Efficient Quality-Factor Estimation of a Vertical Cavity Employing a High-Contrast Grating

Alireza Taghizadeh, Jesper Mørk, and Il-Sug Chung*
Department of Photonics Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
*Email: ilch@fotonik.dtu.dk

***Abstract*—Hybrid vertical cavity lasers employing high-contrast grating reflectors are attractive for Si-integrated light source applications. Here, a method for reducing a three-dimensional (3D) optical simulation of this laser structure to lower-dimensional simulations is suggested, which allows for very fast and approximate analysis of the quality-factor of the 3D cavity. This approach enables us to efficiently optimize the laser cavity design without performing cumbersome 3D simulations.**

I. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) have been suggested as candidate light sources for near-future optical interconnects [1]. They consist of two distributed Bragg reflectors (DBRs), which form an optical cavity and provide the required feedback for the lasing action. Recently, it has been suggested that other types of reflectors such as high-contrast gratings (HCGs) [2] or hybrid gratings [3], [4] can replace one or even both DBRs, which result in novel functionality and properties for the vertical cavity lasers. In particular, the possibility of integration to Si in a hybrid vertical-cavity laser (VCL) structure makes it a potential candidate for chip-level optical interconnects [5]. This hybrid VCL comprises a III-V material including several quantum wells (QWs) for light generation and a HCG which is formed in the Si layer of a Si-on-insulator (SOI) wafer [2], [5] as shown schematically in Fig. 1(a).

The 3D optical simulation of this structure typically requires a long simulation time and a large amount of computer memory, since the entire simulation domain of a HCG-based VCL is much larger than the operational light wavelength (e.g. tens of μm) while its smallest characteristic dimension is subwavelength (e.g. a few hundreds nm). Here, a method to simplify a 3D simulation to several lower-dimensional simulations is suggested and analyzed. This method is implemented and tested in our in-house developed optical simulator, which is based on the Fourier modal method (FMM) [6]. Based on this method, one can approximately determine the quality-factor (Q-factor) of the 3D cavity with orders of magnitude less time and required computer memory, which is particularly valuable for optimization of the laser cavity design.

II. INVESTIGATED STRUCTURE AND SIMULATION METHOD

The details of the simulation method has been already reported in Ref. [7]. We use a test HCG-based VCL at 1550 nm wavelength similar to the one reported in Ref. [2] for showing the capability of the proposed method. The structure dimensions and refractive indices are shown in Table I. Even though, only a passive structure is investigated here for simplicity, the introduction of optical loss/gain is straightforward by adding an imaginary part to the refractive index value in the model.

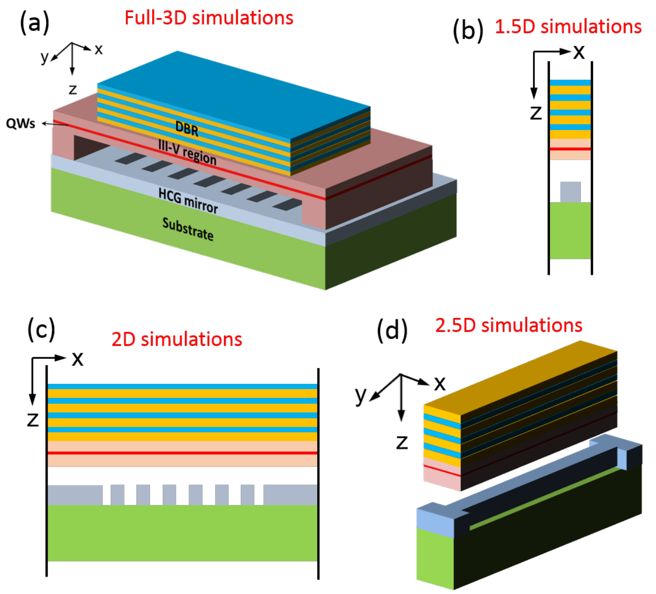

Fig. 1. Schematic view of a HCG-based VCL used for full-3D or low-dimensional simulations, (a) full-3D simulations, (b) 1.5D simulations, (c) 2D simulations, and (d) 2.5D simulations.

TABLE I
LAYER REFRACTIVE-INDICES AND THICKNESSES USED IN SIMULATIONS.

Layer name	Refractive index	Thickness	Comment
Superstrate	n_{sup}=1	$t_{sup} = \infty$	Air infinite half space
DBR-h DBR-l	n_h=3.48 n_l=1.48	t_h=111.4 nm t_l=261.8 nm	4-pairs Si/SiO$_2$ DBR
III-V	n_a=3.166	t_a=704.4 nm	InP active region
Low-index gap	n_c=1.0	t_c=704.4 nm	Air
Grating	n_h=3.48, n_l=1.0	t_g=430 nm	Si grating
Substrate	n_{sub}=1.48	$t_{sub} = \infty$	SiO$_2$ infinite half space

978-1-5090-5323-0/17/$31.00 ©2017 IEEE

TABLE II
LOW-DIMENSIONAL SIMULATION RESULTS FOR THE EXAMPLE HCG-BASED VCL.

