Modeling of and Experimentation on Vertical Cavity Surface Emitting Laser Arrays

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Abstract—Modal behavior of a 2D (square lattice geometry) antiguided vertical cavity surface emitting laser (VCSEL) array was studied by the 3D bidirectional beam propagation method. Above-threshold operation of leaky modes was simulated using multiple iterations. In addition, a method based on functions of Krylov’s subspace was developed to find the number of array optical modes in a VCSEL array with gain and index distributions established by the oscillating mode. In calculations, both Fourier and space variable descriptions of beam propagation were combined. Analysis of an effective-index approximation is made, and explicit expressions are derived for the effective index and blue shift of the laser frequency. Conditions are found for favorable lasing of the in-phase mode providing high laser beam quality. The 2D antiguided array results from shifting the cavity resonance between the element and interelement regions and is fabricated by selective chemical etching and two-step metalorganic chemical vapor deposition (MOCVD) growth. In-phase and out-of-phase array mode operation is observed from top-emitting rectangular arrays as large as 400 elements, depending on the interelement width, in good agreement with theory. The experimentally realized set of laser arrays of variable size was studied numerically.

1. INTRODUCTION

Coupled vertical cavity surface emitting laser (VCSEL) arrays are an attractive means of increasing the coherent output power of VCSELs. A single-mode VCSEL with output powers greater than 10 mW would be useful as telecommunication transmitters ($\lambda = 1.3–1.55 \mu m$) or sources for optical connections. Commercially available single-mode VCSELs, even at short wavelengths ($\lambda = 0.85 \mu m$), are generally limited to a few mW of output power. The conventional VCSEL structure incorporates a built-in positive-index waveguide designed to support a single-fundamental mode. Promising results in the 3–5 mW range ($\lambda = 0.85 \mu m$) have been obtained from wet-oxidized, positive-index-guided VCSELs [1, 2] with small emission apertures (<3.5 \mu m in diameter). The small aperture size leads to a high electrical resistance and high current density, which can affect device reliability. A larger emitting aperture is essential to reduce thermal rollover and achieve higher output powers with reliable operation. However, poor intermodal discrimination, gain-spatial-hole burning, and thermally induced self-focusing prevent single-mode outputs from larger aperture devices. Furthermore, a relatively large built-in index step is desirable for mode stability in active devices to minimize nonlinear above-threshold effects. Unfortunately, positive-index-guided structures possess an inherent tradeoff between aperture size and index step due to the modal cutoff conditions for single-mode operation.

By contrast, antiguided VCSEL structures have shown promise for achieving larger aperture single-mode operation. To obtain high single-mode powers with a larger emitting aperture, the use of a negative-index guide (antiguide) is beneficial. Antiguides have demonstrated high-power, single-mode operation from edge-emitting lasers [3] and, more recently, have been implemented in VCSELs [4–6]. The coupled-lasing modes of the VCSEL array represent the allowed bands of propagating Bloch waves in the two-dimensional active photonic lattice. Previous VCSEL array designs have attempted to select a single-mode (i.e., all elements are phase-locked) from the allowed bands of guided modes of the 2D photonic lattice. However, stable, high-power, diffraction-limited beam operation from 2D VCSEL arrays has not been realized [7–9]. All previously reported phase-locked 2D VCSEL arrays operate in either the out-of-phase mode or a mixture of various modes characteristic of weakly index-guided arrays with poor intermodal discrimination. To achieve in-phase-like emission characteristics, external phase shifters have also been used on optically pumped VCSEL arrays [10]; however, the resulting beam is quite broad. The progress in phase-locked 2D VCSEL arrays parallels closely that of edge-emitting phase-locked arrays. Weak coupling and poor intermodal discrimination found in evanescently coupled edge-emitting laser arrays have severely limited their single-mode output power due to gain spatial hole burning at the array level [11].
In contrast to positive-index-guided VCSEL arrays, antiguided VCSEL arrays operate in the allowed leaky-mode bands of the 2D photonic lattice. As a result, the antiguided array structure exhibits strong leaky-wave coupling leading to high intermodal discrimination [12]. The large built-in index step and strong lateral radiation leakage from an antiguide make them well suited for array integration. Serkland et al. [13] have recently demonstrated leaky-wave coupling between two antiguided VCSELs (coupled in-phase or out-of-phase) using structures fabricated with a cavity-induced resonance shift. We have recently demonstrated that two-dimensional (4 × 4) 16-element VCSEL arrays can be designed to operate in a stable in-phase mode in good agreement with theory [14, 15]. Since the VCSEL elements are coupled by traveling wave radiation, resonant coupling [14, 15] for the in-phase (out-of-phase) mode occurs when the interelement spacing s corresponds to an odd (even) integral number of half-waves of the antiguide radiation leakage.

