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Spectrally Resolved Near-Field Intensity Measurements from Gain-Guided Twin-Stripe Laser Diode Arrays

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PREFACE

The authors wish to acknowledge Dr. M. B. Chang and Prof. E. M. Garmire for helpful discussions. We would also like to thank J. A. Podosek and R. D. Reel for assisting in the fabrication and characterization of the devices.



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SPECTRALLY RESOLVED NEAR-FIELD INTENSITY MEASUREMENTS FROM GAIN-GUIDED TWIN-STRIPE LASER DIODE ARRAYS

The twin-stripe laser diode is the simplest laser diode array; consequently, understanding its properties should provide valuable insights into the operation of closely spaced laser diode arrays. In our study of the array-like properties of the twin-stripe device, we have made spectrally resolved near-field measurements that reveal the presence of two distinct near-field intensity distributions and their corresponding families of longitudinal modes. The spectral separation of the two families of longitudinal modes is typically greater than $10 \text{ \AA}$, a value considerably in excess of that predicted by supermode theory. The relation between these two lateral modes in the same device is described here for the first time.

The laser diodes used in this study were fabricated from a double heterostructure AlGaAs-GaAs wafer grown by metal-organic chemical vapor deposition (MOCVD).¹ The layer structure included a $0.1\text{-}\mu\text{m}$ -thick undoped active region of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x = 0.05$) surrounded by $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x = 0.35$) doped isolation layers.

Stripes were plasma-etched in sputter-deposited silicon nitride through a photoresist mask. Each stripe was $4 \text{ }\mu\text{m}$ wide and had a center-to-center spacing of $8 \text{ }\mu\text{m}$ to allow for evanescent optical coupling² between the stripes. A single Ti-Pt-Au ohmic contact was e-beam evaporated over both stripes. Single-stripe laser diodes with $4\text{-}\mu\text{m}$ stripe widths were also fabricated from the same wafer to provide a point of comparison. The devices were cleaved to produce an optical cavity $250 \text{ }\mu\text{m}$ long.

The lasers were driven with 100-ns current pulses. Typical light-output-power versus current (L-I) curves for the twin-stripe (solid line) and single-stripe (dashed line) devices are shown in Fig. 1. Compared to single $4\text{-}\mu\text{m}$ -stripe lasers (dashed curve in Fig. 1), the current at lasing threshold is lower,³⁻⁸ the knee at threshold is sharper,^{3,4} and there is a kink in the L-I curve^{3,4,6} where the slope efficiency changes from 0.21 to 0.38 mW/mA . (The slope efficiency is computed for the light from only one end of the laser.)