Simulation	λ_r (nm)	Q-factor	Result in
1.5D	1550.000	$Q_{1.5D}$=118098	Q_z=118098
2D	1549.062	Q_{2D}=4777	Q_x=4978
2.5D	1546.103	$Q_{2.5D}$=4622	Q_y=4811
3D	1545.260	Q_{3D}=2308	Eq. [1] Q=2303

III. LOW-DIMENSIONAL SIMULATION

For a 3D HCG-based VCL, we will show that it is possible to analyze the cavity by considering lower-dimensional structures, as illustrated in Fig. 1(b)-(d). Thus, by performing low-dimensional simulations, one can estimate the cavity loss in each transverse direction separately. In this approach, it is assumed that the wave propagation in the x, y and z-directions are not closely related, which seems to be a valid assumption for HCG-based cavities. Firstly, a so-called 1.5-dimensional (1.5D) simulation is carried out, where only one period of the HCG is used as shown in Fig. 1(b), and the structure is assumed to be uniform in the y-direction. Indeed, it is a two-dimensional (2D) simulation for a structure with an infinite number of grating periods due to the periodic boundary condition in the x-direction. This 1.5D simulation can be employed to compute the reflectivity, transmissivity and cavity dispersion [7]. For a 2D simulation, a finite number of grating periods is considered as illustrated in Fig. 1(c), and the structure is assumed to be uniform in the y-direction, similar to the 1.5D case. Absorbing boundary conditions are implemented in the x-direction. A 2D simulation can be employed to estimate the loss in the x-direction.Figure 1(d) shows a structure used for 2.5-dimensional (2.5D) simulations, in which only a single grating period is considered, similar to the 1.5D structure. However, the structure is not uniform in the y-direction any more, and absorbing boundary conditions are employed in this direction.

The Q-factor of the 3D cavity, Q, can be approximately determined by:

$$\frac{1}{Q} = \frac{1}{Q_x} + \frac{1}{Q_y} + \frac{1}{Q_z}, \tag{1}$$

where Q_i with $i = x, y, z$ are the Q-factors corresponding to the each direction. For a HCG-based cavity, Q_z, Q_x and Q_y can be estimated by performing 1.5D, 2D and 2.5D simulations of the structure, respectively.

IV. SIMULATION RESULTS

In order to prove the accuracy of low-dimensional simulations in optical modeling the HCG-based VCL, we perform 1.5D, 2D, 2.5D and 3D simulations of the test structure. Table II shows the simulation results. A 2D and a 1.5D simulation of the structure are performed to estimate Q_{2D} and Q_z, respectively. Based on these two Q-factor, Q_x can be determined: $1/Q_{2D}$=$1/Q_z + 1/Q_x$. Similarly, a 2.5D simulation estimates $Q_{2.5D}$, which determines Q_y by using the relation, $1/Q_{2.5D}$=$1/Q_z + 1/Q_y$. Finally, by inserting the obtained Q_x, Q_y, and Q_z values into Eq. (1), the total Q-factor can be estimated. As shown in Table II, the Q value obtained from low-dimensional simulations agrees pretty well with the Q_{3D} value that is directly determined from a 3D simulation. The relative difference between these two Q-factors is less than 1%. It should be mentioned that the resonance wavelength of the 3D cavity can also be approximately estimated using the method explained in Ref. [8]. The calculation times on a workstation with the Intel Xeon processor with 4 cores (CPU model E5-1620) and 64 GB memory were less than 1 second, 20 seconds, 5 minutes, and 10 hours for the 1.5D, 2D, 2.5D and 3D simulations, respectively. The time required for performing all 1.5D, 2D and 2.5D simulations is approximately two orders of magnitude shorter than that for a single 3D simulation.

V. CONCLUSION

The HCG-based VCL is a potential light source for optical interconnect applications. 3D optical simulation of this laser is challenging due to its large dimensions and small feature size compared to the wavelength. Here, a method for analyzing a 3D cavity by performing consecutive lower-dimensional simulations, has been proposed and tested in our in-house developed simulator. This method can accurately estimate the Q-factor, with much less computational effort, i.e. simulation time and memory, compared to a 3D simulation. This approach can easily be implemented in other numerical techniques such as finite-difference time-domain (FDTD) and finite-element method (FEM).

ACKNOWLEDGMENT

The authors gratefully acknowledge support from the Innovation Fund Denmark through the HOT project (Grant No. 5106-00013B).

REFERENCES

[1] D. A. B. Miller, "Optical interconnects to electronic chips," *Appl. Opt.*, vol. 49, no. 25, pp. F59–F70, 2010.

[2] G. C. Park, W. Xue, A. Taghizadeh, E. Semenova, K. Yvind, J. Mørk, and I. S. Chung, "Hybrid vertical-cavity laser with lateral emission into a silicon waveguide," *Laser Photon. Rev.*, vol. 9, no. 3, pp. L11–L15, 2015.

[3] A. Taghizadeh, G. C. Park, J. Mørk, and I.-S. Chung, "Hybrid grating reflector with high reflectivity and broad bandwidth," *Opt. Express*, vol. 22, no. 18, pp. 21 175–21 184, 2014.

[4] A. Taghizadeh, J. Mørk, and I.-S. Chung, "Ultracompact resonator with high quality-factor based on a hybrid grating structure," *Opt. Express*, vol. 23, no. 11, pp. 14 913–14 921, 2015.

[5] I.-S. Chung and J. Mørk, "Silicon-photonics light source realized by iii–v/si-grating-mirror laser," *Appl. Phys. Lett.*, vol. 97, no. 15, p. 151113, 2010.

[6] M. Moharam, T. Gaylord, E. B. Grann, and D. A. Pommet, "Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings," *J. Opt. Soc. Am. A*, vol. 12, no. 5, pp. 1068–1076, 1995.

[7] A. Taghizadeh, J. Mørk, and I.-S. Chung, "Numerical investigation of vertical cavity lasers with high-contrast gratings using the Fourier modal method," *J. Lightwave Technol.*, vol. 34, no. 18, pp. 4240–4251, 2016.

[8] A. Taghizadeh, J. Mørk, and I. S. Chung, "Vertical-cavity in-plane heterostructures: Physics and applications," *Appl. Phys. Lett.*, vol. 107, no. 18, p. 181107, 2015.