Modeling Modal Properties of Antiresonant VCSEL with Bessel Expansion Transfer Method

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***Abstract*—We study optical properties of an ARROW-VCSEL, in which the anti-resonant effect is provided by an oxide island manufactured with planar oxidation inside the optical cavity. We implement a novel Bessel Expansion Transfer Method to show how this effect alters the nature of the laser modes by forcing qualitative change in the optical field profiles.**

***Index Terms*—ARROW-VCSEL, resonance, single-mode, oxidation, modal transfer method, Bessel expansion, orthogonality**

I. Introduction

While Vertical-Cavity Surface Emitting Lasers (VCSELs) are nowadays an important class of semiconductor lasers, there are still some significant challenges in their design. One of such challenges is ensuring their operation on a single lateral mode with high power emission. The reason for this is that these goals are contradictory: large powers require large laser aperture, while the single lateral mode operation is most easily achieved by decreasing the aperture size. Hence, there is a need for finding alternative methods of eliminating higher order modes. One of the possibilities is an application of Anti-Resonant Reflecting Optical Waveguides (ARROWs) [1], [2].

In this work we study optical properties of an ARROW-VCSEL, in which the anti-resonant effect is provided by an oxide island located inside the optical cavity and manufactured with a novel planar oxidation technique [3], [4]. By using the Bessel Expansion Transfer Method—which is a variant of our earlier Plane-Wave Admittance Method [5], suited for axisymmetric structures—we show that this oxide island strongly influences all lateral modes. By merely altering its radius (which can be easily controlled through the time of the planar oxidation process), we can put different lateral modes into resonance or anti-resonance states, strongly affecting their optical losses and profiles.

II. Bessel Expansion Transfer Method

The numerical analysis, presented below, has been performed with a novel Bessel Expansion Transfer Method (BETM). The core of this method is based on our Plane-Wave Admittance Method [5] (PWAM), which solves Maxwell equations in multi-layer structures analytically in the z direction, perpendicular to the layers (usually, this is the epitaxial growth direction), and employs the Fourier plane-waves expansion in the two other (lateral) directions. BETM differs from PWAM by application of different expansion in lateral direction. In this case, the Maxwell equations are solved in cylindrical coordinates and Fourier-Bessel expansion is used in the radial direction r. In the angular direction φ, the electric and magnetic fields are assumed to have an analytical solution in the form E_r, E_z, $H_\varphi \propto \cos(m\varphi)$ and E_φ, H_r, $H_z \propto \sin(m\varphi)$, where m is an arbitrary integer, indicating the angular mode number.

Following the approach from Ref. [6], we can expand the electric and magnetic fields in the basis of uniform infinite waveguide solutions [7]:

$$\begin{aligned}
E_r(r,z) &= \sum_k \left[A_m(kr)\,E_s^k(z) + B_m(kr)\,E_p^k(z)\right], \\
E_\varphi(r,z) &= -\sum_k \left[A_m(kr)\,E_p^k(z) + B_m(kr)\,E_s^k(z)\right], \\
H_r(r,z) &= \sum_k \left[A_m(kr)\,H_p^k(z) + B_m(kr)\,H_s^k(z)\right], \\
H_\varphi(r,z) &= \sum_k \left[A_m(kr)\,H_s^k(z) + B_m(kr)\,H_p^k(z)\right],
\end{aligned}$$

where $A_m(kr)/B_m(kr) = J_{m-1}(kr) \pm J_{m+1}(kr)$, J_m is the Bessel function of the first kind and k are zeros of J_m. E_s^k, E_p^k, H_s^k, and H_p^k are unknown z-dependent expansion coefficients of the electric and magnetic field, respectively. Using orthogonality of the Bessel functions, we can use the above expansion to formulate matrix equation relating the z-derivatives of the unknown coefficients and their values:

$$\begin{aligned}
\partial_z\left(E_s^g + E_p^g\right) &= -\frac{i}{k_0}\Bigg\{\Bigg(k_0^2 - \sum_k \frac{k^2}{\eta_m^g}\left\langle J_{m-1}^{(g)}\middle|\varepsilon^{-1}\middle|J_{m-1}^{(k)}\right\rangle \\
&\qquad - \sum_k \frac{k}{\eta_m^g}\left\langle J_{m-1}^{(g)}\middle|\left(\partial_r\varepsilon^{-1}\right)\middle|J_m^{(k)}\right\rangle\Bigg) H_p^k + k_0^2\,H_s^g\Bigg\}, \\
\partial_z\left(E_s^g - E_p^g\right) &= -\frac{i}{k_0}\Bigg\{\Bigg(-k_0^2 + \sum_k \frac{k^2}{\eta_m^g}\left\langle J_{m+1}^{(g)}\middle|\varepsilon^{-1}\middle|J_{m+1}^{(k)}\right\rangle \\
&\qquad - \sum_k \frac{k}{\eta_m^g}\left\langle J_{m+1}^{(g)}\middle|\left(\partial_r\varepsilon^{-1}\right)\middle|J_m^{(k)}\right\rangle\Bigg) H_p^k + k_0^2\,H_s^g\Bigg\}, \\
\partial_z\left(H_p^g + H_s^g\right) &= -\frac{i}{k_0}\Bigg\{\Bigg(\frac{k_0^2}{\eta_m^g}\sum_k \left\langle J_{m-1}^{(g)}\middle|\varepsilon\middle|J_{m-1}^{(k)}\right\rangle - g^2\Bigg) E_s^k \\
&\qquad + \frac{k_0^2}{\eta_m^g}\sum_k \left\langle J_{m-1}^{(g)}\middle|\varepsilon\middle|J_{m-1}^{(k)}\right\rangle E_p^k\Bigg\},
\end{aligned}$$

