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AlGaAs Single-Mode Stability

D. Botez and I. Ladany

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PREFACE

This Final Report covers work performed at RCA Laboratories during the period 17 June 1981 to 31 January 1983 under Contract No. NAS1-15440. This work was carried out in the Solid State Devices Laboratory, under the direction of B. Hershenov. The Group Head was M. Ettenberg, and the Project Scientist was D. Botez. I. Ladany was involved with the fiber coupling and wrote Section III of this report. Staff members and support personnel who have contributed to this work in addition to the authors, and their areas of contribution, are listed below.

J. C. Connolly	-- LPE growth
A. R. Dholakia	-- Fiber polishing
D. Gilbert	-- Device characterization
M. Harvey	-- Device processing
J. J. Hughes	-- Lifetesting
H. Kowger	-- Facet coating
D. P. Marinelli	-- Device processing

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*Abbreviations: CDH = constricted-double-heterojunction
LOC = large-optical-cavity
TH = terraced-heterostructure

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SUMMARY

The thrust of the program has been toward increasing single-mode spectral purity and stability both for unaged and aged devices. The results obtained include a study of single-mode behavior in aged constricted-double-heterojunction (CDH) lasers, the elimination of fiber-related effects on the spectrum upon coupling to optical fibers, and the realization of the most powerful single-mode cw diode laser reported to date.

Ten CDH devices were aged at 70°C and a constant output power of 3 mW per facet. After 5000 and 10,000 h of aging, the devices remained single-mode, thus representing the longest-lived single-mode diode lasers. The median life of CDH devices at 70°C is 7800 h, a figure comparable with the best results obtained from diode lasers. With an activation energy of 0.7 eV, the room-temperature extrapolated mean time to failure for CDH devices exceeds 10^6 h.

The well-known spoiling of single-mode spectra upon coupling to optical fibers has been eliminated through the use of wedge-shaped fibers. The wedge-shaped fibers reflect virtually no light back into the laser while providing good laser-to-fiber coupling efficiencies. Wedge-shaped multimode fibers were fabricated at RCA Laboratories by a special polishing technique.

In the quest for achieving higher power in a single longitudinal mode, two experiments were performed: (a) the spectra of high-power CDH-large-optical-cavity (CDH-LOC) lasers were measured on decibel (dB) scales; and (b) LOC structures were grown on substrate misoriented perpendicular to the direction of the channels. Thus it was found that rejection ratios between the main mode and the satellite modes in CDH-LOC spectra can reach values as high as 30 dB at 30-mW cw output power. Growing on substrates misoriented perpendicular to the channels' direction yielded a novel device: the terraced-heterostructure large-optical-cavity (TH-LOC) diode laser. This device operates in large spot sizes to 50 mW cw in both a narrow-beamwidth ($\theta_{||}$ = 6°; $\theta_{\perp}$ = 23°) fundamental mode and a single longitudinal mode. This represents the highest cw power ever achieved in a single longitudinal mode.

I. INTRODUCTION

In this report we describe the results of a year of study carried out to improve the characteristics of single-mode diode lasers for a variety of NASA applications including wavelength-multiplexed fiber-optic communications, optical recording, free-space communications, and ranging.

We have determined the long-term single-mode stability of single-mode CDH lasers, eliminated the feedback from optical fibers that led to mode instabilities, and improved the single-mode high-power capability of CDH-LOC-type structures.

II. CDH LASERS

There are a number of NASA requirements for single-mode AlGaAs lasers, such as spectral purity and spectral stability as a function of device aging. Although single-mode operation has been demonstrated for CDH* and CDH-LOC** devices, improvements remain to be made for increasing the rejection of the satellite modes, lowering the spontaneous emission, and determining the spectral stability as a function of life.

For the study of spectral-mode behavior with aging we used CDH devices. Specifically, we analyzed CDH lasers of the "ridge-guide" type (fig. 1), that is, CDH devices for which the lasing cavity is mainly a crescent-shaped active layer above a substrate mesa. Such devices are grown by one-step liquid-phase epitaxy above channeled substrates of misorientation direction parallel to the direction of the channels [1] (i.e., the [011] direction). As a result, the structures thus grown have a symmetrical geometry in the lateral direction. A typical spectral behavior as a function of output power is shown in figure 2. Unlike the CDH-LOC device [2], the CDH has tight optical-mode confinement, which provides relatively small spot size (2-3 μm at $1/e^2$ points in intensity) and single-mode cw operation to 6-7 mW per facet. Due to the small spot size, the reliable output-power levels are in the range of 3-5 mW per facet; thus, there is little or no interest in extending the single-mode operation in this structure to powers above 7 mW per facet. Single-mode powers above 7 mW are provided reliably by CDH-LOC devices.

