Efficient Full-Wave Modeling of Electromagnetic Field Propagation Through Micro-Optical Link

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ABSTRACT

Low dimensions of contemporary micro-optics imply the necessity of inclusion of vector diffraction effects into optical models. Classical geometrical optics and Gaussian beam calculation approaches are too coarse approximations. They do not properly take into account all the diffraction phenomena. We have developed a new optical modeling tool (EM_LINK) based on the wave optics and separate propagation of each component of the electromagnetic field between optical surfaces. The software enables three-dimensional (3D) modeling of electromagnetic field propagation through optical systems. The method is very fast because no 3D discretization mesh is needed, and the Fast Fourier Transform is used when the optical source surface is flat. The software is well suited for analysis of the optical link between a VCSEL and a fiber or photodetector, taking into account the associated lenses. The VCSEL-fiber coupling efficiency and its dependence on the misalignment can be quickly and accurately calculated.

Keywords: microoptics, optical links, full-wave modeling, electromagnetic, coupling efficiency.

1 INTRODUCTION

Dimensions of contemporary micro-optical systems, comparable with the light wavelengths, imply the necessity of inclusion of vector diffraction effects into optical models. CFD Research Corporation (CFDRC) has continued to develop optical modeling tools for light generation and propagation within vertical-cavity surface-emitting lasers (VCSELs). These tools solve appropriate full-wave three-dimensional (3D) boundary value problems for Maxwell equations [1]. Exact calculation of the fiber coupling efficiency also requires knowledge of the vector electromagnetic field at the fiber input face. However, application of the Maxwell equations solvers using the meshing techniques to calculate propagation of the optical beams from VCSEL output face through an optical system is an expensive approach due to much larger distances and beam widths. Instead, we can use surface-to-surface propagation methods taking advantage of weak coupling between the fields reflected at the surfaces of the optical systems. Classical geometrical optics and Gaussian beam calculation approaches are too coarse approximations to describe light propagation in micro-optical systems [2-5]. They do not properly take into account the diffraction at large angles, the dependence of diffraction on polarization, and many other electromagnetic diffraction phenomena. VCSEL optical beam propagation, especially when higher modes are playing dominant role, and diffraction on the small apertures of arrayed micro-optical elements are exemplary problems where full-wave electromagnetic modeling has to be applied. Efficient no-meshing method is needed that calculates light propagation, preserving information of vectorial electromagnetic field and that can be coupled to VCSEL and fiber full-vector codes. This paper presents our approach to that task and some example results.

2 NEW OPTICAL LINK MODEL

We have developed a new optical modeling tool, called EM_LINK, based on the wave optics and separate propagation of each component of the electromagnetic field between optical surfaces. The software enables 3D modeling of electromagnetic field propagation through an optical system. The method is very fast because no 3D discretization mesh is needed, and the Fast Fourier Transform (FFT) is used when the optical source surface is flat, as is usually the case of the VCSEL top surface. The software is well suited for analysis of the optical link between a multimode VCSEL and a fiber or photodetector, taking into account the associated lenses.

The method is based on the scalar diffraction theory applied to calculation of a homogeneous-medium propagation of each component of the electromagnetic vector field. Diffracted fields are then obtained on the arbitrary shaped optical surface of the system. It can be a surface of an aspheric lens integrated with the VCSEL. The boundary conditions for the vector electromagnetic field are applied to obtain fields just behind the surface. The light propagation to the next surface in the optical interconnection is calculated using the Rayleigh-Sommerfeld first diffraction formula.

Effectiveness of the computation is assured by the combined application of the FFT to obtain plane wave

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decomposition on the VCSEL top surface and integral over the spectrum to synthesize the field on a possibly curved optical element (e.g. lens) surface. We would like to stress that the conventional application of the Fast Fourier Transform and the angular spectrum representation is limited to computation of a diffraction between the planes. Moreover, it would require prohibitive amount of RAM for the considered application due to the large product of the VCSEL collimating lens diameter and the VCSEL output beam divergence.