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$$\partial_z \left(H_p^g - H_s^g\right) = -\frac{i}{k_0}\Bigg\{\Bigg(-\frac{k_0^2}{\eta_m^g}\sum_k \Big\langle J_{m+1}^{(g)}\Big|\varepsilon\Big|J_{m+1}^{(k)}\Big\rangle + g^2\Bigg)E_s^k + \frac{k_0^2}{\eta_m^g}\sum_k \Big\langle J_{m+1}^{(g)}\Big|\varepsilon\Big|J_{m+1}^{(k)}\Big\rangle E_p^k\Bigg\},$$

where $\langle J_m(gr)|\Psi|J_n(kr)\rangle = \int_0^{r_{\max}} J_m(gr)\,\Psi\,J_n(kr)\,r\,dr$. Having the above expansion, the numerical procedure is to find eigenmodes in each later and to match them using the admittance transfer technique, as described in [5]. As a result we obtain the complex resonant frequency and optical fields distribution.

III. Shaping ARROW-VCSEL modal profiles with oxidized island of the emitted radiation

We numerically analyze an impact of an oxide island on VCSEL modes for a laser designed for 850 nm wavelength emission. In the resonant cavity there are two oxidation layers: one forming the 10 µm electrical aperture and the other providing the oxidation island with diameter changing in the range between 0 and 6 µm. By investigating the dependence of the oxidation island diameter on the resonant wavelength and photon lifetime, we show that oxide ARROW structure can increase modal discrimination.

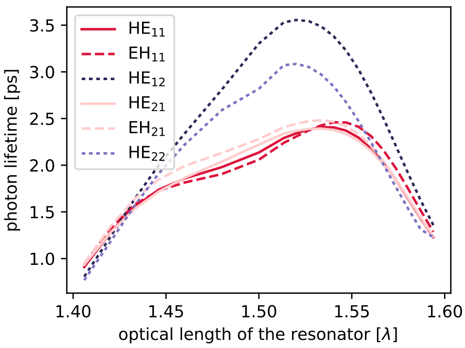

Fig. 1. The dependence of a lifetime of a photon on the length of resonant cavity for different modes, the diameter of the oxidized island 8.30 µm.

The the strength of modal discrimination (Fig. 1) and the impact of the oxide island on the modes (Fig. 2) strongly depend on the cavity length: for $3/2\,\lambda$ cavity, the photon lifetimes show strong oscillatory behavior, especially for the modes HE_{12} and HE_{22}. Photon lifetimes for these modes are the shortest for the oxide island diameter in the range of 2 µm to 6 µm and they start increasing sharply until about 8 µm. Each of them reaches a peak at 8.5 µm: at this point the photon lifetime is 3.33 ps for HE_{12} mode, 2.85 ps for HE_{22} mode, and 2.28 ps for the next closest mode, EH_{21}.

For strongly detuned cavities (below $1.43\,\lambda$ and above $1.57\,\lambda$) the oscillations are strongly suppressed and the overall photon lifetime drops.

The main reason for such behavior is strong resonance and anti-resonance of the VCSEL modes with the oxide island. Using BETM we are able to model these effects and to explain their physical origin [8].

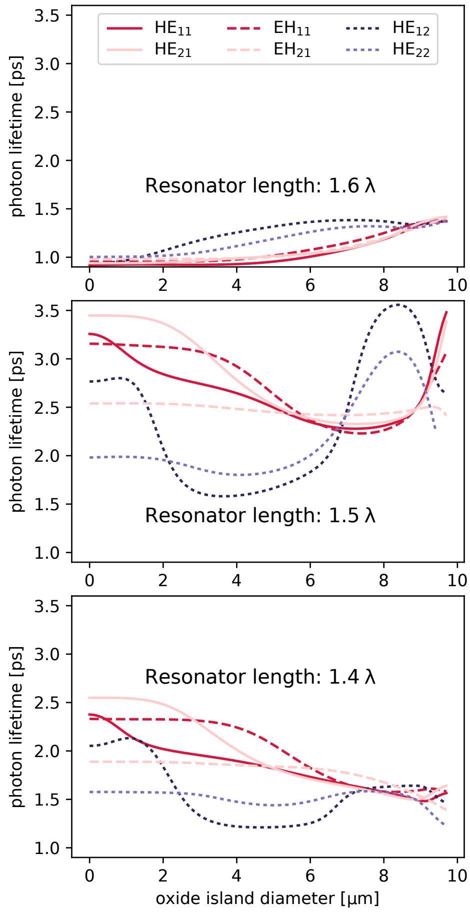

Fig. 2. The dependence of photon lifetime on oxidized island diameter for different modes for different lengths of the cavity. Slight change in the cavity length results in strong qualitative change in the response of the modes to the oxide island.

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