A. SPECTRAL BEHAVIOR WITH AGING

As part of our study of CDH diode lasers we have placed on lifetest five devices for which the spectra were carefully measured at a 3-mW output power level. Of these, three lasers displayed single-mode spectra with rejection ratios between 10 and 20 dB; the other two had spectra composed of two dominant longitudinal modes (i.e., they were multimode devices). Before lifetest, the devices were screened by a "burn-in" of a 100 hours' duration.

*Constricted-double-heterojunction.
**Large-optical-cavity.

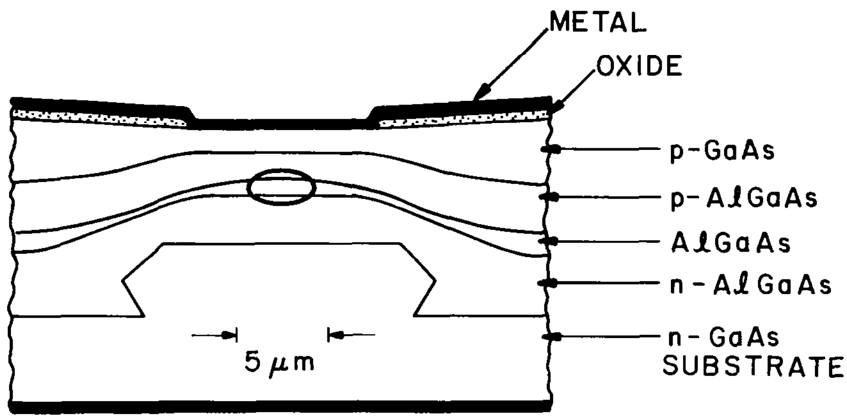


Figure 1. Schematic representation of the "ridge-guide" type of CDH laser structure.

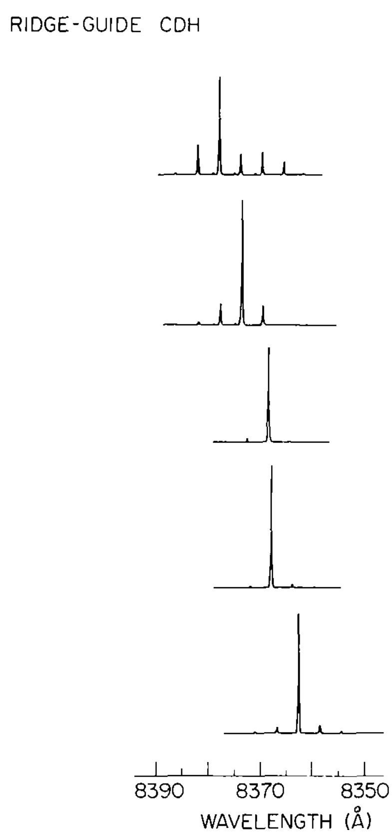


Figure 2. Typical cw spectral behavior at various output power levels for CDH lasers.

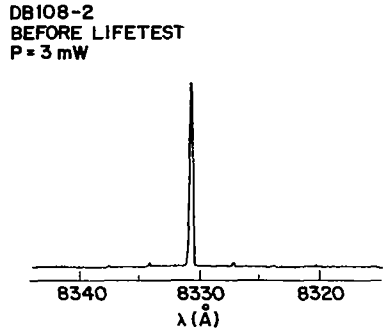
The burn-in permits "weeding out" all the devices with infant mortality and helps stabilize the electrical contact for low electrical and thermal resistance. All lasers were aged at elevated temperatures (50 or 70°C) and 3 mW constant output power. After 4000-5000 h of continuous operation the devices were removed from the lifetest and their spectral characteristics were recorded. The results are summarized briefly in table I.

TABLE I. SPECTRAL BEHAVIOR OF CDH LASERS AS A FUNCTION OF AGING TIME

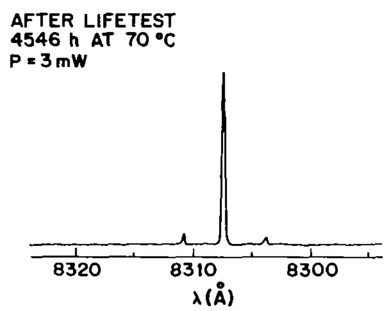
(#) Laser	Initial-Peak Wavelength (Å)	Duration of Lifetest (h)	Temperature (°C)	Wavelength Shift (Å) at 3-mW Output
(1) 108-73*	8383	3922	70	-38
(2) 108-2*	8331	4546	70	-24
(3) 148-43*	8500	5159	50	-5
(4) 159-9	8383	5136	50	-16
(5) 108-74	8343	4546	70	-16

*Initial single-mode device.

