variation perpendicular to the layers is unchanged throughout the supermode cycle.[7] Assuming $\lambda_x \gg \lambda_0$, we obtain

$$\Delta\lambda = \lambda_0 - \lambda \simeq \lambda_0^3/(2n^2\lambda_x^2). \qquad (2)$$

With $n = 2.83$ as a fitting parameter, over 80% of the data points fit within the indicated error bars (Fig. 3). Although the parabolic form of the dispersion relation is apparent, the value for n (2.83) is not in close agreement with the value of 3.5 indicated by the longitudinal mode spacing and the length (263 μm) of the diode. The discrepancy is probably caused by the finite extent of the active region width. As mentioned above, as the order of the mode is increased the optical field tends to fill more of the 100-μm array width. The resulting change (reduction) in effective gain for the higher order transverse modes will affect the spectral distribution of supermodes.[13] Also, variation in the optical field perpendicular to the layers, as the transverse modes are altered, would affect the result.

In conclusion, the spectral distribution of the transverse modes is presented for a high-power, short-wavelength multiple stripe laser. The parabolic dispersion relation is similar to that of a broad area laser having a relatively flat profile, and is indicative of the large gain between stripes. Also, the near and far fields of a multiple stripe laser under various feedback conditions are shown. The presence of higher order transverse modes having more emitters than stripes, as well as the smooth near-field pattern when the feedback is removed, supports the contention that the gain is distributed relatively evenly across the active region.

The authors are grateful to J. T. Verdeyen for helpful discussions. For technical assistance the authors wish to thank Y. K. Moroz, B. L. Marshall, R. T. Gladin, and B. L. Payne (Illinois), and H. Chung, R. D. Yingling, Jr., F. Endicott, M. Bernstein, W. Mosby, J. Walker, G. L. Harnagel, and A. Alimonda (Xerox). The work of the Illinois group has been supported by NSF Grant ECS 82-00517, Army Research Office Contract DAAG-29-82-K-0059, and NSF Grant DMR 80-20250.

[1] D. R. Scifres, W. Streifer, and R. D. Burnham, Appl. Phys. Lett. **33**, 616 (1978).
[2] D. R. Scifres, C. Lindström, R. D. Burnham, W. Streifer, and T. L. Paoli, Electron. Lett. **19**, 169 (1983).
[3] P. Gavrilovic, K. Meehan, J. E. Epler, N. Holonyak, Jr., R. D. Burnham, R. L. Thornton, and W. Streifer, Appl. Phys. Lett. **46**, 857 (1985).
[4] H. Temkin, R. D. Dupuis, R. A. Logan, and J. P van der Ziel, Appl. Phys. Lett. **44**, 473 (1984).
[5] E. Kapon, C. P. Lindsey, J. S. Smith, S. Margalit, and A. Yariv, Appl. Phys. Lett. **45**, 1257 (1984).
[6] J. E. Epler, N. Holonyak, Jr., R. D. Burnham, T. L. Paoli, and W. Streifer, Appl. Phys. Lett. **45**, 406 (1982).
[7] J. E. Epler, N. Holonyak, Jr., R. D. Burnham, T. L. Paoli, and W. Streifer, J. Appl. Phys. **57**, 1489 (1985).
[8] R. D. Burnham, D. R. Scifres, and W. Streifer, Appl. Phys. Lett. **41**, 228 (1982). See also, R. D. Dupuis, L. A. Moudy, and P. D. Dapkus, in *Proceedings of 7th International Symposium on GaAs and Related Compounds*, St. Louis, 1978, edited by C. M. Wolfe (Institute of Physics, London, 1979), pp. 1–9.
[9] R. D. Burnham, C. Lindström, T. L. Paoli, D. R. Scifres, W. Streifer, and N. Holonyak, Jr., Appl. Phys. Lett. **42**, 937 (1983).
[10] J. K. Butler, D. E. Ackley, and D. Botez, Appl. Phys. Lett. **44**, 293 (1984).
[11] J. Katz, E. Kapon, C. Lindsey, S. Margalit, and A. Yariv, Appl. Opt. **23**, 2231 (1984).
[12] T. L. Paoli, W. Streifer, and R. D. Burnham, Appl. Phys. Lett. **45**, 217 (1984).
[13] G. H. B. Thompson, *Physics of Semiconductor Laser Devices* (Wiley, New York, 1980), pp. 225–230.