Because of the desirable far-field pattern, we would like to design the 2D array to operate in the resonant in-phase mode. Therefore, it is important to understand the mode selection mechanisms in the antiguided structure. There are three primary mechanisms which result in mode selectivity: (1) lateral edge radiation losses, (2) 2D modal overlap with the active layer gain, and (3) modal absorption losses due to placing lossy layers within the structure (typically in the interelement, high-index regions) and/or absorption in a metal (Ti) patterned electrode. In antiguided VCSEL arrays, the 2D modal gain overlap is similar for all supported modes in a uniformly pumped device, so this plays a small role in mode selection. Calculations indicate that the combination of lateral radiation losses, which are highly mode-dependent, and interelement losses result in a design space allowing the resonant in-phase mode to oscillate. This is because losses placed in the interelement regions of the array selectively affect the nonresonant modes, which have relatively large field intensity in the high-index regions of the array.

Numerical simulations can give valuable information for device design. Nowadays, there exist a number of numerical codes for modeling a single VCSEL and VCSEL arrays. The most rigorous finite-difference time-domain (FDTD) method involved a tremendous volume of calculations, which require a lot of time on powerful computers even for simple constructions [16]. It is unrealistic to employ this code for simulations of the antiguided VCSEL arrays. An effective-index approach was suggested in [17] based on an approximate factorization of axial- and transverse-field dependences. An important still missing issue is the exact criteria required to evaluate the accuracy of this method. Here, we derive explicitly the equation of the effective-index model and provide the necessary conditions for its applicability.

It is quite common to model the VCSEL in paraxial approximation by a cavity with the DBR mirrors replaced by hard mirrors separated by an effective cavity length [18]. The effective cavity length is defined [18] as a sum of the distance between the DBR mirrors and diffraction equivalent distances for both mirrors. It was shown in [19] that for paraxial beams the DBR appears as a flat hard mirror located at a distance $L_p$. An expression for this length generalized for an arbitrary number of mirror pairs was derived in [18]. This approach with modeling of the VCSEL with the plane microweak cavity is questionable for the antiguided constructions with additional transversely shaped layers. Here, the 3D diffraction code is described which treats the antiguided VCSEL arrays in scalar approximation and has a productivity that is orders of magnitude higher than the FDTD code.

2. NUMERICAL MODEL

A 3D diffraction numerical code was developed to describe array structures of the type shown in Fig. 1. Assuming the polarization effects can be neglected, the optical field obeys the scalar wave equation

$$\Delta U + \left( k_0^2 n(x, y, z) \right) - ik_0 g) U = 0. \quad (1)$$

Here, $k_0$ is the reference wave number, $n(x, y, z)$ is the refraction index, and $g$ is the gain coefficient, which may be replaced by the absorption coefficient in the loss layers. The VCSEL array is usually composed of transversely uniform layers forming $p$- and $n$-distributed Bragg reflectors (DBR), thin spacer and loss layers located between elements at some distance from the active layer, and an active layer consisting of a few quantum wells (QW) surrounded by spacers. In addition, openings in the metal electrode may pattern the output facet.

The Helmholtz equation was solved using a combination of the bidirectional beam propagation method and the matrix approach for Fourier components within the structure of plane layers [20]. The wave field within blocks of the uniform layers was decomposed into the angular spectrum of plane waves, the propagation of each of which was described with the translation matrix for amplitudes. Thin active and spacer/lossy layers were treated as screens with modulated phase and gain (attenuation). Such a methodology allows us to find optical modes with a high rate not unattainable in other methods. In particular, optical modes were calculated for the active cavity with self-consistent gain and 2D laser-intensity profiles for antiguided arrays of variable size up to $20 \times 20$.

The 2D Fourier transform of the wave field is defined by

$$\psi_{nm}(z) = F \{ U(x, y, z) \}, \quad (2)$$

where $n$ and $m$ are numbers of harmonics and $F$ is the discrete Fourier transformation operator over trans-
verse variables. The FFT algorithm was used to evaluate the Fourier transform and its inversion \( F^{-1} \). For a plane layer of the VCSEL array structure, the wave equation in the \( j \)th layer can be expressed in the form

\[
\frac{d^2 \psi_{nm}}{dz^2} + \kappa_n^2 \nu_m^2 \psi_{nm} = 0, \tag{3}
\]

where \( \kappa_n \) and \( \nu_m \) are the transverse wave vectors. Omitting indices \( n \) and \( m \), the general solution of the last equation has the form

\[
\psi(z) = A_j e^{iq_jz} + B_j e^{-iq_jz}, \quad \text{Re}(q_j) \geq 0. \tag{4}
\]