For all diodes the driving current needed to maintain a 3-mW output power has increased with aging. Devices #1 and #2 maintained the single-mode behavior, in that virtually the same rejection ratio values were obtained after lifetest as before: namely, 10 and 17 dB for lasers #1 and #2, respectively. In figures 3(a) and 3(b) we show how the spectra of laser #2 looked before and after lifetest. In both cases, the spectral line-width is the same (i.e., 0.15 Å, as limited by the spectrometer). This clearly indicates not only that the device remained in the fundamental spatial mode, but also that no self-sustained oscillations, known to cause line broadening, have occurred. By contrast, device #3 went from single-mode operation to a multimode unstable condition (i.e., self-pulsations). Thus, the rather small spectral shift (i.e., -5 Å) could be misleading since the device has changed modes of operation during testing. The multimode devices #4 and 5 kept similar multimode spectra after lifetest. We, therefore, conclude that spectral shifts at a constant output power of 16-38 Å, with an average of 23.5 Å (i.e., devices #1, 2, 4, and 5) are typical of CDH lasers aged for 4000-5000 h at 50 or 70°C ambient temperature.



(a)



(b)

Figure 3. Spectra of CDH laser at 3-mW cw output power: (a) before lifetest; (b) after almost 5000 h of 70°C-aging.

In terms of room-temperature laser operation, these lifetests correspond to time periods between 50,000 and 200,000 h.

The fact that all aged devices displayed spectral shifts to shorter wavelengths is somewhat puzzling because increases in junction temperature normally associated with aging (i.e., due to intermetallic formation the thermal resistance increases) would shift the gain peak to longer wavelengths. The only known mechanism for spectral shifts to shorter wavelengths has been band filling [3], that is, shifts in gain peak associated with increased carrier concentrations needed for lasing. However, the shifts we recorded cannot be attributed solely to band filling as the injected carrier concentration needed for lasing is increased [3] at a fixed junction temperature. For example, according to Stern's calculations [3], a 10% increase in threshold should provide only a 7-Å shift to a shorter wavelength. Thus it appears that, as the device ages, an annealing process takes place. This affects the shape of the gain profile [3] and/or mechanism responsible for single-longitudinal-mode selection [4] in such a way that oscillation to a shorter wavelength is preferred. As the devices continue to age, the junction temperature increases, causing, in turn, the expected spectral shifts toward longer wavelengths. As can be seen (Section II.B) in comparing devices aged for 10,000 h with devices aged for 5000 h, relative shifts to longer wavelengths do in fact happen.

B. CDH-LASER RELIABILITY

We have reported previously that the cw operational characteristics of CDH lasers include very low threshold-current temperature sensitivity [5] as well as lasing up to 170°C [6], the highest heatsink temperature ever reported for cw operation of a semiconductor diode laser. Such excellent characteristics should make CDH lasers quite reliable. As shown below, we have found the reliability of CDH devices to be on a par with the best reliability obtained for AlGaAs lasers [7-9]. A median life of 7800 h is found at 70°C; this extrapolates to 45 years of median life at room temperature when a 0.7-eV activation energy is assumed. Furthermore, the single-mode character of CDH devices (i.e., single-longitudinal-mode cw operation and fundamental-spatial-mode operation) is maintained after 10,000 h of accelerated aging at 70°C. This represents the longest reported diode-laser lifetime in single-longitudinal-mode operation.

The CDH laser structure that was lifetested is of the "ridge-guide" type [1,10], that is, a device with a convex-lens-shaped active layer above a substrate mesa (see fig. 1). Such devices have been shown to be single mode in cw operation to cw power levels as high as 7 mW per facet, and to have threshold-current temperature coefficients, T_0, in the 180-400°C range [5,6]. Ten devices from two CDH wafers were placed on lifetest at power levels between 3 and 4 mW. Threshold currents were between 60 and 100 mA, and the initial thermal resistances were between 25 and 40°C/W. The lasers were mounted with In solder on Cu heatsinks and were coated with (λ/2) passivation coatings of Al_2O_3 [11] on the emitting facets, and dielectric-stack reflecting coatings [12] on the rear facets. The devices emitted in a single mode at 8300 or 8700 Å, depending on which wafer they came from. For a given device, all through the lifetest, the output power was kept practically constant by adjustment of the drive current whenever a ±10% change in output power was observed. The only preselection for the devices was a 100-h burn-in at room temperature, at 3-mW cw output power. The devices that showed little or no change in their operational characteristics after this burn-in were then placed on lifetest.

