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invited paper

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Abstract – **The single-mode properties and design issues of three vertical-cavity surface-emitting laser (VCSEL) structures incorporating nano structures are rigorously investigated. Nano structuring enables to deliver selective pumping or loss to the fundamental mode as well as stabilizing the output polarization state. Comparison of three vectorial simulation methods reveals that the modal expansion method is suitable for treating the nano structured VCSEL designs.**

Index Terms—**subwavelength grating, photonic crystal, HCG**

I. INTRODUCTION

High single-mode output power of vertical-cavity surface-emitting lasers (VCSELs) can be of high interest in many applications. Various approaches have been investigated to increase the single-mode output power, e.g. [1]−[3]. Among them, employing nano structures looks promising since it can not only improve single-mode output power but also stabilize the polarization state. The optical simulations of the nano structured VCSELs should be vectorial in order to accurately treat scattering, diffraction, and polarization-related effect.

This presentation consists of two parts: In the former part, three vectorial simulation methods for VCSELs are compared in terms of computational speed, memory demand, and capability of quantitatively measuring various optical losses. In the latter part, the single mode properties of three nano structured VCSEL designs are investigated: a photonic crystal (PhC) VCSEL, a long wavelength VCSEL with an intra-cavity air gap, and a high-index-contrast sub-wavelength grating (HCG) VCSEL.

II. COMPARISON OF VECTORIAL METHODS

Three vectorial methods compared in this section are the finite element method (FEM), the finite-difference time-domain method (FDTD), and a modal expansion method with coupled mode approach [1]. The FEM and FDTD use spatial grids to express a field distribution within a computational domain of interest while the modal expansion method uses a linear combination of basis functions, i.e., expansion coefficients of the basis functions. For VCSEL simulations, the modal expansion approach is much faster and requires less memory than the spatial grid approaches, as summarized in Table I. This is because the number of

expansion coefficients involved is typically much smaller than

TABLE I
COMPARISON OF VECTORIAL METHODS

	FEM [4]	FDTD	Modal expansion
Simulation time*	$10 - 30$ hrs	10 hrs $- 2$ wks	A few sec $- 3$ hrs
Memory	$20 - 50$ GB	$30 - 130$ GB	$0.1 - 3$ GB

* Simulation time taken to find a mode.

that of spatial grids. As shown in Fig. 1(a), the field distribution
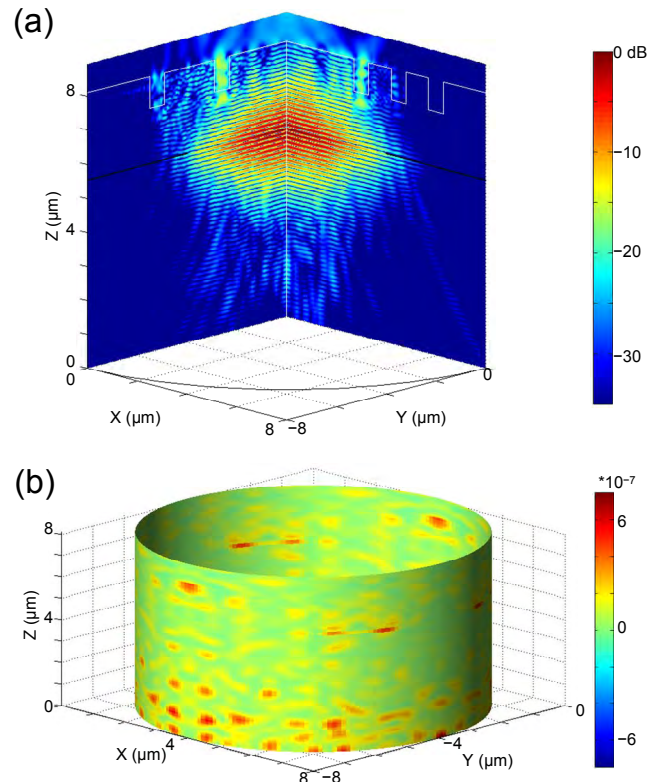

Fig. 1. (a) A normalized intensity profile $|E|^2$ and (b) a normalized radially-outward Poynting vector profile of the fundamental mode of a VCSEL structure with photonic crystal air holes in the top DBR.

within a VCSEL structure can be obtained precisely by using the modal expansion method.