The coefficients \( A_j \) and \( B_j \) are coupled by the translation matrix:

\[
T_{j+1} = \frac{1}{2q_{j+1}} \begin{pmatrix}
(q_{j+1} + q_j)e^{-i(q_{j+1} - q_j)\zeta_{j+1}} & (q_{j+1} - q_j)e^{-i(q_{j+1} + q_j)\zeta_{j+1}} \\
(q_{j+1} - q_j)e^{i(q_{j+1} + q_j)\zeta_{j+1}} & (q_{j+1} + q_j)e^{i(q_{j+1} - q_j)\zeta_{j+1}}
\end{pmatrix}.
\]

Multiplying the translation matrices for the neighboring layers, \( T \) matrices for the top DBR and bottom DBR can be found:

\[
T^t = T^t_{l-1} \cdots T^t_1 = \begin{pmatrix}
t^t_{11} & t^t_{12} \\
t^t_{21} & t^t_{22}
\end{pmatrix}, \tag{6}
\]

\[
T^b = T^b_{m+1} \cdots T^b_1 = \begin{pmatrix}
t^b_{11} & t^b_{12} \\
t^b_{21} & t^b_{22}
\end{pmatrix} \quad \tag{7}
\]

where \((l + 1)\) is the number of quarter wavelength layers above the spacer/lossy layer and \((m + 1)\) is the number of layers below the spacer/lossy layer. Note that the boundary between the last top DBR layer and the metal or air outside the device is not included in the \( T^t \) matrix.

The round-trip operator was built up in order to compute oscillating modes and their losses. Starting with the upward wave \( U_0 \) on the spacer/lossy layer boundary (signs “±” denote the upward and downward directions, respectively), the Fourier transform of this field \( A_0 = F(U_0^t) \) was calculated. The wave \( B_0 \), reflected from the top Bragg mirror and incident to the spacer/lossy layer is to be found from the system of equations

\[
t^t_{11} A_0 + t^t_{12} B_0 = A_t, \quad t^t_{21} A_0 + t^t_{22} B_0 = B_t,
\]

\[
U^+_t = F^{-1} \{ A_t \exp(iq_{j+1}) \}, \quad U^-_t = F^{-1} \{ B_t \exp(-iq_{j+1}) \},
\]

where \( \zeta_{j+1} \) is the number of layers below the spacer/lossy layer. Note that the boundary between the last top DBR layer and the metal or air outside the device is not included in the \( T^t \) matrix.

\[
U^+_t = \left( \frac{n_0 - 1}{n_0 + 1} F(x, y) + \frac{n_0 - n_{T_1}}{n_0 + n_{T_1}} (1 - F(x, y)) \right) U^+_t,
\]
which can be solved using an iterative procedure. Here, \( n_0 \) is the index of the layer adjoining the metal contact and \( n_T \) is the complex index of the metal (Ti). The form factor \( F(x, y) = 1 \) at the semiconductor–air boundary and is equal to 0 at the semiconductor–Ti contact.

To describe wave-field transmittance through the spacer/lossy layer, reverse FFT is performed \( U_0 = F^{-1}(B_0) \). Then, the wave field transmitting through the phase screen is expressed as \( V_0 = U_0 \exp(-d(x, y) + i\phi(x, y)) \). Here, \( \phi(x, y) \) is the phase shift and \( d(x, y) \) is the attenuation.

The propagation of downward and upward waves through the active layer is described by approximating it with a phase screen where both the wave amplitude and phase difference are functions of space variables \( x \) and \( y \) calculated from the 2D carrier diffusion equation [21]:

\[
\frac{\partial^2 Y}{\partial x^2} + \frac{\partial^2 Y}{\partial y^2} - \frac{Y}{D\tau_{nr}} - \frac{B N_u Y^2}{D} \left( |E_i|^2 + |E_o|^2 \right) g \nabla_n D \tau_{sr} = \frac{-J}{q D d N_u}.
\] (9)

The following notations were introduced:

\[
N_u = \left( \sqrt{1 + 4B\tau_{nr}\Gamma_u}qd - 1 \right)/2B\tau_{nr},
\]

\[
Y = N/N_u, \quad n = \bar{n}_o - \frac{R}{2k}g, \quad k = \frac{2\pi}{\lambda},
\]

\[
|E_i|^2 + |E_o|^2 = \frac{I}{I_s}, \quad I_s = \frac{hc}{\lambda g N_u D \tau_{sr}}.
\]