The setup of the new optical modeling tool, EM_LINK, is illustrated in Figure 1. In this figure, the following elements are included:

V – VCSEL, with possible linear shifts _xV, _yV from its nominal position;

S – Spacer, between the VCSEL and the lens;

L – Lens, with possible linear shifts _xL, _yL, _zL, and angular displacements __L, __L from its nominal position;

A – Air (or any other homogeneous medium);

F – Fiber, with possible linear shifts _xF, _yF, _zF, and angular displacements __F, __F from its nominal position.

The new proposed methods have enabled creation of a very powerful, general-application tool, allowing for exact modeling of important optical interconnects problems, e.g. the impact of system components misalignment on the VCSEL-to-receiver coupling efficiency. The method can be easily interfaced with comprehensive electromagnetic codes for VCSEL and photodetector (e.g. FDTD-based codes, [1]), due to its vector electromagnetic formulation.

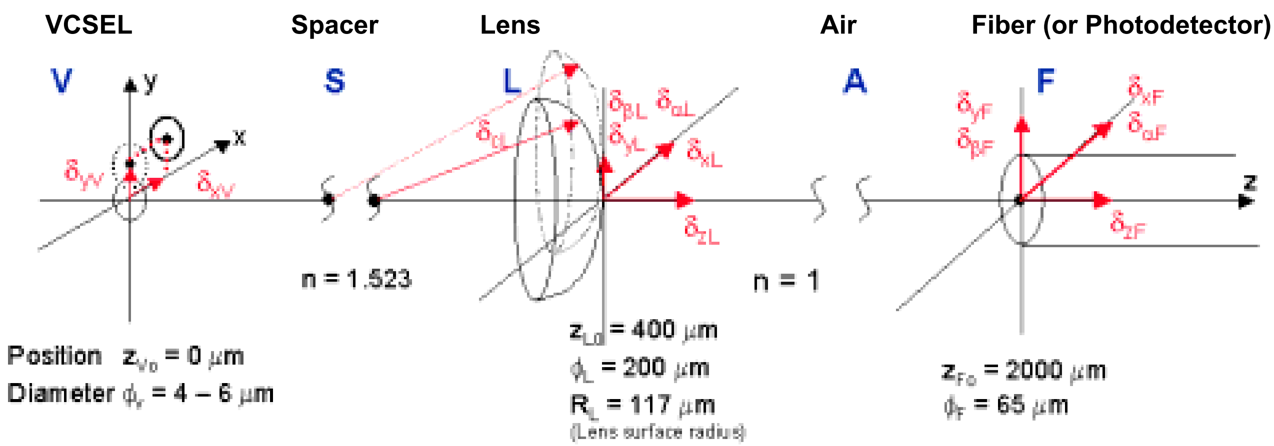
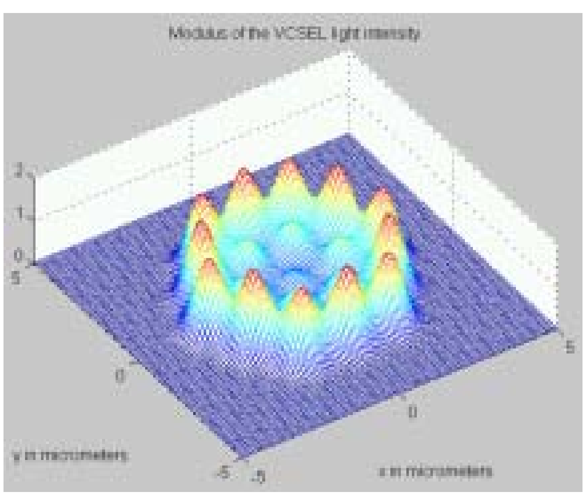