Tilted-mirror semiconductor lasers

J. Salzman, R. Lang, S. Margalit, and A. Yariv
California Institute of Technology, Pasadena, California 91125

(Received 7 February 1985; accepted for publication 1 April 1985)

Broad-area GaAs heterostructure lasers with a tilted mirror were demonstrated for the first time, with the tilted mirror fabricated by etching. These lasers operate in a smooth and stable single lateral mode with a high degree of spatial coherence. The suppression of filamentation manifests itself in a high degree of reproducibility in the near-field pattern.

A common feature of broad-area semiconductor lasers is the filamentary nature of the output optical radiation.[1] Lasing filaments manifest themselves by a nonuniform near-field intensity distribution, unpredictable changes in the field distribution with increasing injection current, and a degradation of the spatial coherence of the optical field. These properties can limit the peak output power available from the laser, cause kinks in the light-current characteristic, and broaden the far-field intensity pattern.

Recently, it was shown that a broad-area semiconductor laser with an unstable resonator can be operated with a smooth, stable, and highly coherent lateral optical field.[2] The suppression of filaments in these lasers was explained in terms of the magnifying effect of the cavity.[2,3] As a result of a modal analysis of the unstable resonator semiconductor laser,[4] we concluded that filamentation can be suppressed not only by the *magnifying* effect of the resonator, but also by a *shift* of the optical field in every round trip. This effect may

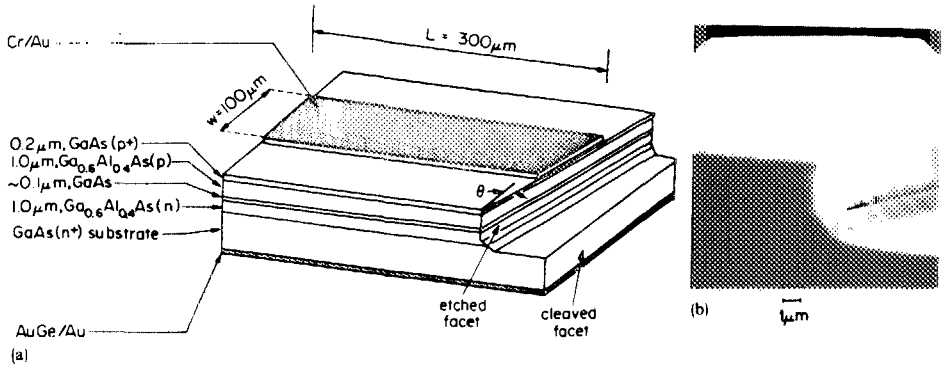

FIG. 1. (a) Schematic picture of the tilted-mirror semiconductor laser. (b) SEM picture of the etched mirror.

have important applications in the design of new resonator configurations in semiconductor lasers.

A lateral shift of the optical field is related to a misalignment of the resonator end mirrors. In the simplest case of a Fabry–Perot (FP) resonator, this misalignment can be accomplished by tilting one of the planar feedback mirrors. FP resonators with tilted mirrors have been analyzed before[5,6] but in these works, the tilt was considered to be a very small perturbation to the ideal cavity, and its effect was studied from the point of view of the tolerances of FP cavities to mechanical imperfections. However, in order to completely suppress filaments in a semiconductor laser, the necessary tilt angles are quite large and the approximations made in previous analyses break down.