Here, \( E_i \) is the complex amplitude for upward or downward propagating wave field, \( N_u \) is the carrier density for conditions of active layer transparency, \( D \) is the diffusion coefficient, \( \tau_{nr} \) is the nonradiative recombination time, \( B \) is the spontaneous emission coefficient, \( \Gamma \) is the drive current density, \( g \) is the electron charge, \( d \) is the active layer thickness, \( \bar{n}_o \) is the drive current density at transparency conditions, \( I_s \) is the saturation intensity, and \( R \) is the line enhancement factor. The last term in the left-hand side of Eq. (9) describes stimulated emission. The gain coefficient as a function of the carrier density \( N \) was approximated by a simple logarithmic approximation. The drive current was assumed to be uniformly distributed over the region restricted by \( H^+ \) ion implantation (see Fig. 1).

Reflection from the bottom Bragg mirror is also computed using multiplication of corresponding translation matrices. To complete the round-trip operator \( P \), it is necessary to calculate transmission through the active layer and phase screen in the opposite direction.

The eigenfunctions of the operator \( P \) for a passive device are the optical modes, and the corresponding eigenvalues \( \gamma \) determine the losses \( \delta = 1 - |\gamma|^2 \). In the active device, an iterative procedure is employed up to convergence to the solution; then, \( |\gamma| = 1 \). Our program package provides an opportunity to calculate higher order optical modes in the VCSEL array with gain and index distributions within an active layer established by the oscillating mode. A number of higher order modes can be computed using Krylov’s subspace methods for solving eigenproblems. We choose the Arnoldi algorithm [22] because of its simplicity and robustness.

3. ANALYTICAL THEORY

The numerical model formulated allows us to make comprehensive studies on realistic constructions and search for the optimum parameters of a device. However, to get deeper insight into correlations between the parameters of devices and their output characteristics, it is highly desirable to have a simplified model allowing for fast evaluations of trends in variations of optical-mode patterns and their losses and competition. Our analysis closely follows the algorithm of the numerical model. Consequently, the round-trip operator includes reflection from the top Bragg mirror, transmission through the phase screen, transmission through the active layer, reflection from the bottom Bragg mirror, and transmission through the active layer and phase screen in the opposite direction. By setting the traditional requirement of wave-field reproduction after the round-trip, the eigenvalues and optical modes are defined.

Following the numerical procedure, the propagation of waves in plane layers is described using decomposition of the wave field to plane waves with transverse wave vector \( k_\perp \), which is found from the vacuum wave vector \( k = \omega/c \) and local values of longitudinal components of the wave vector. An expression for a complex reflection coefficient for paraxial waves reflected from a Bragg mirror composed of \( N \) mirror pairs is derived in [19]. In the following, we consider the small index difference limit and keep only leading terms in \( \delta n \), where \( \delta n = n_1 - n_2 \) is the index step, \( n = \sqrt{n_1 n_2} \), and \( n_{1,2} \) are the refractive indices of two quarter-wave layers. In this limit, the expression for the reflection coefficient from [19] can be simplified:

\[
R_N = \frac{\tanh N \Psi}{1 - i\pi n \delta n \left( k_\perp^2 - \frac{k_\perp^2}{2k^2 n^2} \right) \tanh N \Psi},
\] (10)

where

\[
\Psi = \left( \frac{\delta n}{n} \right) \left( 1 + \frac{k_\perp^2}{k^2 n^2} \right) - \frac{\pi^2 n \left( \delta k \right)^2}{2 \delta m k}
\]

and \( \delta k \) characterizes frequency detuning from the resonance \( k \). For simplicity, the refractive index of the layer adjacent to the mirror was taken equal to \( n_2 \). For the
plane wave in resonance (\(\delta k = 0, k_\perp = 0\)), the reflection coefficient grows with \(N\) asymptotically approaching unity. The denominator defines the complex phase of \(R_N\). For paraxial beams, higher order transverse terms should be neglected.

Generally, the Bragg mirror is embedded into a material with different refractive indices on the sides. Let us denote the refractive indices for incoming and outgoing layers as \(n_i\) and \(n_e\), respectively. The simplified expression for this general case is still rather cumbersome. Therefore, we restrict our consideration to the limit of high-reflecting Bragg mirrors practically realiz-able in VCSEL devices:

\[
R_N = 1 - \frac{2t_N n_e}{n_i} + i\pi \frac{n_i n_e}{\delta n n_i} \left( \frac{\delta k}{k} - \frac{k_\perp^2}{2k^2 n_i^2} \right). \tag{11}
\]

Here, \(t_N = \exp(-2N\delta n/n)\).

