Design considerations for large-aperture single-mode oxide-confined VCSELs

V. P. Kalosha*, N. N. Ledentsov†, and D. Bimberg*
*Institute for Solid State Physics, Technical University Berlin, Hardenbergstr. 36, 10623 Berlin, Germany
†VI Systems GmbH, Hardenbergstr. 7, 10623 Berlin, Germany

***Abstract*—Three-dimensional cold-cavity optical modes of oxide-confined AlGaAs/GaAs VCSELs at 850 nm were simulated taking into account the material dispersion to study dependencies of the lasing modal content upon the thickness of the aperture, its position with respect to the mode standing wave and the separation from the cavity. Positioning the thin aperture layer in the mode nodes to decrease the diffraction at low-index oxidized areas or utilizing the thick aperture and thick low Al-content layers above the aperture to promote the lateral leakage of the transverse higher-order modes allow single-mode laser operation to extend to the aperture diameters as large as 10 μm.**

High-power and single-mode vertical-cavity surface-emitting lasers (VCSELs) are of great importance for a number of applications ranging from multiple Gb/s data transmission to sensor systems, illumination, and displays. There is a perpetual search for approaches allowing the realization of single-mode VCSELs at large-sized apertures, that would result in increased output power and improved far-field profile and spectral width. In oxide-confined VCSELs, which present the most mature VCSEL technology, the higher-order transverse modes can be suppressed by thinning of the Al-rich aperture layers below a quarter-wavelength thickness of the distributed Bragg reflectors (DBRs) and positioning them precisely at the nodes of the longitudinal mode. This prevents mode diffraction by low-index oxide layers and promotes index-guiding only of the preferable single-lobe fundamental mode. For high speed VCSELs, thick oxide apertures are advantageous, since they decrease the parasitic capacitance of the VCSEL mesa and hence increase the frequency response [1]. We address also the design of GaAs/AlGaAs VCSELs at 850 nm, where these two apparently contradictory requirements, large diameter apertures and thick oxide layers, on one side, and the single-mode operation, on the other side, are met simultaneously. Thus a large optical confinement factor, current and temperature robustness of the far-field, simple and reliable fabrication technology, high speed operation and other advantages of selectively oxidized VCSELs can be merged to advantages of single-mode operation up to large aperture sizes [2].

The field $E = E(\boldsymbol{\rho}, z)$ and the complex wavenumber k of linearly polarized (LP) modes in axially-symmetric VCSELs satisfy the scalar wave equation in the frequency domain

$$(\Delta_{\boldsymbol{\rho}} + \Delta_z + k_0^2 n^2)E = \nu n n_g E, \tag{1}$$

which is treated as an eigenvalue-eigenstate problem [3]. Here the material dispersion is taken into account by the refractive and group indices $n(\boldsymbol{\rho}, z)$ and $n_g(\boldsymbol{\rho}, z) = d(kn)/dk$ calculated at some nominal wavenumber k_0; the wavenumber $k = k_0 - \nu/2k_0 = k' + ik''$ defines the mode wavelength $\lambda = 2\pi/k'$ and the photon lifetime $\tau = 1/ck''$; $\boldsymbol{\rho} = (\rho, \varphi)$ is the cylindrical transverse radius-vector component and z is the vertical coordinate.

Within the scalar approach the solutions of Eq. (1) allow to account for the diffraction directly and examine the discrimination and selectivity of the cold-cavity modes quantitatively by their lifetimes and confinement factors (or generation thresholds) taking into account the material dispersion of the VCSEL constituent layers [4]. We have solved the eigenvalue problem Eq. (1) for realistic VCSEL structures by using the parallel numerical algorithms [5].

Oxidation allows precise control of the aperture radius, thickness and shape, when the oxidized layer has adjacent layers with considerably different Al contents [1]. We consider a modification of the layer sequence in standard VCSEL at 850 nm, when the high-Al content aperture layer subject to oxidize is intentionally made thinner than the quarter-wavelength and shifted precisely to the node of the longitudinal mode by changing the thicknesses of a layer pair in the corresponding Bragg period.

