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COMPARISON OF METHODS FOR SIMULATION OF THE OPTICAL PROPERTIES OF VCSELs

This paper presents the differences arising from the use of scalar (Effective Frequency Method) and vector (Fourier's and Bessel's Admittance Methods) calculation methods in optical analysis of arsenide Vertical-Cavity Surface-Emitting Lasers (VCSELs). Discussed results demonstrate that the vector methods are more accurate than the scalar one, but also they are more time consuming. By comparing two vector methods, it can be seen that the Bessel's Admittance Method allows to obtain similar qualitatively and quantitatively results in a slightly shorter time. The calculations were performed for structures with varied aperture radius and its location in the resonant cavity. Moreover, this paper includes the comparison of calculation results for a structure in which there are layers with gradually changing refractive index, and the structure in which these layers are replaced by a layer with a constant average refractive index.

1. INTRODUCTION

Today, semiconductor lasers are used in many different areas of everyday life. An important class of such lasers consists of Vertical-Cavity Surface-Emitting Lasers (VCSELs), which have very good beam parameters and provide low cost of mass production. Because of their advantages, these lasers are becoming more and more popular among physicists, technologists and entrepreneurs. As a result, there is a demand for their accurate modelling in order to design the new generations of VCSELs [6]. The simulation methods include

optical, electrical and thermal models, which all together can give almost full view on the VCSEL's properties. Optical models are expected to determine several points, such as modal losses and gain, wavelength of emitted radiation or intensity profile [4]. At the same time, this modelling process should be performed within computational resources and time. Hence, the choice of the most appropriate computational method becomes an important issue [7].

In this paper we present three of such computational methods: the scalar Effective Frequency Method (EFM) [1], the vector Fourier's Admittance Method [2], and the vector Bessel's Admittance Method [3]. We compare these methods by presenting the dependence of the wavelength and the photon lifetime on the size of the VCSEL oxide aperture. We also show the average time of calculation of each method, to investigate the applicability of each of these methods for VCSEL analysis. As both the accuracy and the numerical effort of the vector methods depend on the size of expansion basis, we also analyze the convergence of these methods for increasing basis size.

2. COMPUTATIONAL METHODS

In the first step of our analysis we compare the computational methods. These methods are: the Effective Frequency Method (EFM), which is an example of a scalar model, and two vector admittance methods: Bessel and Fourier. Below, the main assumptions and the main differences between them are shown.

2.1. Effective Frequency Method

The Effective Frequency Method [1][5] is one of the scalar computational methods. It is assumed that the optical field is linearly polarized in the fixed direction throughout the analyzed structure and that in a VCSEL laser it can be divided into factors, each of which depends on one variable:

$$E(r,z,\varphi) = E_{r,z}(r,z)E_r(r)\exp(iL\varphi) \qquad (1)$$

where $L = 0, 1, 2, \ldots$ is azimuthal modal number and $E_{r,z}(r,z)$ just slowly changes along the coordinate $r\left(\partial E_{r,z}/\partial r \approx 0\right)$. This makes it possible to find each of the factors in Eq. (1) independently. In particular, in a VCSEL laser - which can be treated as a set of constant layers (perpendicular to the z axis (Fig. 1)), each of which is a collection of homogeneous cylinders - solutions in each such homogeneous region can be found analytically and then matched at borders using the continuity of the electric field and its derivative.

2.2. Fourier's Admittance Method

The Fourier's Admittance Method [2] is an example of a vector method. In this method, the electric field is expanded as a series of exponential plane-wave functions:

$$E(x, y, z) = \sum_{n=-\infty}^{\infty} c_n(z) \exp\left(ig_x x + ig_y y\right) \tag{2}$$

where g_n are successive reciprocal-lattice vectors of periodically repeated computational area. The above expansion is exact for the infinite number of components. However, in reality we are limited to using a finite number of functions. The actual number of considered series elements - hereafter referred to as N - should be chosen with consideration of the required accuracy of the calculations and the computation time constrains.