To illustrate our approach in analyzing the VCSEL device, a simplified version of the construction is considered, which consists of top and bottom Bragg mirrors and a \(\Lambda\) cavity between them. The refractive index in the \(\Lambda\) cavity with optical length \(\lambda\) was taken equal to \(n_2\), and the refraction index at the output of the top mirror, \(n_e\). The diffraction equivalent distance for the top mirror in this approximation is \(L_D = \lambda/4\delta n\). The active layer in the center of the \(\Lambda\) cavity was modeled by the phase screen with phase advance \(\Phi(r)\), where \(r\) is the in-plane coordinate. For simplicity, the number of pairs in the bottom mirror was taken to be infinite. Provided the phase advance is small, every term in the round-trip operator can be thought of as the identity operator (unity in space variables) with an additional small-magnitude operator. For example, in the coordinate representation, the reflection coefficient \(R_N\) has the form

\[
R_N = 1 - \frac{2t_N n_e}{n_i} + i\pi \frac{n_i n_e}{\delta n n_i} \left( \frac{\delta k}{k} - \frac{\Delta_\perp}{2k^2 n_i^2} \right), \tag{12}
\]

where \(\Delta_\perp\) is the transverse Laplacian. Thus, the round-trip operator is reduced to the identity operator plus first-order terms accounting for the diffraction of waves while propagating in mirrors, the \(\Lambda\) cavity, and transmittance through the phase screen. The resulting equation has the form

\[
\frac{1}{2k^2 n_i^2} \Delta_\perp u(r) + \left( \frac{\Phi(r)}{kn_i L_c} + \frac{\delta k}{k} \right) u(r) = 0, \tag{13}
\]

where the effective cavity length \(L_c\) for this simplest construction can be expressed as \(L_c = \left(2 + \frac{n_i n_e}{\delta n} \frac{\lambda}{2n_i}\right)/\delta n\). The imaginary term in Eq. (13) is responsible for losses through the top Bragg mirror for the plane wave. The term \(\delta k/k\) plays the role of an eigenvalue whose imaginary part describes total mode losses. By incorporating the transmittance loss into the eigenvalue, we obtain the following equation:

\[
\frac{1}{2k^2 n_i^2} \Delta_\perp u(r) + \left( \frac{\Phi(r)}{kn_i L_c} + \tilde{\vartheta} \right) u(r) = 0, \tag{14}
\]

where \(\tilde{\vartheta} = \frac{\delta k}{k} + \frac{i t_M n_e n_i}{kn_i L_c}\). Equation (14) exactly corresponds to the effective-index approximation suggested by Hadley [17], with the effective index explicitly expressed through the complex phase advance in the screen in the active layer proportional to the gain and phase difference, which can vary in the plane in the self-consistent manner with the wave-field amplitude. Thus, we can conclude that the effective-index method holds valid in the paraxial approximation for low-contrast Bragg mirrors.

A simple example of possible phase modulation could be the function \(\Phi(r) = -r^2/r_0^2\), corresponding to a thin focusing lens in the active layer. Such a lens can effectively describe thermal focusing in the VCSEL. The resulting equation has a well-known spectrum of Hermite (Laguerre)–Gaussian modes vanishing at infinity. The fundamental solution is the Gaussian beam exp\((–r^2/r_0^2)\). From the solution, one can find the blue shift \(\delta k = 2(n_r r_0^2)^{1/2}(2kn_i L_c)^{-1/2}\) and the beam width \(r_1 = (2r_0^2/L_c kn_i)^{1/4}\).

In practical antiguide devices [15, 16], thin spacer layers shifting the cavity resonance are placed behind a couple of \(p\)-mirror pairs. This means that, for such a construction, the round-trip operator should additionally include propagation in the Bragg mirror layers separating the spacer layers from the \(\Lambda\) cavity. Performing the respective analytical calculations, the resulting differential equation has the form

\[
\frac{\Delta_\perp u(r)}{2k^2 n_i^2} + \left( \frac{\Phi(r)}{kn_i L_c} + \frac{\delta k}{k} \right) u(r) = 0, \tag{15}
\]

where \(t_M = \exp(-2M\delta n/n)\) and \(M\) is the number of mirror pairs between the \(\Lambda\) cavity and spacer layer. The latter is modeled by a phase screen with phase shift \(\varphi(r)\). For a binary function \(\varphi(r)\) with values 0 and \(\varphi\), the effective index step is

\[
\frac{\delta n_{\text{eff}}}{n_i} = \frac{t_M \varphi}{kn_i L_c}. \tag{16}
\]

The value of the effective index step calculated by this simple formula agrees within an accuracy of 10% with that found from Hadley’s relation and the resonance shift calculated by the 1D transfer matrix method.
4. EXPERIMENTAL DEVICES AND RESULTS