To obtain a single transverse-longitudinal mode operation for large-size aperture by weakening the field diffraction at the aperture, we have sequentially modified the first, the second and the third period of the top DBR above the cavity with the active areas [Fig. 1 (a)]. For a given aperture size, a sharp decrease of the number of the confined modes occurs by thinning the aperture and moving it away from the cavity. For a quarter-wavelength thick aperture located in the first Bragg period and $R_{\text{aper}} = 5$ μm, more than 40 modes are confined with consierable confinement factors $\Gamma > 1\%$ for the azimuthal index $m = 0 \dots 7$. At the same time, three LP$_{mn}$ modes are confined with $mn = 01, 11, 21$ when the 30-nm thick aperture is positioned exactly in the mode node in the modified first period, two modes with $mn = 01, 11$ when the aperture is in the second modified period, and only one LP$_{01}$ mode when the aperture is in the third period. Simultaneously, the mode lifetime is also decreased. In the true single-mode regime the mode has a wavelength of 854.7 nm, a confinement factor of 2.3% and a lifetime of 13.2 ps.

The transverse-longitudinal pattern and the transverse output near-field of the single mode confined by the oxide aperture with a large radius of 5 μm are presented in Fig. 1 (b) and (c), respectively. They illustrate the weak diffraction of the mode and field spreading well beyond the aperture for this case of the aperture thickness and location. Correspondingly the mode has a narrow output far-field with as small full width at half-maximum as 3.7° (Fig. 1 (c)).

Single transverse-longitudinal mode operation for large-

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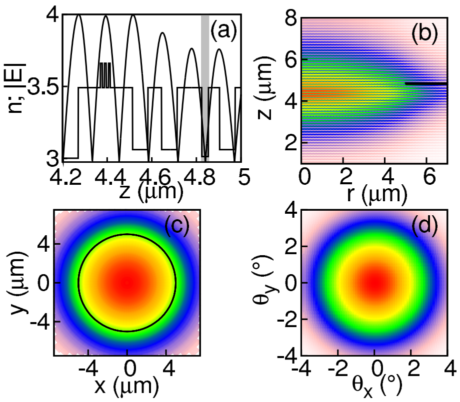

Fig. 1. (a) Refractive index and longitudinal mode profile versus the vertical coordinate in the vicinity of the VCSEL cavity and 30-nm thick oxidized layer (gray area) shifted to the mode node in the third DBR period. (b) Transverse-longitudinal pattern of LP_{01} mode for the aperture radius of 5 μm. (c) Near- and (d) far-field transverse pattern of LP_{01} mode. Aperture edges are shown by black segment (b) and circle (c).

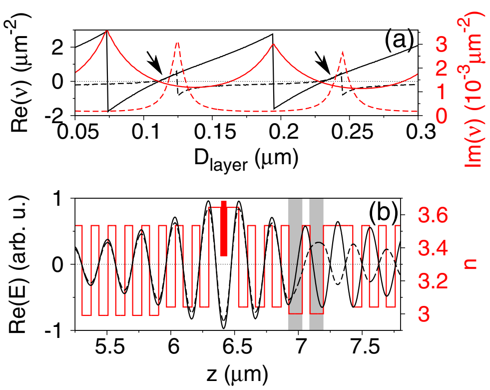

Fig. 2. (a) Dependence of the real (black curves, left scale) and imaginary parts (red curves, right scale) of the effective frequencies of the vertical modes in the aperture (solid) and in the oxidized (dashed) regions versus the thickness of the layer above two 105-nm thick apertures and the quarter-wavelength spacing. Arrows show the regions, where $\nu_{\rm aper}$ and $\nu_{\rm oxide}$ are approximately equal. (b) Refractive index profile (solid red curve) and field profiles of the modes in the aperture (solid black) and in the oxidized regions (dashed black) for $D_{\rm layer} = 230$ nm. Gray areas show the aperture positions and their thicknesses.

size and thick apertures is achieved by modifying the low Al content layer above the thick apertures to thicknesses exceeding $\lambda/4$ to promote in-plane leakage of the high-order modes. The modification provides compensation of the field phase shift at the low-index oxidized layers and adjusts the longitudinal modes at the same wavelength in both in-plane lateral areas inside and outside the aperture. We illustrate the design principles based on the approximate effective frequency method [3], followed by the exact numerical solutions of 3D modes taking into account the field diffraction as well as the material dispersion of all the layers comprising the laser.

