Electron-beam-pumped two-dimensional semiconductor laser array with tilted mirror resonator

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The spatial and spectral emission characteristics of a two-dimensional CdS laser array, pumped by a high-energy electron beam, have been experimentally investigated. The near-field emission from each cell or array element is found to arise from a virtual line located behind the cell. The results are consistent with a geometric ray model of a tilted mirror resonator.

Large-area semiconductor laser arrays pumped by electron beams can generate high-power pulses at high conversion efficiency. 1-3 A room-temperature CdS array in the form of a matrix with 625 lasing cells, covering a square of 0.5 cm on its side, has generated 1 green laser intensity of 1.4 MW/cm² when excited by a 250 kV electron beam in 4 ns pulses. It appears that, with some further refinements, an array of several cm² in area with efficiencies in the 10-20% range can be fabricated; energy densities around 0.1 J/cm² would then be possible. 4

The spatial emission characteristics of these laser arrays remain far from diffraction limited, with no coherence among the various cells of the array or, in general, between any two points of a given cell. The emission characteristics of each individual cell have been ignored thus far. 1-3 In the present letter, we report experiments where these characteristics were investigated. It is shown that a residual wedge, 10⁻³-10⁻⁴ rad, in the CdS wafer used to fabricate the laser array in Ref. 1 determines the laser emission characteristics. This wedge can also provide substantial discrimination against higher order modes; in this connection, unstable resonators formed with intentionally tilted mirrors have recently received attention as a method of achieving high-power, single-mode operation in laser diode structures. 5 An important additional result of this letter is the analysis of the optical properties of such wedge-type unstable resonators with a purely geometric ray optics approach.

The laser array used in our experiments consisted of a thin (55 μm) CdS wafer, epoxied to a flat sapphire disk and cut into square cells with a size of 220 μm using a laser technique. 6 The wafer face that is bombarded by the electron beam has a 98% reflectivity multilayer dielectric coating; the epoxied face, with a coating reflectivity of 88%, is used as the laser output side. The threshold and efficiency characteristics of this laser are given in Ref. 1.

Figure 1(a) shows the experimental setup. An f/1.4 projection lens with 35 mm focal length images the front surface of the laser array with a magnification factor of 60 onto the photographic film; a neutral density filter (not shown in the figure), placed after the lens, attenuates the emission by a factor of 10². The near-field laser emission from a group of adjacent cells is shown in Fig. 1(b). As the projection lens is moved closer to the laser, the pattern in each cell first contracts as in Fig. 1(c) and then becomes a line as in Fig. 1(d), going through a maximum width at a lens displacement of 1.0 mm. These virtual line sources are parallel to the interference fringes at 632.8 nm, shown in Fig. 1(e), and used to characterize the value and orientation of the wafer wedge. The far-field emission is also influenced by

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FIG. 1. (a) Experimental arrangement. A lens is used to image the plane of the CdS wafer and record the near-field pattern of the laser. Projections on the image screen from a group of cells of size a = 220 μm for different displacement of the lens: (b) object plane coincident with back surface of the CdS wafer, (c) lens displaced 0.5 mm closer to the laser, (d) lens displaced by 1.0 mm. The interference fringes shown in (c) were obtained with a HeNe laser at 632.8 nm. The arrow indicates the direction of increasing wedge thickness.

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the wedge; Fig. 2 shows the far field of the full laser array obtained by direct illumination (no lens was used) of a screen, 50 cm away from the array. That illumination pattern is recorded using a television camera; the stored video image is then used to display the intensity profiles of the far field in the two main orthogonal planes. Notice that the beam is tilted in the direction of increasing wedge thickness by a 5° angle, about 100 times larger than the wedge angle $\alpha \sim 10^{-3}$ rad. The measured far field is the incoherent addition of the fields from the individual cells of the array, all with the same far field. We will now introduce a single-cell resonator model consistent with these observations.