Top-emitting large-area antiguided VCSEL array structures are fabricated using a selective etching process and a two-step metal-organic chemical vapor deposition (MOCVD) growth. The first growth includes 32 pairs of AlAs/GaAs n-DBR, a λ cavity consisting of 3 InGaAs quantum wells, 4 GaAs barrier layers and 2 Al<sub>0.3 Ga</sub><sub>0.70</sub>As confinement layers for 980-nm emission, 4 pairs of AlAs/GaAs p-DBR, an InGaP spacer layer, and an absorbing QW GaAs/InGaAs/GaAs loss layer. Then, the InGaP spacer layer and loss QW GaAs/InGaAs/GaAs layer are etched selectively to define the element regions (6 μm wide) of the array, generating an effective index step δn<sub>eff</sub> between interelement and element regions. Next, another 20.5 pairs of Al<sub>0.15</sub>Ga<sub>0.85</sub>As/AlAs p-DBR and a quarter λ<sub>p</sub> + GaAs contact layer are deposited during MOCVD regrowth. This is followed by making top and bottom ohmic contacts and by opening the optical window (5-μm wide in the element region). The interelement spacing s is adjusted in the range 1.5–3.5 μm so as to select either in-phase or out-of-phase array modes. Finally, we use H<sup>+</sup> ion implantation to define the electric current aperture. A schematic cross section of the 5 × 5 2D antiguided array structure described above is shown in Fig. 1.

Detailed layer structure in both the array element region and interelement region can be found in Tables 1 and 2.

<table>
<thead>
<tr>
<th>#</th>
<th>Material</th>
<th>n</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap layer</td>
<td>GaAs</td>
<td>3.512</td>
<td>t&lt;sub&gt;cap&lt;/sub&gt; = 0.07</td>
</tr>
<tr>
<td>p-DBR</td>
<td>20.5 pairs Al0.15GaAs</td>
<td>3.442</td>
<td>0.071</td>
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<tr>
<td></td>
<td>AlAs</td>
<td>3.007</td>
<td>0.081</td>
</tr>
<tr>
<td>λ/2 buffer</td>
<td>GaAs</td>
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<td>0.14</td>
</tr>
<tr>
<td>p-DBR</td>
<td>4 pairs GaAs</td>
<td>3.512</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>AlAs</td>
<td>3.007</td>
<td>0.081</td>
</tr>
<tr>
<td>Cavity</td>
<td>Al0.25GaAs</td>
<td>3.366</td>
<td>0.113</td>
</tr>
<tr>
<td></td>
<td>GaAs</td>
<td>3.512</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>In0.18GaAs</td>
<td>3.6</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>GaAs</td>
<td>3.512</td>
<td>0.01</td>
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<tr>
<td></td>
<td>In0.18GaAs</td>
<td>3.6</td>
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<td></td>
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</tr>
<tr>
<td>Substrate</td>
<td>GaAs</td>
<td>120</td>
<td></td>
</tr>
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</table>

Method is to intentionally add an absorbing layer (InGaAs QW) to the interelement regions of the array, as described above. The other is loss originating from the metal contact above the interelement regions. Combination of these two loss mechanisms, if sufficiently large, is expected to effectively suppress nonresonant modes as well as guided modes. Pulsed (100 ns, 1% duty cycle) far-field measurements are performed to study the modal behavior. Despite the various interelement widths, 1.5–3.5 μm, the in-phase mode and out-of-phase mode are found to be dominant in the measurement results. Near diffraction-limited-beam, in-phase mode emission has been found for 5 × 5 (s = 3.5 μm) antiguided arrays. The measured far-field scans under pulsed operation (100 ns, 1% duty cycle) just above the laser threshold are shown in Figs. 2b and 2c. The corresponding calculated far-field pattern is also shown in Fig. 2a for comparison. The measured central beam width is about 1.01°, which is close to the estimated diffraction limit (DL) based on the total aperture size. This indicates that the array is oscillating in a single spatial mode.

In-phase mode and out-of-phase mode operation have also been found in larger arrays (20 × 20) under pulsed conditions. One 20 × 20 antiguided array with an interelement width s = 3.0 μm exhibits an in-phase mode, far-field pattern at near-threshold operation (Fig. 3). The width of the main lobe is about 1.21°, which is approximately 3.78 times the diffraction limit. This indicates that more than one array mode is oscillating. Increasing the amount of loss in the interelement regions allowing only the resonant mode to have the
Table 2. Detailed layer structure in the interelement region of the antiguided VCSEL array shown in Fig. 1

<table>
<thead>
<tr>
<th>#</th>
<th>Material</th>
<th>$n$</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
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lowest threshold gain is expected to improve modal discrimination. Out-of-phase operation in another $20 \times 20$ antiguided array ($s = 3.5$ µm) is also shown and compared with the far-field calculation in Fig. 4. Larger aperture array structures also operate primarily in phase with increasing driving current. Actually, at the given $s$, statistical scatter in the type of the array mode realized was observed for different devices. This indicates a weak discrimination between modes. It was found that some devices maintain a relatively stable far-field pattern with a driving current $>7I_{th}$, indicating that the in-phase mode dominates over a large current range. Nevertheless, broadening of the central lobe at high drive currents indicates the onset of additional (adjacent) array modes.