Figure 1. Parameters (with some exemplary values) that can be varied in the misalignment analysis of the optical link in the new EM_LINK optical modeling tool from CFDRC. The possible translational and angular displacements of the components are represented by the _ parameters.

a) 

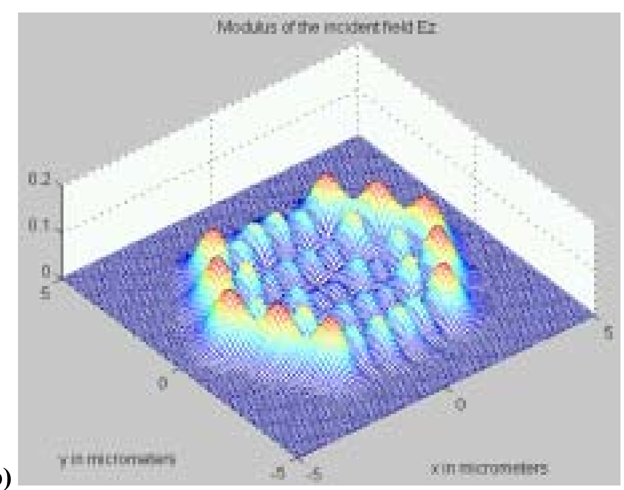
b) 

Figure 2. a) Light intensity profile at the VCSEL top surface , and b) the derived Ez component of electromagnetic field at the VCSEL surface.

3 FULL-VECTOR SIMULATION OF LIGHT PROPAGATION

Some results of the application of the new optical modeling tool are presented in the figures below. Figures 3 and 4 illustrate specific light components at the lens surface. Selected examples of EM_LINK analysis of the light intensity and phase at the input surface of the optical fiber are shown in Figures 5 and 6.

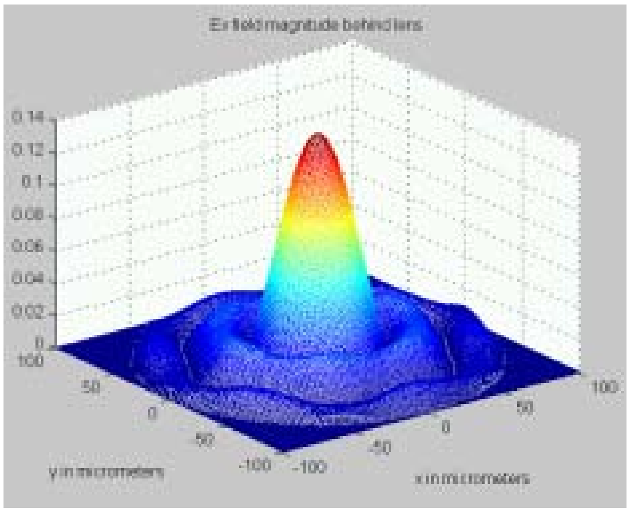


Figure 3. Magnitude of the dominant polarization of the electric field (Ex) just behind the lens surface

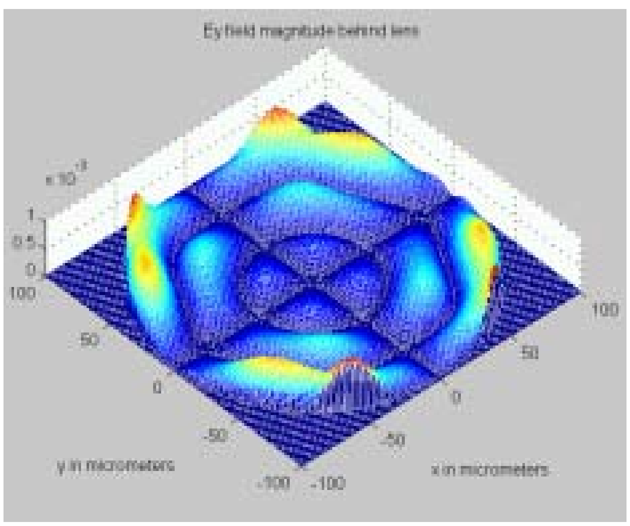


Figure 4. Distribution of the Ey component of electromagnetic field behind the lens surface.