The field distributions and the values of the losses corresponding to various transverse-order modes of our optical cavity can be obtained numerically using a wave description of the resonator. However, our experimental data can be more simply explained by means of a geometric ray model. This model ignores diffraction effects from the mirror edges which are not expected to be important at the large Fresnel number value ($N = 1.1 \times 10^7$) of our tilted mirror resonator. In our model (Fig. 3), the flat mirrors are replaced, for analysis purposes, by convex cylindrical surfaces of a large radius of curvature $R$, chosen so as to intersect the flat surfaces of the wedge at their upper and lower edges. We expect this model to break down as the maximum separation between the flat and cylindrical surfaces approaches or exceeds a wavelength; this condition, reduced to Eq. (4) below, justifies the mirror replacement approximation for the lasers in this work. Any ray approach to obtain a mode solution of the flat-flat wedge resonator does face the difficulty that there is no virtual point source which can reproduce itself after a round trip in the cavity; the modified wedge resonator with curved mirrors, on the other hand, has easily determined virtual points.

The two-dimensional solution for the resonator field can be constructed from the solutions of two separate one-dimensional descriptions of the resonator. In the first di-

FIG. 2. Far-field emission characteristics of the matrix laser array. The normal to the wafer is determined by the reflection of a HeNe laser.

FIG. 3. Unstable resonator with a residual wedge angle $\alpha$. The location of the virtual source $O$ is determined by $\rho$ and $\theta$. $R$ is the radius of curvature of the cylindrical surface, $d$ is the average cavity length, and $a$ is the cell size.

mension we have a symmetric unstable resonator, while there is a wedge-free, flat-flat resonator in the second dimension. We shall now concern ourselves with the first dimension and find a solution based on the geometric ray model. It can be shown that the field inside the resonator can be described by two counterpropagating cylindrical wave fronts originating from two symmetric virtual line sources identified by points $O$ and $O'$ in Fig. 3. These points are the foci of one possible pair of hyperbolic cylinders with radius $R$ replacing the original flat mirrors. Point $O$ is specified by the distance $\rho$ to the center $P$ of the cell and the angle $\theta$ that $OP$ forms with the normal to the wafer; for $R \ll 4d/a^2$ they are given by

$$\rho = \frac{\sqrt{d}}{2}$$

and

$$\theta = \frac{\alpha R}{2d},$$

d being the average mirror separation and $\alpha$ the wedge angle. The locus of the virtual source, $O[\rho(R), \theta(R)]$, as determined by Eqs. (1) and (2), is shown in Fig. 3. A cylindrical wave originating at any point $O$ of the locus will reproduce itself after traveling inside the resonator a distance of twice an equivalent cavity length, $d_e$; this length corresponds to the minimum mirror separation (nearly equal to $d$) and determines the longitudinal mode structure of the resonator.

The value of $R$ that minimizes the cavity loss selects the actual virtual source point. A fraction of the power circulating inside the resonator is spilled and lost at one or both of the mirror edges on each bounce. As the virtual point $O$ moves along the locus, the spillover or geometric loss of the resonator goes through a minimum value

$$L_{min} = \frac{1}{3/4 + \sqrt{a/8\rho}},$$

for $R = R_e = a/\alpha$ at a point $O_e$ with coordinates $\rho = \sqrt{d/2a}$ and $\theta = \sqrt{a/2d}$. Notice that $\theta$ is the angle by which the laser beam is offset from the normal (see Fig. 2) and that the angle $a/\rho$, subtended by the cell from $O_e$ has a value of $2\theta_e$. For points in the locus other than $O_e$, the geometric loss increases ($L > L_{min}$).

\[ L = \frac{1}{3/4 + \sqrt{R / 8d}} \quad \text{for} \quad R < R_c. \]  
(3b)

and

\[ L = \frac{1/2 + \alpha R / 2a}{3/4 + \sqrt{R / 8d}} \quad \text{for} \quad R > R_c. \]  
(3c)

Introducing the index of refraction \((n = 2.58\) for CdS\) into the model, the virtual source is expected to be at a distance \(\rho_0/n\) behind the matrix and the far-field angle to be \(2\theta_0\), and tilted by \(\theta_0\). In our case, with \(a = 220 \pm 11\ \mu m, d = 55 \pm 1\ \mu m, \) and \(\alpha = (8.6 \pm 0.6) \times 10^{-4}\) rad, the model predicts \(R_c = 257\ mm\) and \(\rho_0/n = 1.03\ mm\), which agrees with the observed distance of \(1\ mm\) that the lens has to move towards the matrix in order to image the virtual source; the predicted value \(\theta_0 = 6^\circ\) agrees well with the observed \(5^\circ\) tilt of the far field, and \(2\theta_0 = 12^\circ\) with the observed \(14^\circ\) far-field angle (see Fig. 2).