The modal expansion method can also quantitatively estimate the scattering loss due to nano structures and the absorption loss in the active region; this evaluation is not feasible using the spatial grid approaches. It is because the
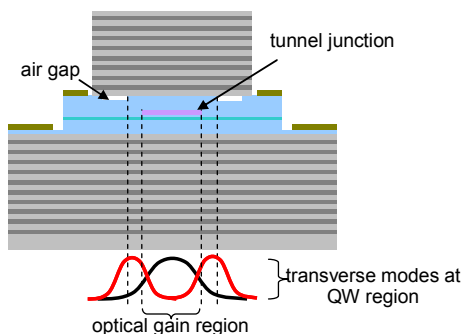
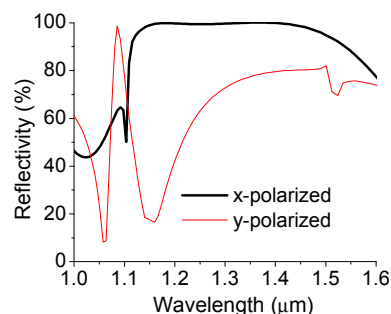Fig. 2. Schematic diagram of the long wavelength VCSEL with a tunnel junction and an intra-cavity air gap.

Fig. 3. Reflectivity of the investigated HCG vs. wavelength. The HCG is highly reflective to the x-polarized electric field whose is polarized perpendicular to the grating groove directions.

spatial grid approach cannot decompose the upward and downward propagating modes, which is necessary for this evaluation. Fig. 1(b) shows a radially-outward Poynting vector profile that is used for the measurement of scattering loss. This capability of measuring the scattering and absorption losses is essential to understand the single mode mechanisms, as discussed in the next section.

In conclusion, the modal expansion approach is adequate for the simulation of nano structured VCESLs, due to its numerical efficiency and capability of estimating various losses.

III. RESULTS AND DISCUSSIONS

Using the modal expansion method, the single mode properties of three VCSEL structures are rigorously investigated.

A. Photonic crystal VCSEL

The single-mode operation of the PhC VCSEL relies on the high scattering loss of higher order modes. As shown in Fig. 1(a), strong scattering occurs near the air holes, due to the large index difference. The total scattering loss of the first order mode is 2.7 times larger than that of the fundamental mode; the fundamental mode becomes dominant.

The scattering loss of the fundamental mode can be reduced while keeping the single mode operation, by replacing the semiconductor Bragg mirror with a dielectric Bragg mirror [1].

B. Long wavelength VCSEL with an intra-cavity air gap

The single-mode operation results from the selective pumping of the fundamental mode. As schematically shown in Fig. 2, the gain region and the transverse mode profiles are independently determined by the tunnel junction and by the air gap, respectively. This makes it possible that most of optical gain is delivered to the fundamental mode. Higher order modes experience high absorption loss.

The key issues to be solved are the non-uniformity of polarization state of output across a wafer and its instability as a function of injection current. They are closely related to a lithographic misalignment of the intra-cavity air gap and a thermal lensing, respectively. Simulations show that employing a surface or intra-cavity subwavelength grating can effectively remove both problems.

C. Subwavelength grating-mirror VCSEL

The reflectivity of a HCG is sensitive to the polarization of the incident field, e.g., as shown in Fig. 3. This property leads to strong polarization stability.

The moderate single-mode strength of a HCG VCSEL can be greatly enhanced by optimizing the HCG region size. When the size of the HCG region becomes similar as that of gain region, the single-mode strength becomes 2−3 times stronger than a typical single-mode VCSEL structure [7].

IV. CONCLUSION

Among several vectorial methods, the modal expansion approach is desirable for simulations of nano structured VCSEL designs, due to its high numerical efficiency and capability of estimating various losses. Nano structuring can greatly enhance the strength of single mode operation by delivering selective loss or pumping to the fundamental mode as well as stabilizing the polarization state, promising high single-mode output power.

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