In this letter we report on the fabrication and the operation of broad-area GaAlAs/GaAs lasers with tilted mirrors, up to a tilt angle of $\theta = 15°$ [Fig. 1(a)]. The GaAlAs/GaAs double heterostructure structures (DH) were grown by liquid phase epitaxy and subsequently standard photolithographic techniques were used to form resist patterns on top of the DH wafers. These were then etched, using procedures recently developed[7] to produce high-quality laser facets [Fig. 1(b)]. The laser fabrication was completed by contact metallization. We obtained an estimate of the necessary tilt angle by requiring the optical field to be shifted by $10\,\mu$m (the filament width) after one round trip. In order to compare the losses and the modes of lasers with different tilt angles, we fabricated on the same wafer, side by side, lasers having an etched mirror with $\theta = 0°, 5°, 10°$, and $15°$.

Figure 2(a) shows the near-field pattern of a tilted-mirror laser ($\theta = 10°$) for $I = 1.2I_{\mathrm{th}}$ with the laser driven with 100-ns pulses at 1-kHz repetition rate. The field distribution is very smooth and stable as can be observed in Fig. 2(b), where the near field was recorded for different values of the injection current. The slight maxima at both sides of the emission stripe were present in all the lasers tested both above and below threshold. In many lasers without tilt ($\theta = 0$), these were the places where filaments originated. The increase of the output intensity at the edges of the gain region may be caused by the fact that heating effects are less severe there. The extremely smooth and stable near-field pattern can be explained in terms of the mirror-coupled mode analysis.[4] According to this model, the different (gain) guided lateral modes $E_i(x)$ are coupled at the mirrors with coupling coefficients K_{ij} given by

$$K_{ij} \propto \int E_i(x) R(x) E_j(x) dx, \tag{1}$$

where $R(x)$ is a complex reflectivity which is a function of the lateral coordinate x. In the case of a planar mirror with a small tilt angle θ, we can approximate $R(x)$ by

$$R(x) = R_0 e^{-2i(\beta \tan \theta)x}, \tag{2}$$

where R_0 is the normal-incidence Fresnel reflectivity and β is an average propagation constant for the gain-guided modes. A round-trip propagation analysis of the coupled modes shows[4] that the effect of the coupling at the mirrors is to phase lock all of the propagating waveguide modes to produce a single resonator mode. We therefore expect the near-field intensity distribution not only to be stable with increas-

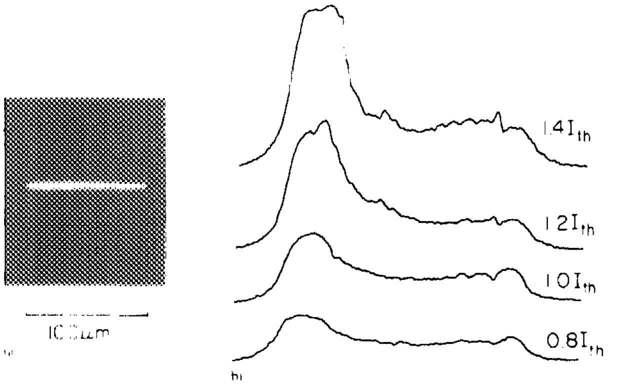

FIG. 2. (a) Near-field pattern of a laser with a mirror tilted by $\theta = 10°$, and for $I = 1.2I_{\mathrm{th}}$. (b) Recorded near-field intensity distribution for different values of the injection current. The right side corresponds to the shorter part of the resonator.

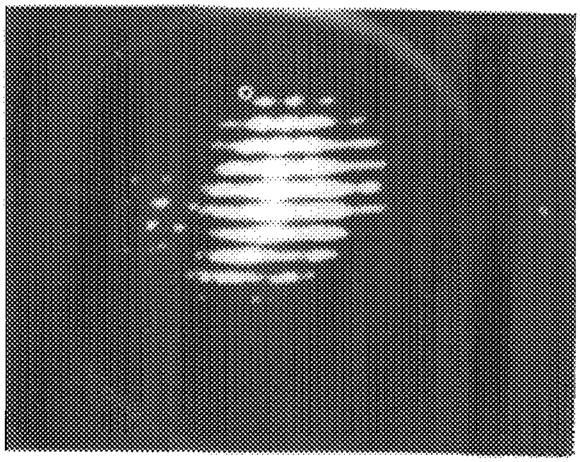

FIG. 3. Picture of the interference pattern between two points in the laser near field, in the double-slit interference experiment.