5. RESULTS OF NUMERICAL SIMULATIONS

To test the numerical code developed, the so-called simplified antiresonant reflecting optical waveguide (s-ARROW) device was simulated. Earlier [16], the s-ARROW VCSEL was simulated numerically by the full-vector FDTD code. A radial waveguide for the s-ARROW structure was created by shifting the cavity resonance toward the red side in the ring surrounding the emitting aperture. A couple of modes were found, and their $Q$ factors in the dependence on the ring width were calculated [16]. Our numerical code predicts the ring width where the resonant mode loss is minimum in reasonable agreement with that found by the FDTD code. It turns out that the effective index evaluated by the simple formula (16) agrees within an accuracy of 10% with the value presented in [16]. Our numerical model provides modal eigenvalues, the magnitude of which defines modal losses. The FDTD method gives the width of the laser cavity resonance line, which is proportional to cavity losses. The proportionality factor includes the effective cavity length, which can be evaluated by the analytical approach described in Section 3. For the specific device [16], satisfactory agreement was found between the results of numerical calculation by our code and the FDTD code with usage of the effective cavity length evaluated by our formulae.
After testing, numerical simulations were performed for the device structure specified in Tables 1 and 2 with various sizes of the array $N_{arr} \times N_{arr}$ ($N_{arr} = 4; 5; 10; 20$) and a variable number $M$ of p-DBR pairs between the Λ cavity and spacer/loss layers. Variation of $M$ leads to changes in the loss in the interelement regions and effective index step value. Both cold-cavity and above-threshold operation were simulated. The

![Image](image.png)
loss layer has a single QW with an absorption of 8000 cm\(^{-1}\) and a thickness of 7 nm.

Our simulations confirmed the experimentally observed phenomenon that array modes exhibit far-field patterns typical for the in-phase or out-of-phase mode mostly. Modes with mixed symmetry have losses of intermediate magnitude and hence cannot be observed near the threshold. The dependence of the eigenvalue magnitude \(|\gamma|\) on the interelement width \(s\) for \(N_{\text{arr}} = 5\) is shown in Fig. 5 for \(M = 1\) and \(2\). According to theory \([2, 12]\), the in-phase mode has a maximum lateral radiation loss at the resonance point. It was found that the resonance values of \(s\) are equal to 2.3 and 2.6 \(\mu\)m for \(M = 1\) and \(2\), respectively. Despite the fact that the lateral radiation loss is lower at a higher index step \((M = 1)\), the interelement absorption results in a greater total loss for \(M = 1\). Moving the loss layer away from the \(\Lambda\) cavity will result in a further reduction of modal discrimination. In the experiment \((M = 4)\), the interelement absorption plays a minor role in comparison with the lateral losses. In this respect, the experimental situation is similar to the numerically studied case \(M = 2\). It should be noted that the iterations used for the computing mode do not always converge to the stable limit. For some \(s\) values, the calculations do not converge at all.

For further analysis, we take the configuration with the spacer/loss layer positioned 1 p-DBR pair away from the \(\Lambda\) cavity to ensure better mode discrimination. The eigenvalue magnitudes were calculated at \(N_{\text{arr}} = 4, 10,\) and 20 (data for \(N_{\text{arr}} = 5\) are also included) for the out-of-phase (Fig. 6a) and in-phase (Fig. 6b) modes. Note that the out-of-phase mode has the lowest losses, which are proportional to \(-\ln|\gamma|\), at \(s\) from 1.8 to 2.2 \(\mu\)m, and the in-phase mode is the first approaching the threshold at \(s\) in the interval 2.4–2.8 \(\mu\)m. Our primary purpose is to find conditions for stable operation of the in-phase mode. Therefore, we concentrate our efforts

![Fig. 4. Out-of-phase-mode far-field pattern of a 20 \times 20 (s = 3.0 \(\mu\)m) antiguided array: (a) Calculated far-field scan; (b) 3D far-field scan (pulsed) at \(I = 195\) mA; and (c) 1D far-field scan.](image)

