Efficient Optical Modeling of VCSELs using Full-Vectorial FDFD method

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***Abstract*—In this paper, the FDFD is used to analyze Vertical Cavity Surface Emitting Laser (VCSEL). Based on the structure of the VCSEL, two main models can be used; the 2.5D and the 3D Finite Difference Frequency Domain (FDFD). The full vectorial solver is well suited for the fundamental as well as the higher-order modes and includes different field polarization. The method was used to solve both the reference VCSEL and the Surface-Relief VCSEL.**

***Index Terms*—Distributed Bragg reflector lasers, Finite Difference Frequency Domain (FDFD), laser modes, semiconductor lasers, vertical-cavity surface-emitting lasers**

I. Introduction

Due to their unique properties as compact and efficient laser sources, Vertical-Cavity Surface-Emitting Lasers (VCSELs) have received considerable attention from researchers in various fields. [1-4]. In order to design the next generation of VCSELs with even better performance, it is imperative to be able to model the optical, electrical, and thermal effects that come into play in these devices. Full simulation of such structures is quite challenging task as a VCSEL resonator is both large (thousands of cubic wavelengths) and contains sub-wavelength features such as distributed Bragg reflectors (DBR) layers, quantum wells, and structured apertures. Furthermore, the exterior environment must also be modeled to obtain realistic predictions of radiation loss and lasing threshold.

The optical simulation of the VCSEL structure can be performed either using scalar or vectorial solvers. In scalar optical solver, the modal field is assumed to be linearly polarized and spatially separated, thus it can be reduced to a 1D analysis in both the radial and the axial direction. Hence, these approaches are fast and relatively inexpensive (in terms of simulation time and resources). However, these solvers are restricted to dominant modes and small dimensions VCSELs. The vectorial solvers are based on solving full vectorial Maxwell's equation. They can be used to solve for both the dominant modes as well as the higher order modes. Furthermore, arbitrary shapes VCSEL (photonic crystal based and non-circular VCSEL) can be accurately analyzed. The main limitation of such solvers is their relatively higher numerical cost.

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In the Photonic Integrated Circuit Simulator in 3D (PICS3D) simulation software developed by the authors, the Finite Difference Frequency-Domain method (FDFD) was selected to implement the full vectorial optical solver for VCSELs [5]. The FDFD method is considered as a natural frequency alternative to the Finite Difference Time-Domain method (FDTD) method and its accuracy on Yee staggered grid was investigated [6-8]. To terminate the computational window, a Perfectly Matched Layer was used [9].

The solution of the FDFD model (wavelength and optical mode profile) is then used in the rest of the laser model and couples with the electrical transport and quantum-mechanical models.

In this paper, the optical analysis of the VCSEL is performed using the FDFD method with PML layer. First, a brief introduction to the FDFD method will be discussed. This method will then be used to analyze a standard reference VCSEL structure as well as a variation of the same structure with asurface relief feature. Finally, a conclusion section will be addressed.

II. The FDFD Method

In PICS3D simulation, there are two main microcavity optical modules; the 2.5D and the full 3D solvers.

Taking advantage of the circular symmetry of the VCSEL, the azimuthal (φ) dependence can be expressed as exp(jnφ) – where n is an integer. Therefore, the full 3D problem can be reduced to a discretization over a 2D grid, with a semi analytical dependence on φ; this scheme is labeled 2.5D.

For arbitrary VCSEL structure configurations, the 3D solver has been used. The full 3D solver is formed based on the 3D cartesian coordinates system, potentially allowing the user to define VCSELs of arbitrary shapes.

In FDFD analysis, the electromagnetic fields are discretized on a staggered Yee mesh by applying the central difference scheme, allowing the Maxwell equations to be written in matrix form. After some mathematical work and variable substitution, an eigenvalue matrix equation in terms of the electric fields is obtained as

$$\Theta.E = \omega^2 E \tag{1}$$

where, ω is the complex resonance frequency, Θ is the discretization matrix and E is the electric fields.

After solving the eigenvalue problem (using a sparse eigensolver), the electromagnetic fields, the resonance frequency and the cavity quality factor can be calculated.

III. Numerical Results

In this section, two main VCSELs will be analyzed; the reference VCSEL and the Surface Relief VCSEL (SR-VCSEL).

A. Reference VCSEL

The first device is an AlGaAs VCSEL designed for operation around 850 nm. The bottom reflector consists of 29 pairs of DBR, while the top mirror has 19 pairs. The gain in the 5-nm-thick Multiple Quantum Well (MQW) is assumed to have a step index profile.

Figure 1 shows the dominant mode wave intensity. The figure shows that the mode is well confined inside the cavity, as well as the standing wave profile.

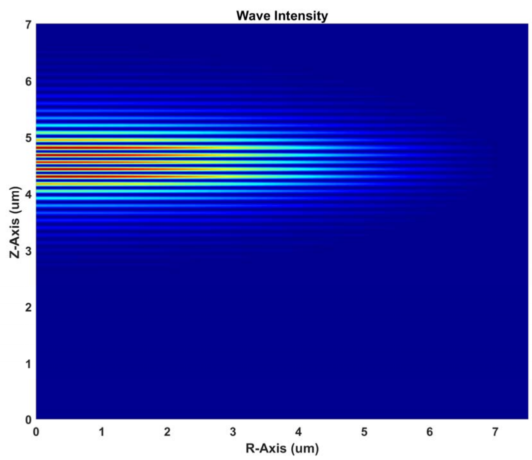
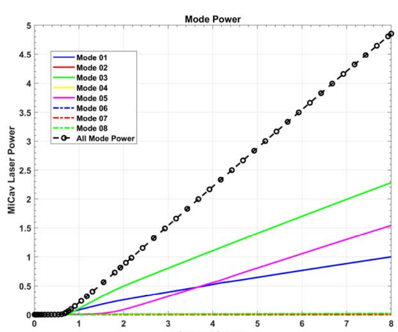
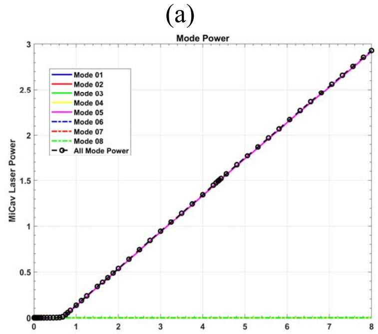


Fig. 1 Dominant Mode



(a)



(b)

Fig. 2 .All mode power (a) Reference VCSEL (b) SR VCSEL

B. SR-VCSEL

Similar to the reference VCSEL, the SR-VCSEL was designed around 850 nm. To control the mode spectra, a self-aligned surface relief layer was added at the top of the DBR layer.

A comparison between the laser power for both the SR-VCSEL and the reference VCSEL is shown in Figure 2. In the reference VCSEL, the power divided between different modes. While the self-aligned surface relief focuses the power in a single mode.

IV. Conclusion

A brief introduction of the optical mode solver using both the 2.5D and the 3D FDFD is discussed. The circular symmetry VCSEL was analyzed using the 2.5D microcavity module in PICS3D. The dominant mode and higher order modes were calculated. For the reference cavity, the laser power split between several modes. While adding a self-aligned surface relief layer acted as a mode selective layer. Similar results were achieved using the optical 3D FDFD solver.

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