The maximum separation \(\delta\) between the flat and cylindrical mirror in the model is

\[ \delta = (1/2R_c) (a/2)^2 = \alpha a/8. \]  
(4)

In our case \(\delta = 0.024\ \mu m\) is small compared to the optical wavelength in the medium \(\lambda/n = 0.2\ \mu m\), justifying the cylindrical approximation. For large enough wedge \((\alpha = 7.3 \times 10^{-3}\) rad for our cell size \(a = 220\ \mu m\)) it is \(\delta = \lambda/n\) and the approximation is no longer valid.

For a very small wedge angle \((\alpha = 10^{-5}\) rad\) the geometric loss \([L_{\text{min}}, 4 \times 10^{-3}\) from Eq. (3a)]\) becomes as low as the diffraction loss at the mirror edges; the resonator behaves as a wedge-free Fabry–Perot cavity and the geometric model is expected to break down. For a large wedge angle \((\alpha = 5 \times 10^{-3}\) rad\), the loss \((L_{\text{min}} = 9 \times 10^{-2})\) may exceed the output mirror transmission, causing an increase in the laser threshold.

The full width \(2\epsilon_m\) of the virtual line source exceeds the diffraction limit \([(\rho_0/a) (\lambda/n) = 9\ \mu m]\); it increases with laser power from \(35\ \mu m\) at an excitation 1.6 times above threshold to \(55\ \mu m\) at 2.6 times above threshold. Our model predicts such an increase.\(^{13}\) As the virtual source \(O_o\) is displaced transversely to the locus by a distance \(\epsilon\), its round-trip image is displaced by only \((1 - 2d/\rho_o)\); their separation is \(2\epsilon\rho_o\). The phase mismatch \(\psi_{\text{rms}}\) between the interfering wave fronts corresponding to the original source and its round-trip image gives rise to an additional loss \(\delta L(\epsilon)\),\(^{11}\) which for \(\epsilon = \epsilon_m\) in our resonator becomes

\[ \delta L(\epsilon = \epsilon_m) = \left( \frac{2 \psi_{\text{rms}}}{\lambda} \right)^2 = \frac{4 \epsilon_m \alpha n}{\lambda} \]  
(5)

This additional loss may be overcome by increasing the electron beam current density \(J\) above the nominal threshold \(J_{\text{th}}\) associated with all other cavity losses \(L_o\). With \(\delta L(\epsilon_m)/L_o = J/J_{\text{th}} - 1\), and \(L_o = 0.4\), the model\(^{13}\) predicts a virtual-source full width \(2\epsilon_m (\mu m) = 40 (J/J_{\text{th}} - 1)^{1/2}\) consistent with the experiment. In addition to the \(14\%\) coupling loss and \(4\%\) spillover loss of the resonator, \(L_o\) includes the nonresonant absorption loss and equivalent inversion loss\(^{12}\) which may be important, although they have not been measured in our case.

The laser emission spectrum shows three longitudinal modes, spaced by \(0.6\ \mu m\); each mode shifts in wavelength according to \(\delta \lambda = (4.9 \pm 0.5) \times 10^{-6}\) \(\epsilon\) as the point being observed is displaced by \(\epsilon\) within the width \(2\epsilon_m\) of the “thick” line source. According to the model,\(^{13}\) a displacement \(\epsilon\) of the virtual source causes a change \(\epsilon a\) in the effective cavity length; the experimental result agrees with the predicted shift in lasing wavelength of \(\delta \lambda = \lambda (a/d) (n/n_o) \epsilon, \) where \(n_o = n - \lambda (dn/d\lambda)\) and the appropriate measured values of the parameters are used.

In conclusion, the near-field, far-field, and spectral emission characteristics of individual cells in a matrix laser have been investigated. A new geometrical ray treatment has been developed that basically agrees with the observations. The detailed characterization of single-cell emission presented in this letter may help to understand and design large-area laser arrays with diffraction-limited emission. Recent advances in that direction have been reported,\(^{14}\) where an external unstable resonator was used to establish intercell coupling.

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\(^{13}\) For details, see F. Tong, Ph. D. thesis, Columbia University, 1987.