Figure 4 displays the log-normal distribution of CDH-laser failures as a function of aging time. Failure is defined as occurring when the device could no longer maintain the 3-mW output power level at 70°C. The median life is 7800 h, a figure comparable with the best results obtained both for oxide-stripe devices [7-9] and for other types of mode-stabilized lasers grown over nonplanar substrates [13,14]. The standard deviation has a value of 1.38, which together with the median life provides a room-temperature extrapolated mean time to failure (MTTF) [15] in excess of 10^6 h. The actual formula used is

$$\text{MTTF} = \tau_m \exp(\sigma^2/2) \tag{1}$$

where τ_m is the median life (i.e., time at which 50% of the tested devices have failed) and σ is the standard deviation.

$$\sigma = \frac{\ln(\tau_m)}{\ln(\tau_o)} \tag{2}$$

where τ_o is the point on the log-normal distribution at which 15.8% of the devices have failed [15]. Together with a τ_m of 7800 h, and an activation energy of 0.7 eV [7], the standard deviation of $\sigma_m = 1.38$ (obtained from fig. 4) gives an extrapolated room-temperature MTTF of 1.1×10^6 h. The 10^6-h figure for MTTF places CDH devices in the forefront of state-of-the-art diode-laser research (7-9]. The extrapolated median life at room temperature is then 4×10^5 h -- that is, approximately 45 years.

As shown in figure 4, four devices of the initial 10 are continuing to lase after 10,000 h on lifetest. The relative drive-current increases needed to keep a constant output power of 3 mW per facet at 70°C were 3%, 6%, 7%, and 21% at the 10,000-h mark. The aging behavior of the devices appears independent of the lasing wavelength. In figure 5 we compare the cw operational characteristics of one of the best CDH devices before aging and after 10,000 h of 70°C aging. The room-temperature light-current characteristics in figure 5(a) show a small increase (3%) in cw threshold current without any observable change in external differential quantum efficiency. The change in pulsed threshold current

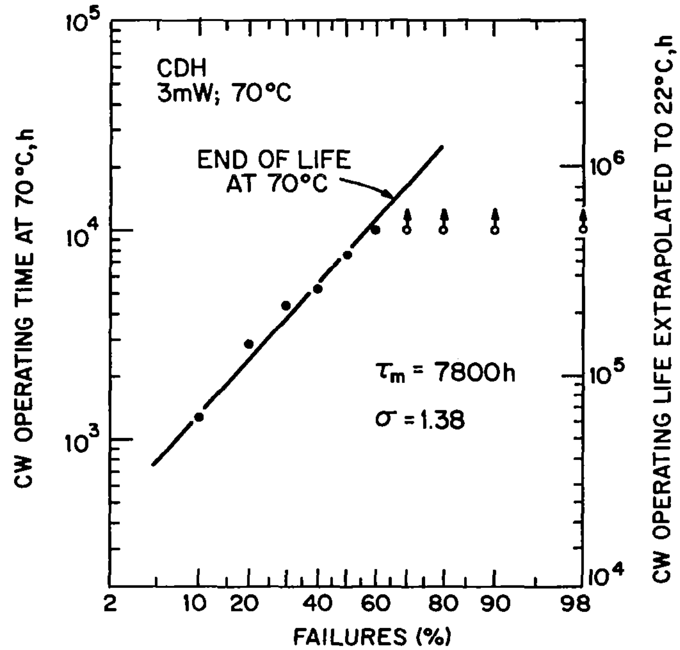


Figure 4. Measured distribution of lifetimes for 10 (Al,Ga)As CDH lasers aged at 70°C ambient and constant 3-mW cw output power level per facet. The solid line represents a log-normal distribution with a 7800-h median lifetime at 70°C and a standard deviation of 1.38. The open circles with arrows in-cate devices that are still operating.

was found to be within the error of measurement. Therefore, the increase in the cw threshold current could be attributed to an increase in device thermal resistance, possibly as a result of intermetallic formation in the In solder [7]. The threshold-current temperature coefficient, T_0, over the temperature interval 20-70°C was found to maintain the initial value (i.e., T_0 = 190 K) after aging.