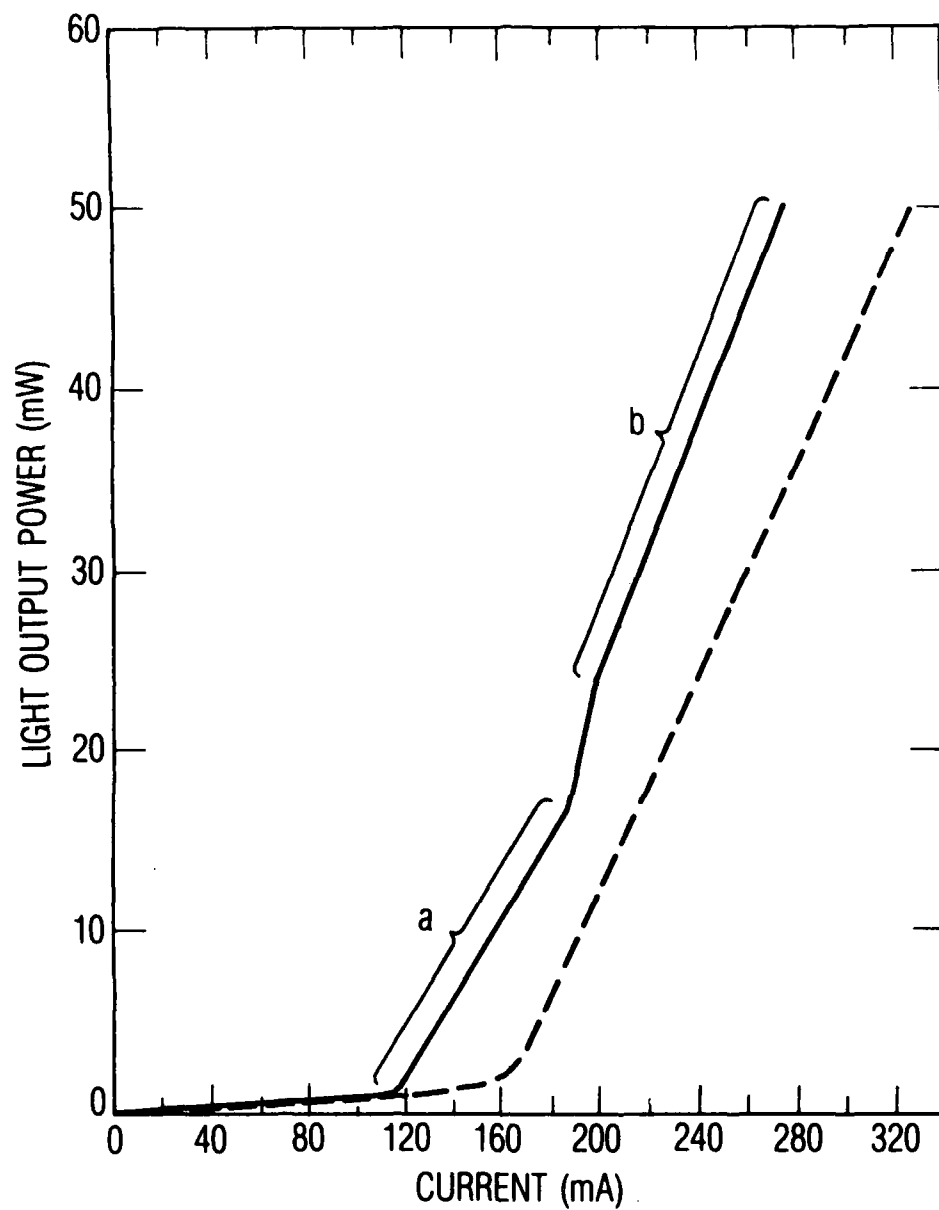


Fig. 1. Light-Output Power (one end) vs. Current for Typical Gain-Guided Twin-Stripe (solid curve) and Single-Stripe (dashed curve) Laser Diodes

Initial measurements of the far- and near-field patterns of the twin-stripe arrays, made above the kink in the L-I curve, gave results similar to those reported elsewhere. The far-field pattern of the twin-stripe device, shown as the solid curve in Fig. 2, is similar to other reported single-lobe patterns,^{4,8-11} in contrast to the characteristic "rabbit-eared" pattern of a single-stripe device (dashed curve). The near-field intensity of the twin-stripe diode (solid curve in Fig. 3) was narrower than that of the single-stripe device (dashed curve).^{3,6} The structure in the near-field of the twin-stripe laser has also been observed before.¹¹ However, measurements made below the kink in the L-I curve gave results that are more characteristic of index-guided single-stripe laser diodes. In addition, two distinct sets of longitudinal modes were observed in the spectrum above the kink. The complexity of these measured characteristics above the kink suggested that a mode shift was occurring at the kink.

To resolve the near-field profile spectrally, the image of the output facet was focused on the input slits of a monochromator and the output was monitored on a solid-state video camera. The vertical dimension of Fig. 4 corresponds to the one-dimensional near-field image (i.e., intensity distribution) parallel to the junction. In the horizontal dimension, the light is broken into its spectral components.

The general trend that gain-guided twin-stripe devices support fewer longitudinal modes than single-stripe devices^{4,10,11} was evident. The image depicted in Fig. 4a corresponds to an operating current below the kink in the L-I curve, while the image in Fig. 4b corresponds to a current above the kink in the L-I curve. The spectrally resolved near-field pattern remains the same over the regions indicated as (a) and (b) on the L-I curve in Fig. 1.