4 OPTICAL COUPLING EFFICIENCY CALCULATIONS

The VCSEL-to-fiber coupling efficiency and its dependence on the misalignment can be calculated. The parameters that may affect the optical link efficiency include both translational and angular displacements of all the link components, which are represented by the _ parameters in Figure 1. The coupling efficiency of the VCSEL light to the *n-th* fiber mode is calculated with the following equation:

$$P_n = \frac{\left| \iint_F \vec{E}_t \times \vec{H}^*_{nt} d\sigma \right|^2}{\iint_F \vec{E}_t \times \vec{H}^*_t d\sigma \iint_F \vec{E}_{nt} \times \vec{H}^*_{nt} d\sigma} \qquad (1)$$

where E_t is the transverse electric field component of the incident wave, H_{nt} is the transverse magnetic field component of the n-th fiber mode, and _ represents the surface area.

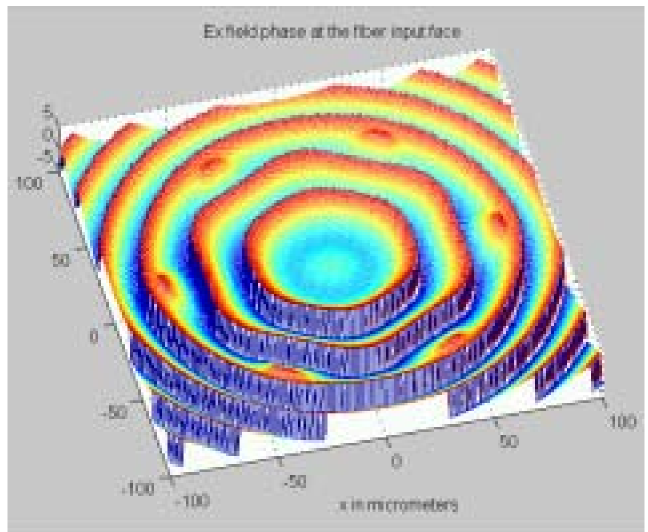


Figure 5. The phase of Ex field component at the fiber input face shows defocus (not flat wave front).

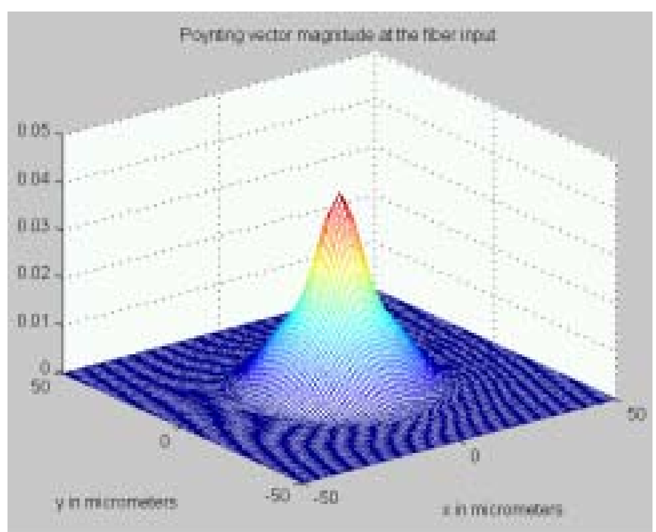


Figure 6. Poynting vector magnitude at the fiber input shows mode mismatch to the LP_{01} fiber mode.