In the admittance method, expansion (2) is performed only laterally. In the vertical direction, the structure is divided into uniform layers. In each of layer a separate solution is obtained and then the results are combined at the layer boundaries using an admittance transfer algorithm [2].

2.3. Bessel's Admittance Method

Bessel's Admittance Method [3] is similar to the Fourier model. The difference is that instead of the expansion in the plane wave basis (Eq. (2)), the field is expanded into a Fourier-Bessel series of cylindrical waves:

$$E(r, \varphi, z) = \exp(iL\varphi) \sum_{n=1}^{\infty} c_n(z) J_L\left(\alpha_n r\right) \tag{3}$$

where J_L is the Bessel function of the first kind and its order L corresponds to the azimuthal mode in the EFM method. The parameter α_n is the n-th zero of the function J_L.

3. COMPARATIVE ANALYSIS OF METHODS

Our simulations were performed using the three computational methods described in section 2. We compared these methods by computing the dependence of the wavelength and the photon lifetime on the size of oxide aperture a.

3.1. Tested structure

The structure analyzed in this paper is a regular VCSEL structure. It consists of arsenide materials epitaxially grown on the gallium arsenide (GaAs) substrate. The active region is composed of three GaAs quantum wells separated by $Al_{0.3}Ga_{0.7}As$ barriers. The 1½-wavelength resonant cavity is surrounded by Bragg's quarter-wave mirrors (Distributed Bragg Reflectors (DBR)) made of $Al_{0.2}Ga_{0.8}As$ / $Al_{0.9}Ga_{0.1}As$. On the bottom there are 33 pairs of DBRs and on the top there are 25 pairs. In one of the simulated structures, there is a smooth transition between the layers made of $Al_{0.2}Ga_{0.8}As$ and $Al_{0.9}Ga_{0.1}As$. In this case the Al content changes gradually from 0.2 to 0.9. In the second structure, the transition layer is approximated by a single solid $Al_{0.55}Ga_{0.45}As$ material. This approximation allows to considerably simplify the calculations.

The schematic diagram of the structure described above is shown in Fig. 1. The symbols used in the figure are consistent with the rest of this paper, and are as follows: a – diameter of electrical aperture, x – aperture position along the active area, where $x = 1$ means the position in the standing wave antinode, and $x = 0$ indicates the position in the node.
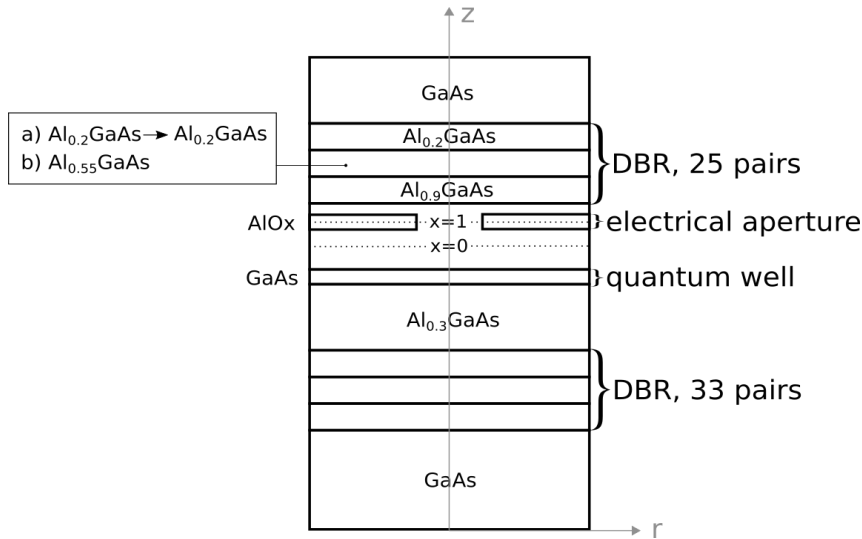