The CDH-device lateral far-field patterns before and after aging [fig. 5(b)] are found to be identical (i.e., $\theta_{||}$ = 11.3° in both cases). This is expected for an index-guided device and is in sharp contrast to the far-field changes common in aged oxide-stripe devices [16]. The invariance in far-field pattern means that the lasing-spot size remains unchanged at ≅3.2 μm ($1/e^2$ points in intensity). It should be noted that CDH devices, when operated at

3- to 4-mW cw output power, have a reliability similar to that of oxide-stripe devices [7-9], even though the power density at the facet is two to three times higher than that of typical oxide-stripe lasers operating at the same output powers.

Finally, in figure 5(c), we compare the 4-mW-output cw spectra of a CDH device before and after 10,000 h of aging. The spectrum is still single longitudinal mode. The only previously published report of single-longitudinal-mode operation after aging was for transverse-junction-stripe (TJS) lasers [17], but then single-mode behavior was reported only after 2500 h at 70°C and at 2-mW-per-facet cw output. This means that CDH lasers have shown the longest reported operation in a single longitudinal mode. In 10,000 h the single-mode cw spectrum of the CDH device has shifted 10 Å toward a shorter wavelength. As reported in Section I.A, already at the 5000-h aging mark all five CDH lasers measured had shown spectral shifts to shorter wavelengths. The laser whose characteristics we display in figures 5(a) to 5(c) is #DB108-2. From table I it is clear that at 5000 h of aging the shift to a shorter wavelength was higher than the shift at 10,000 h (i.e., 24 vs 10 Å). We attribute this relative shift to a longer wavelength to increases in junction temperature during aging between the 5000-h mark and the 10,000-h mark. In fact, the diode thermal resistance at 10,000 h was found to be higher than the initial value. That is, after 10,000 h of aging the thermal resistance was measured to be 63°C/W, whereas the initial thermal resistance had been 38°C/W.

The excellent reliability results obtained with CDH lasers prove that one-step LPE over nonplanar substrates is a reliable method of growing long-lived mode-stabilized diode lasers. Unlike other nonplanar-substrate devices [14,18,19], the CDH laser does not rely on lasing-cavity proximity to the substrate for lateral mode control. CDH devices are therefore less likely to be affected by degradation initiated by defects and/or dislocations in the GaAs substrate.

We conclude that the room-temperature extrapolated median lives of CDH devices are comparable with those of the most reliable diode lasers. Furthermore, CDH devices have a stable mode both spatially and in frequency after being aged for 10,000 h at 70°C ambient temperature. This high degree of reliability and mode stability makes CDH devices quite promising for use in a wide range of applications.