For currents below the kink (Fig. 4a), a single set of longitudinal modes and a lateral-mode intensity distribution principally confined between the stripes (i.e., centered) was observed. This is consistent with "self-focusing" observed in gain-guided twin-stripe lasers.^{3,6,12-15} Self-focusing results from the weak index-guide that occurs in symmetrically pumped twin-stripe lasers as a result of the dip in the injected-current profile between the

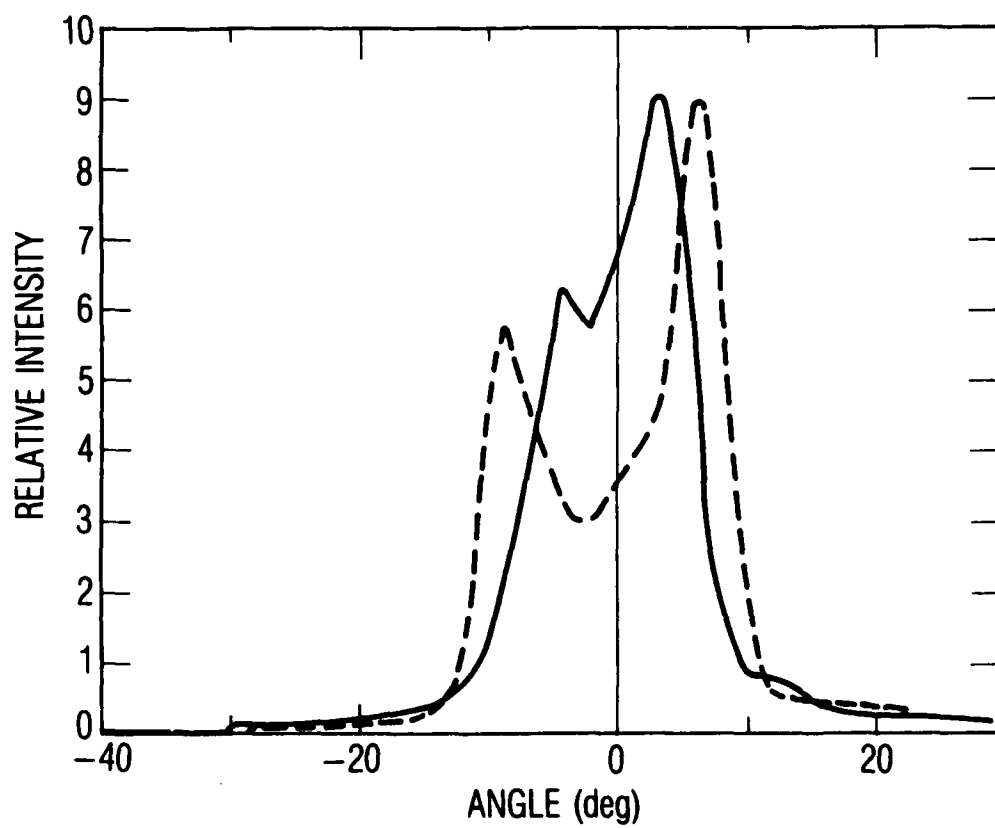


Fig. 2. The Far-Field Intensity Profiles in the Plane of the Junctions for Typical Gain-Guided Twin-Stripe (solid curve) and Single-Stripe (dashed curve) Laser Diodes