Fig. 1. Schematic diagram of the analyzed structure; the material compositions are shown for the first (a) and the second (b) analyzed structure; x is the position of the oxidation layer ($x = 0$ – standing wave node, $x = 1$ – standing wave antinode)

3.2. The comparison of methods

In the basic structure there is an intentional smooth molar composition transition between the DBR layers. As the first step of our analysis, we checked how replacing this smooth transition by one intermediate layer impacts the optical calculations result. For this purpose, we computed the dependence of resonant wavelength and photon lifetime on the aperture diameter for both the exact and approximated structures, using the EFM scalar method. As seen in Fig. 2, this approximation causes a slight change in the resonant wavelength for the fundamental mode, however the photon lifetime is systematically shifted by approximately 30%. This is due to the fact that the smooth layer transition, as in the structure (a), results in the lower DBRs reflectivity than in the structure (b). Fortunately, the photon lifetime difference between both structures remains constant and, hence, the results obtained for the approximate structure can be easily adjusted by scaling by a constant factor.

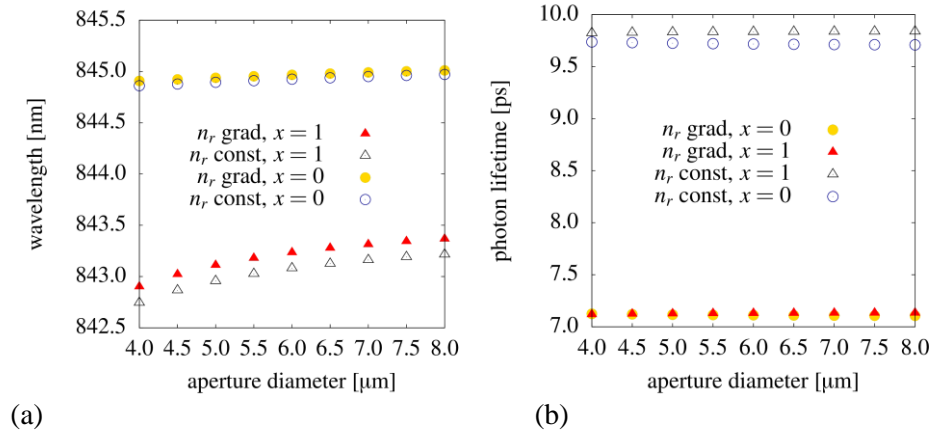(a)   (b)

Fig. 2. The resonant wavelength (a) and the photon lifetime (b) as a function of the aperture diameter in the structures with constant (const) and gradually changing (grad) refractive index, n_r

Because of the above findings, further calculations were made for this second structure. We have compared the resonant wavelength and the photon lifetime on the aperture diameter obtained with different computational methods (Fig. 3). It can be seen that the scalar method differs greatly from the vector methods: the difference in the wavelengths obtained is around 2 nm. For comparison, the wavelength difference for the Bessel and Fourier methods is of the order of