The following components of total light losses contribute to the decrease of coupling efficiency:

<u>Losses at the Lens Surface</u>

- Reflection
- Diffraction at the lens aperture
- Polarization changes

<u>Losses at the Fiber Front Face</u>

- Reflection
- Core aperture misalignment
- Mode mismatch

Our new full-vector approach includes all the above phenomena into the optical coupling efficiency calculations. For the modeled high-numerical-aperture lens, a significant dependence on polarization of light reflection at the lens surface occurs. Polarization effects are also taken into account in the high fidelity fiber-mode-coupling-efficiency formula shown above. Figure 7 shows the influence of VCSEL lateral displacement (y-shift) on the coupling efficiency resulting from the mode mismatch, calculated using the above vector formula (upper, red curve), and total coupling efficiency including also losses at the optical surfaces due to reflection and diffraction (lower, blue curve). Figure 8 shows similar results as a function of the fiber distance from the lens surface.

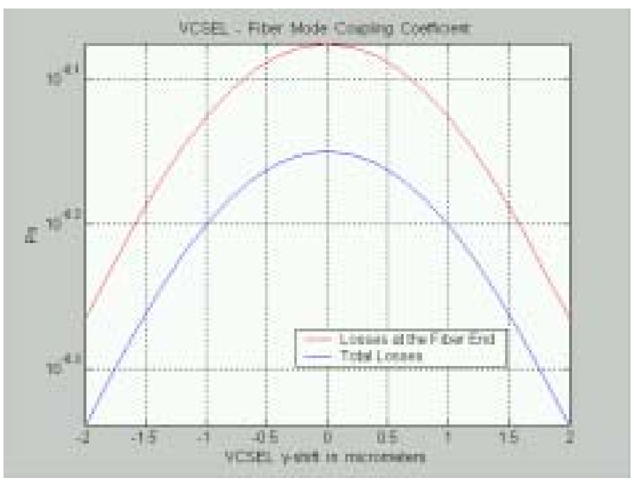


Figure 7. Optical coupling efficiency vs. VCSEL lateral displacement (y-shift), calculated including only the fiber mode matching factor (upper, red curve), and the total coupling efficiency (lower, blue curve).

6 CONCLUSIONS

In this paper, we present a new, very powerful, general-application tool allowing for exact full-vector modeling of important optical interconnection problems, e.g. the impact of misalignment of system components on the VCSEL-to-receiver optical coupling efficiency. The new tool can be easily interfaced with comprehensive 2D/3D electromagnetic codes for VCSEL, photodetector, or fiber, due to its vector electromagnetic formulation. In conjunction with the multi-physics simulator CFD-ACE+ [6], it can be used for a comprehensive analysis of thermal-mechanical phenomena influencing optical performance of advanced opto-electronic systems, like micro-optical-electro-mechanical systems (MOEMS), or free-space optical interconnects (FSOI).

The new 3D optical simulation tool also allows the designer to optimize the placements and geometry of optical link components.

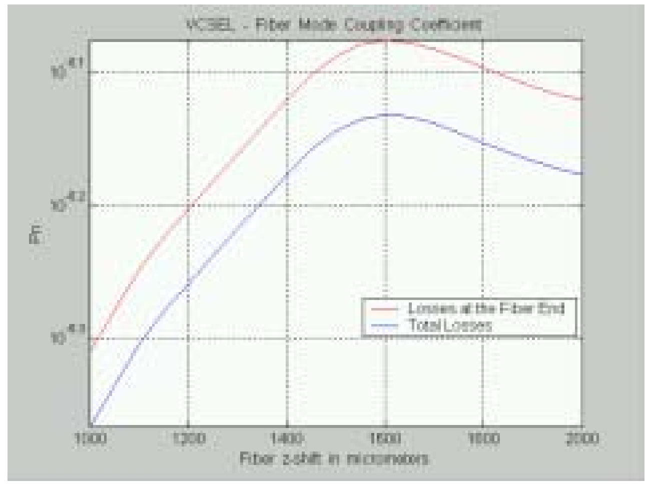


Figure 8. Optical coupling efficiency vs. fiber distance from lens (z-shift), calculated including only the fiber mode matching factor (upper, red curve), and the total coupling efficiency (lower, blue curve).

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