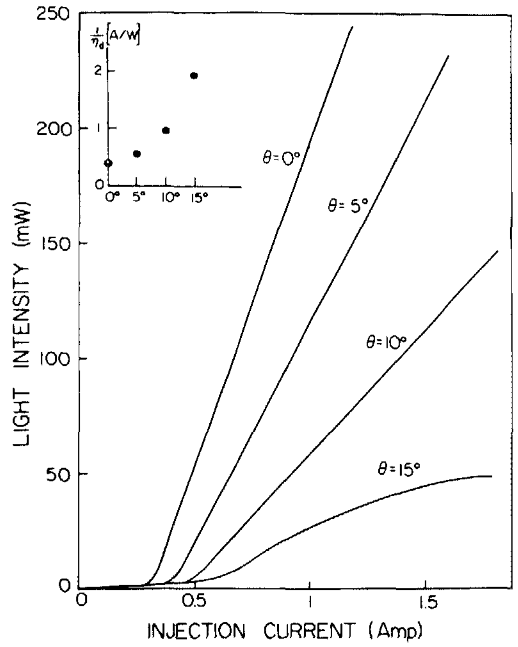

FIG. 4. Light-current characteristic of lasers with different tilt angle. The inset shows the reciprocal external quantum efficiency η_d^{-1} as a function of tilt angles.

ing injection current, but also spatially coherent.

In order to measure the degree of spatial coherence of the output beam, the near field of the tilted-mirror laser was imaged on an opaque mask, with two narrow transparent slits, and the resulting interference pattern was observed with an infrared vidicon camera.[8] High-visibility fringes were recorded for point pairs spread across the laser near field, indicating high spatial coherence over the entire near field (Fig. 3). This shows that the device operates in a single lateral mode (although not necessarily a single longitudinal mode), even though the gain-guided stripe can support many lateral modes.

The light-current characteristic of tilted-mirror semiconductor lasers for different tilt angles is given in Fig. 4. It can be shown[4] that the cavity losses are approximately proportional to η_d^{-1}, where η_d is the external differential quantum efficiency. This is plotted in the inset to Fig. 4, showing a highly nonlinear increase in the losses with increasing tilt angle.

In conclusion, we have demonstrated the operation of tilted-mirror semiconductor lasers, with a tilt angle of up to 15°. These lasers operate in a smooth and stable lateral mode with a high degree of spatial coherence.

By observing the output of a large number of devices we found that, unlike the case of regular FP broad-area lasers, the near-field pattern in all of them is very similar, showing a high degree of reproducibility. This suggests that the tilted-mirror semiconductor laser may be an appropriate candidate for applications in which a high-power extended source is needed.

This research is supported by grants from the Army Research Office, the Air Force Office of Scientific Research, and the Office of Naval Research. J. Salzman would like to acknowledge the support of the Bantrell Post-doctoral Fellowship and the Fullbright Fellowship. R. Lang would like to acknowledge the support of the National Science Foundation.

[1] G. H. B. Thompson, Opto-electronics **4**, 257 (1972).
[2] J. Salzman, T. Venkatesan, R. Lang, M. Mittelstein, and A. Yariv, Appl. Phys. Lett. **46**, 218 (1985).
[3] Yu A. Anan'ev, Sov. J. Quantum Electron. **1**, 565 (1972).
[4] R. Lang, J. Salzman, and A. Yariv (unpublished).
[5] A. G. Fox and T. Li, Proc. IEEE **51**, 80 (1963).
[6] J. L. Remo, Appl. Opt. **19**, 774 (1980).
[7] J. Salzman, T. Venkatesan, S. Margalit, and A. Yariv (unpublished).
[8] M. Mittelstein, J. Salzman, T. Venkatesan, R. Lang, and A. Yariv, Appl. Phys. Lett. **46**, 923 (1985).