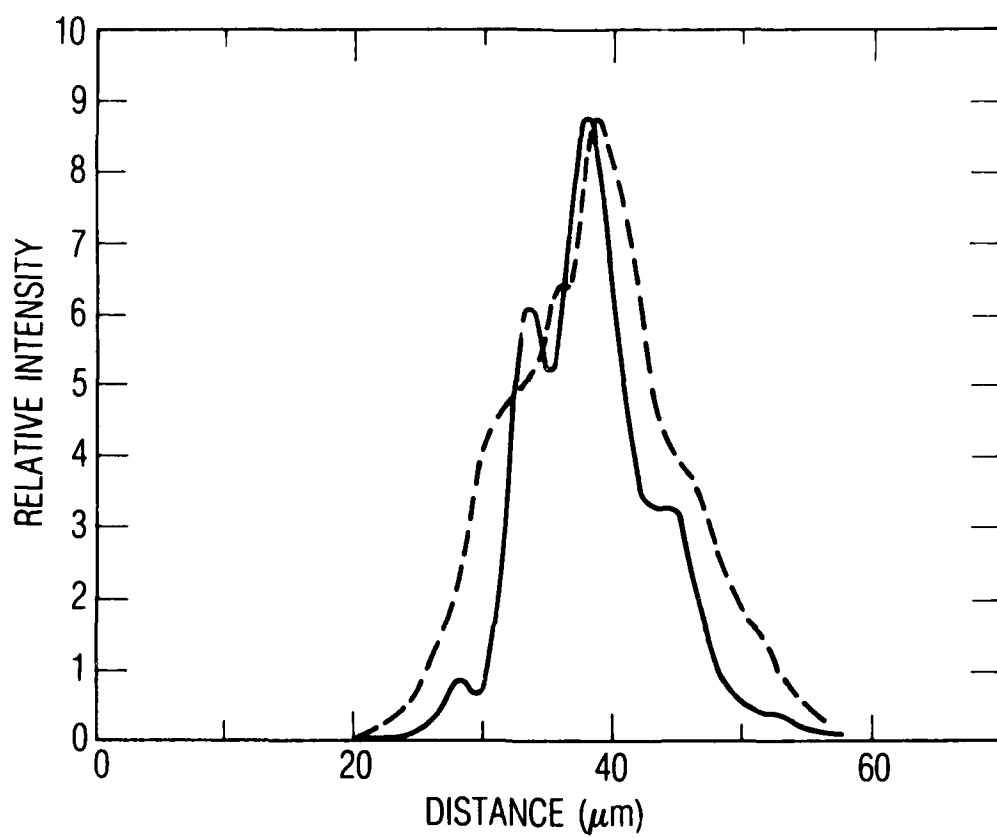


Fig. 3. The Near-Field Intensity Profiles in the Plane of the Junction for Typical Gain-Guided Twin-Stripe (solid curve) and Single-Stripe (dashed curve) Laser Diodes

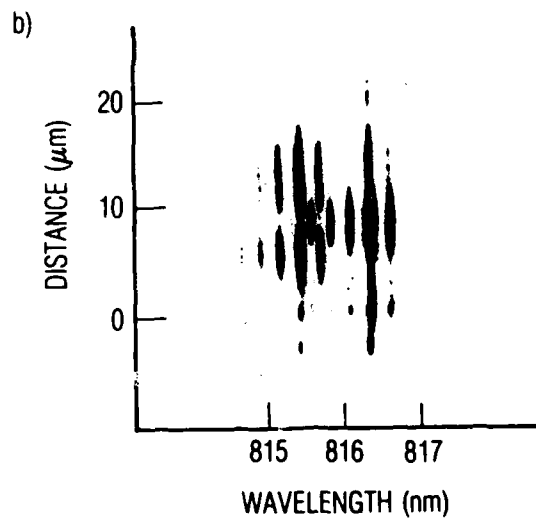
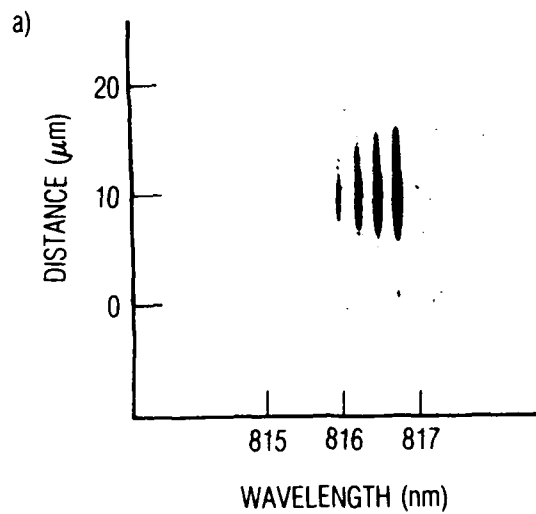


Fig. 4. Spectrally Resolved Near-Field Intensity Distributions from Typical Gain-Guided Twin-Stripe Laser Diodes for Currents below (a) and above (b) the Kink in the L-I Curve

stripes. The reduced loss due to the weak index-guide offsets the smaller optical gain between the stripes, permitting lasing at lower thresholds than for the single-stripe laser diode.