![Fig. 5. Eigenvalue magnitude for in-phase (+) and out-of-phase (\(\circ\)) modes vs. interelement spacing for the 5 \times 5 array.](image)
on analyzing devices with an interelement width \( s = 2.6 \, \mu m \). It was found in general that the near- and far-field patterns of the array mode suffer small variations with gain growth. Hence the mode patterns calculated for a passive cavity also give a good idea of above-threshold patterns. Figure 7 shows the in-phase mode profiles in the center or near-center element row for laser arrays of variable size. Due to the double symmetry with respect to the two orthogonal spatial axes, it is sufficient to show half of the symmetrical profile along one of the axes. It is seen that the mode has a negligible intensity in the interelement space. The height of the peaks located in the elements has a maximum near the center and smooths down away from the optical axis of the device.

The next step in our studies concerns active devices operating above the threshold. Numerical simulations of laser operation with variable drive current allowed us to find the threshold current density \( J_{th} \), the point where modal gain and loss are equalized, for a set of laser arrays with \( s = 2.6 \, \mu m \). Figure 8 illustrates how the \( J_{th} \) normalized by the transparency current density depends on the array size. As expected, the threshold diminishes with the array size because the transverse radiation losses diminish. The theory developed for the antiguided arrays of edge-emitting lasers [3] predicts a \( 1/N_{arr} \) dependence of the mode losses on the number of elements in the linear array without absorption between elements. In the devices under consideration, there are two factors: absorption between elements (in the metal electrode and in the loss layers) and lateral radiation losses. Interference between these factors results in some deviations from the line in the graph in Fig. 8.

Figure 9 demonstrates how the 2D gain profile in the active layer consisting of 3 InGaAs quantum wells saturates by laser radiation. The formation of gain-depleted regions at locations of the elements is clearly seen. This is a manifestation of the well-known effect of gain spatial-hole burning at the array level. Exactly this effect is the reason for entering into oscillations of higher order modes benefiting from the high gain remaining in the shaded regions. Using our code capabilities to calculate higher order modes accounting for the background spatial gain distribution (like that...
shown in Fig. 9), the eigenvalues were calculated of a couple of higher order modes.

Figure 10 shows the computed dependence of the eigenvalue magnitudes for two higher order modes in the $10 \times 10$ VCSEL array with $s = 2.6 \, \mu m$ on above-threshold drive current. It is seen that one may expect stable, single in-phase mode oscillation up to seven times that of the threshold current. Viewing the patterns of modes entering into oscillation after approaching the critical currents reveals that both of these modes have the field localized in the interelement space. One of these modes has central symmetry, and the other has mixed symmetry—eigen and odd with respect to the orthogonal axes. Both these modes give practically no input to the laser output, being almost completely absorbed in Ti at the electrode surface and in loss layers. It is expected that the modes localized between elements mostly influence laser efficiency. This explains why the far-field pattern of the in-phase mode observed experimentally maintains its symmetry up to pumping high above threshold. Broadening of the far-field central and side lobes can be associated with the thermal lensing effect.

6. CONCLUSIONS

Rectangular ($5 \times 5$ and $20 \times 20$ elements) geometry top-emitting antiguided VCSEL arrays were fabricated using a two-step MOCVD growth process and selective wet chemical etching. Tests of the $5 \times 5$ array with an interelement spacing $s = 3.5 \, \mu m$ demonstrated the achievement of in-phase mode operation under both pulsed and CW conditions. Thermal broadening was observed by comparison of pulsed and cw operation. Larger arrays ($20 \times 20$) exhibit in-phase mode operation at $s = 3 \, \mu m$ and out-of-phase mode operation at $s = 3.5 \, \mu m$. Beam divergence larger than the diffraction limit indicates the presence of higher order modes in the laser array output.

A 3D diffraction numerical code was developed for theoretical description of active antiguided VCSEL arrays. To get better insight into the mechanisms of mode pattern formation, a simplified approach was developed allowing us to derive an effective-index equation with an explicit expression for the effective-index step. The formulae derived satisfactorily agree...
with numerical calculations and may serve as a basis for detailed analytical studies on VCSEL arrays. Results of simulations performed under the experimental conditions demonstrated good agreement in far-field distributions with observations for the $5 \times 5$ and $20 \times 20$ arrays. The numerical model provides a detailed description of the modal structure and above-threshold behavior for pulsed conditions of the experiments (neglecting thermal lensing effects). Calculations indicate that optical-mode patterns are quite insensitive to interelement losses. In contrast, the intermodal discrimination and above-threshold drive current range ensuring stable single-mode operation are strictly controlled by the amount of interelement losses. At a low loss level, an optical mode localized in the interelement regions comes into oscillation.

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**REFERENCES**