Crystal VCSELs” Opt. Express, vol. 18, pp. 16042 -16054, 2010

[5] T. Czyszanowski, M. Dems, H. Thienpont, K. Panajotov “Optimal radii of photonic crystal holes within DBR mirrors in long wavelength VCSEL” Opt. Express vol. 15, pp 1301–1306, 2007

[6] L. Mutter, V. Iakovlev, A. Caliman, A. Mereuta, A. Sirbu, E. Kapon “1.3 mm-wavelength phase-locked VCSEL arrays incorporating patterned tunnel junction” Opt. Express vol. 17, pp 8558–8566, 2009