hundredths of nm (Fig. 3a). A similar relationship can be observed for the photon lifetime. The difference between both vector methods is approximately 0.1 ps, while the values obtained by the EFM method deviate by about 1.0 ps (Fig. 3b). This is due to the approximation used in the scalar method (Eq. 1), which causes a systematic error to occur.
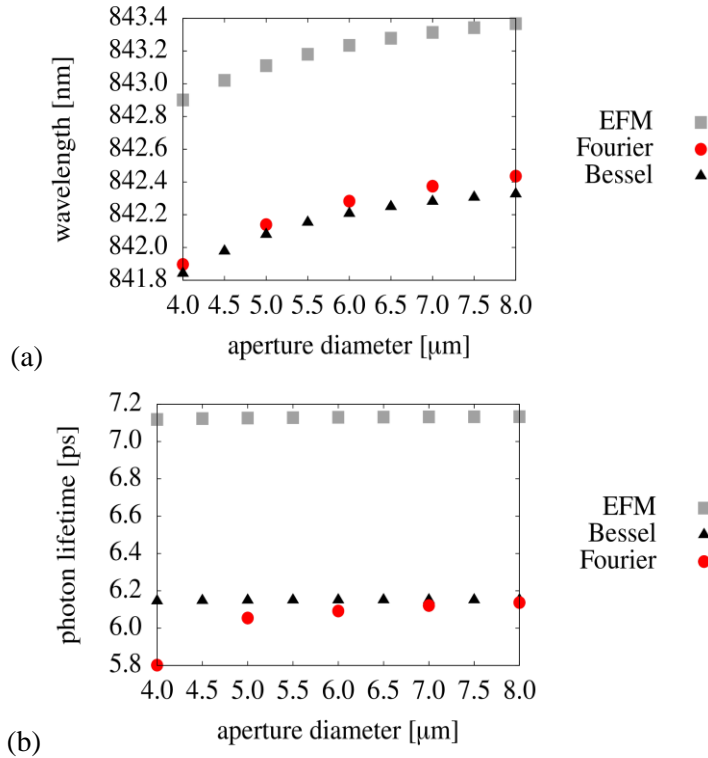

(a)

(b)

Fig. 3. The resonant wavelength (a) and the photon lifetime (b) as a function of the aperture diameter with $x = 1$

3.3. Convergence of the vector methods

Vector methods require the declaration of the N number of coefficients that will be used for a truncated Fourier of Fourier-Bessel series expansion. We investigated the influence of this parameter on the accuracy of our results. In the case of the Fourier model (Fig. 4), a shift in values can be observed, both in the wavelength and in photon lifetime. From $N = 20$ a stabilization can be seen. For the Bessel method (Fig. 5a), there is a 0.2 nm shift in the computed

wavelengths for $N < 10$. In the same compartment, a difference of 0.015 ps can be observed in the photon lifetime Fig. 5b). These shifts decrease in the range of $10 < N < 15$, while the stabilization is reached for $N \geq 15$.
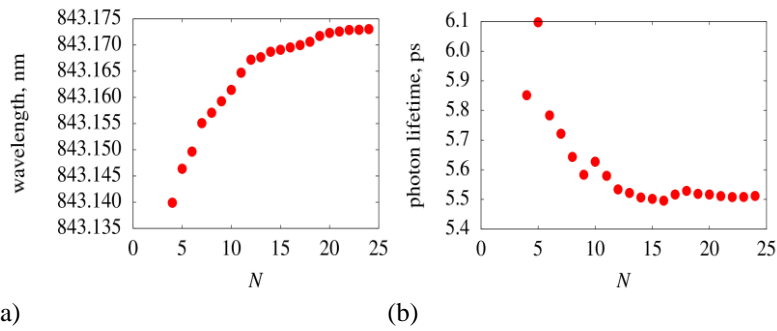

(a)   (b)

Fig. 4. The wavelength (a) and the lifetime of a photon (b) as a function of waves quantity with $x = 0.5$, $a = 4$ μm, Fourier method.