According to the effective frequency method [3], the vertical modes $E_{\rm aper}(z)$ and $E_{\rm oxide}(z)$ of the high-speed VCSELs [2] inside and outside the aperture have substantially different effective frequencies ν. Increasing the thickness $D_{\rm aper}$ of the aperture layers and correspondingly increasing the thickness $D_{\rm layer}$ of the low Al content layer above the apertures makes the values of the real and the imaginary parts of the effective frequencies very close (Fig. 2). The ranges of $D_{\rm aper}$ and $D_{\rm layer}$ with small difference $\nu_{\rm aper} - \nu_{\rm oxide}$ (marked by arrows in Fig. 2 (a)) are relatively large and periodic in $D_{\rm layer}$. In these ranges the vertical modes $E_{\rm aper}(z)$ and $E_{\rm oxide}(z)$ are adjusted in shape and phase. Within the aperture layers and the layer above, the phase of $E_{\rm oxide}(z)$ is shifted exactly by π in respect to the phase of $E_{\rm aper}(z)$ and this compensates for the low refractive index of the oxide [Fig. 2 (b)]. For the chosen $D_{\rm aper}$ and $D_{\rm layer}$, the radius-dependent Schrödinger-like equation describing the lateral mode confinement has small 'potential' step $\nu_{\rm aper} - \nu_{\rm oxide}$ and demonstrates an extreme in-plane leakage of the VCSEL modes.

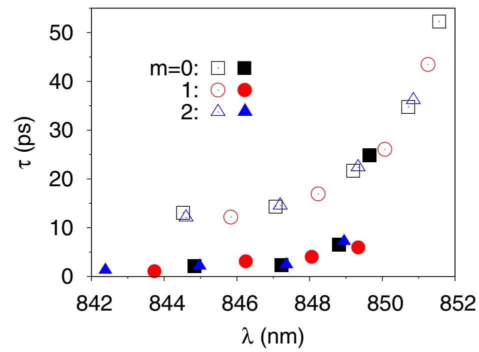

Fig. 3. Lifetime versus wavelength of LP_{mn} modes of the reference VCSEL [2] with two quarter-wavelength apertures (empty symbols) and the VCSEL with the thicknesses $D_{\rm aper} = 105$ nm, $D_{\rm layer} = 230$ nm (filled symbols) for the aperture radius $R = 4$ μm. The mode azimuthal index $m = 0$ (squares), 1 (circles) and 2 (triangles), the radial index $n = 0 \ldots 5$.

The exact solutions of the wave Eq. (1) reveal the confined modes with strong leakage depending on mode number and aperture diameter. For large diameter of two thick apertures the lifetime of the modes versus their wavelength are shown in Fig. 3 by filled symbols. For comparison similar data are presented for the reference laser [2] by empty symbols. The lifetime values for the modified VCSEL are naturally smaller than those for the reference VCSEL due to the in-plane leakage enhancement. For the reference VCSEL the lifetime is gradually decreased with mode number with small relative difference from mode to mode, whereas for the modified VCSEL the lifetime of the LP_{01} mode is several times larger than that of all higher-order modes. The same is true for the confinement factors of the modes for selected aperture diameter. This ensures single fundamental mode emission of the modified VCSEL without the contribution of the multi-lobe higher-order modes also at gain values exceeding the laser threshold.

References

[1] P. Moser, J. A. Lott, P. Wolf, G. Larisch, H. Li, N. N. Ledentsov, and D. Bimberg, Electron. Lett. **48**, 1292 (2012).

[2] P. Westbergh, J. S. Gustavsson, B. Kögel, Å. Haglund, and A. Larsson, IEEE J. Sel. Top. Quantum Electron. **17**, 1603 (2011).

[3] H. Wenzel and H.-J. Wünsche, IEEE J. Quantum Electron. **33**, 1156 (1997).

[4] V. P. Kalosha, N. N. Ledentsov, and D. Bimberg, Appl. Phys. Lett. **101**, 071117 (2012).

[5] V. P. Kalosha, K. Posilovic, and D. Bimberg, IEEE J. Quantum Electron. **48**, 123 (2012).