The principal effect established by the weak-index waveguide is an increase in the photon flux over that provided by the antiwaveguide of a gain-guided single-stripe laser. The increase in photon flux allows the laser to operate farther from the superluminescent regime, which results in a lower threshold current,^{3-8,17,18} a sharper knee in the L-I curve,^{3,4,17,18} a narrower lateral near-field intensity profile,^{3,6} and fewer longitudinal modes.^{4,10,11,17,18} In addition, the propagating wavefront inside the weak-index waveguide is flatter than that in the antiwaveguide. The flat propagating wavefront inside the laser cavity diffracts into a single far-field lobe,^{4,8-11} in contrast with the double-lobe pattern from the curved wavefront provided by the antiwaveguide of a gain-guided single-stripe laser.³ This centered near-field mode is not to be confused with the in-phase supermode of a twin-stripe laser,^{19,20} which would extend under the two stripes instead of between them.

At currents above the kink (Fig. 4b), there are two spectrally separated sets of longitudinal modes, one associated with the centered distribution described above, the other with two distinct peaks in the near-field intensity distribution positioned under the stripes. The wavelengths of the longitudinal modes corresponding to the centered near-field distribution are typically 10 Å longer than those corresponding to the double-lobe lateral distribution. Together, the two near-field distributions form the three main peaks shown in Fig. 3.

We attribute the double-lobe near-field distribution to the out-of-phase twin-stripe supermode, since (1) the intensity between the spots in the near field seems to go to zero and (2) there is a remnant of a double-lobe pattern in the composite far-field pattern (Fig. 2). The spectral separation between the in-phase and out-of-phase supermodes for a gain-guided ten-stripe array has been reported to be on the order of 0.1 to 0.3 Å,²¹ too small to be resolved in the spectrally resolved near-field patterns of Fig. 4, and much

smaller than the 13-Å separation of the centered and double-lobe near-field modes. The observation that the first supermode to lase is the out-of-phase supermode is consistent with previous reports of higher-order modes from twin-stripe lasers.^{8,22,23}

The far-field pattern appears to be dominated by the centered self-focused mode and thus looks principally single-lobed, even at currents above the kink in the L-I curve. The onset of the supermode is probably responsible for the increase in slope efficiency above the kink and the small side structure in the far-field intensity distribution.

Although we believe this is the first specific report of the spectral separation between the self-focused mode and the out-of-phase supermode in gain-guided twin-stripe lasers, previously reported measurements on the bistable operation of twin-stripe lasers do include spectral shifts^{4,6} as large as those depicted in Fig. 4. Reported shifts to shorter wavelengths occur as the current to each stripe is individually increased to induce bistable switching of the near-field intensity distribution. The magnitude and direction of this spectral shift are in agreement with the spectrally resolved near-field measurements presented here.

The simultaneous operation of two spectrally separated near-field intensity distributions has also been reported in a phase-locked filament laser²⁴ and in a gain-guided ten-stripe array.²⁵ Spectrally resolved near-field measurements of the phase-locked filament laser indicate two lateral near-field intensity distributions having spectral separations of the same magnitude as those reported here; however, the centered intensity distribution is reported to occur at shorter wavelengths, instead of at longer wavelengths as observed here.²⁶

The spectrally resolved near-field measurements on the gain-guided ten-stripe array reported²⁵ the onset, at higher pump levels, of a near-field intensity distribution positioned between the stripes in conjunction with the distribution positioned under the stripes. The spectral separation of these modes was reported to be 4 Å. In agreement with our observations, the mode positioned between the stripes had a longer wavelength.

At this time we believe the large spectral separation between the two modes reported here is due to band filling.²⁷ The greater carrier density under the stripes requires more conduction band states to be filled, which in turn moves the peak of the gain curve to shorter wavelengths. Consequently, the out-of-phase supermode pumped by the carriers under the stripes lases at wavelengths shorter than does the self-focused mode pumped by the carriers between the stripes.

In conclusion, gain-guided twin-stripe laser diodes have been characterized by means of spectrally resolved near-field measurements. These measurements indicate there are two distinct near-field intensity distributions spectrally separated by over 10 Å. We believe the longer-wavelength distribution to be a self-focused lateral mode centered between the two stripes. The shorter-wavelength distribution is positioned under the two stripes and is believed to be the out-of-phase twin-stripe supermode. The spectral separation of these two modes is attributed to band filling, and consequently forces the out-of-phase supermode to lase at shorter wavelengths than does the self-focused mode.

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