(a)   (b)
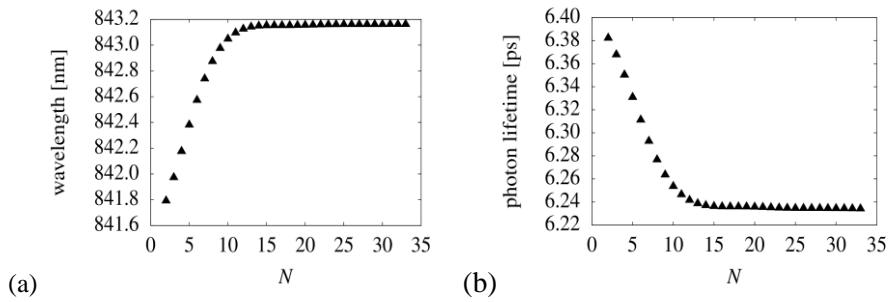
Fig. 5. The wavelength (a) and the lifetime of a photon (b) as a function of waves quantity with $x = 0.5$, $a = 4$ μm, Bessel method
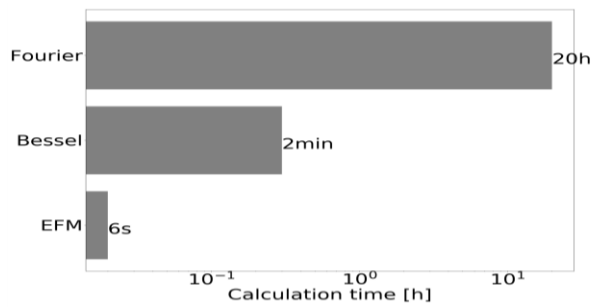

Fig. 6. The average calculation time for calculation methods

4. SUMMARY

This paper presents the results of a computer simulation for a VCSEL arsenide laser. The analysis consists of three parts. The first is dedicated to comparison of a structure in which there are layers with gradual refractive index change and for a structure in which these layers have been replaced by a solid material with a constant refractive index. The wavelength difference between these two structures is of the order of one tenth of a nanometer, while the calculation time for the structure with the gradual refractive index is several times longer than for the single-layer structure. For this reason, the calculations used to compare the models, which is the second objective of the paper, were performed for the second case.

Our calculations have shown that the scalar method differs greatly from vector methods. The difference in the resonant wavelengths between these models is much greater than the difference between the results obtained by both vector methods. A similar dependence can be observed in the case of differences in photon lifetime. The difference between the results obtained by the vector methods is much lower than the difference between them and the scalar EFM method. This is due to the approximation used in the EFM method. If it comes to the comparison of two vector methods, it can be seen that the Bessel's Admittance Method allows to obtain similar qualitatively and quantitatively results in a slightly shorter time. The average time of calculations for Fourier Method is 20 hours while the average time of calculations for Bessel model is 2 minutes.

The above analysis has shown that vector methods are more accurate than the scalar one. However, the accuracy of the latter ones depend on the number of considered coefficients. Our results show that their convergence can be assumed for $N \geq 20$ for the Fourier method and for $N \geq 15$ in the Bessel model. Fig. 6 shows the average computation times of the EFM scalar method and vector methods with the values of N as given above. The calculation time for the Fourier method is several times higher than for the other methods. The quickest is the scalar method, at the expense of accuracy.

Based on the analysis, it can be concluded that in the semiconductor structures modelling, it is worth using vector methods that give much more accurate results.

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PORÓWNANIE METOD SYMULACJI WŁAŚCIWOŚCI OPTYCZNYCH LASERÓW VCSEL

Streszczenie

W niniejszej pracy przedstawiono wyniki obliczeń propagacji emitowanej fali elektromagnetycznej (jej długości i czasu życia fotonów) dla arsenkowego lasera typu VCSEL. Celem pracy jest przedstawienie różnic płynących z zastosowania skalarnych i wektorowych metod obliczeniowych. Omówione wyniki pokazują, iż metody wektorowe są dużo dokładniejsze od metody

skalarnej, ale jednocześnie bardziej czasochłonne. Obliczenia przeprowadzono dla struktur różniących się wartością średnicy apertury oraz jej położeniem wzdłuż wnęki rezonansowej. Ponadto metodą skalarną wykonano obliczenia dla struktury, w której występują warstwy o gradientowo zmieniającym się współczynniku załamania, oraz dla struktury, w której warstwy te zastąpiono warstwą pośrednią o stałym współczynniku załamania. Celem pracy jest również pokazanie różnic w wynikach otrzymanych dla powyższych przypadków.