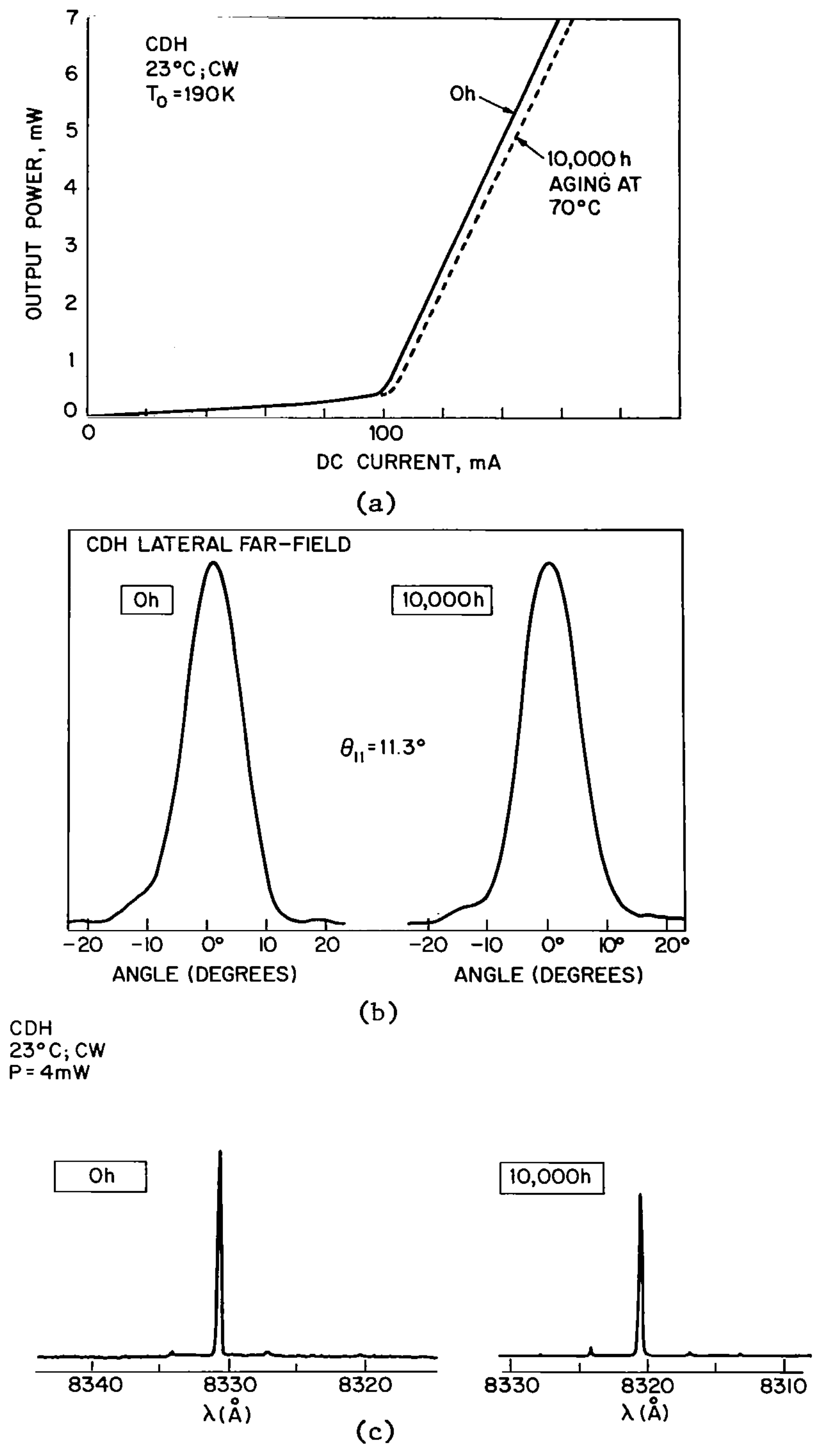


Figure 5. Comparison between key electro-optical characteristics of an aged CDH laser before and after 10,000 h of 70°C-aging: (a) light-current characteristics, (b) lateral far-field patterns, and (c) spectra at 4-mW output power.

III. COUPLING OF SINGLE-MODE LASERS INTO MULTIMODE FIBERS

During the previous contract we noticed that the spectrum of our lasers was frequently disturbed by the fiber. That is, a single-mode spectrum was often changed into a multimode one as measured at the output end of the fiber. It appeared quite clear that feedback effects were involved, and we tried to alleviate them by tilting the fiber relative to the laser so as to reduce the power returned into the cavity. Although this method was occasionally successful, it neither did allow maximizing the coupling efficiency, nor did it assure that the energy in the fiber was traveling mainly in the core region. About this time we were made aware by H. Hendricks, of NASA, of a trade-journal publication dealing with wedge or "roof prism" fiber input configurations. In this section we report on our work with this structure.

The coupling efficiency between diode lasers and multimode fibers whose input end is polished to an obtuse-angled wedge or "roof" configuration can be very high [20]. The angles of incidence presented by a wedge are similar to those obtained by beveling or tilting of the fiber, which has been reported to reduce the optical feedback into the laser [21]; convenience in fabrication is aided by the use of flat surfaces to achieve the input coupling (fig. 6).

In the case of step-index fibers, the connection between the wedge angle and the fiber acceptance half-angle, θ, is easily shown to be

$$\theta = \sin^{-1} \{n_1 \sin [\phi + \cos^{-1} (n_2/n_1)]\} - \phi \qquad (3)$$

where ϕ is the complement of the wedge half-angle ψ, and the other symbols are defined in figure 7.

For a given θ and ϕ (or ψ), the fiber-to-laser distance must be set less than $(\cot\theta - \cot\psi)d/2$ to avoid truncation losses at the input. The minimum value of ψ occurs when the incident ray is at the grazing angle, i.e., when $\theta = \psi$. From this it follows that

$$\psi_{min} = 90 - [\sin^{-1} (1/n_1) - \cos^{-1} (n_2/n_1)] \qquad (4)$$

A typical ψ_{min} is 56°, and a reasonable ψ is a few degrees larger. For the experiments carried out here, wedges with $\psi = 62°$ were polished, one side at a

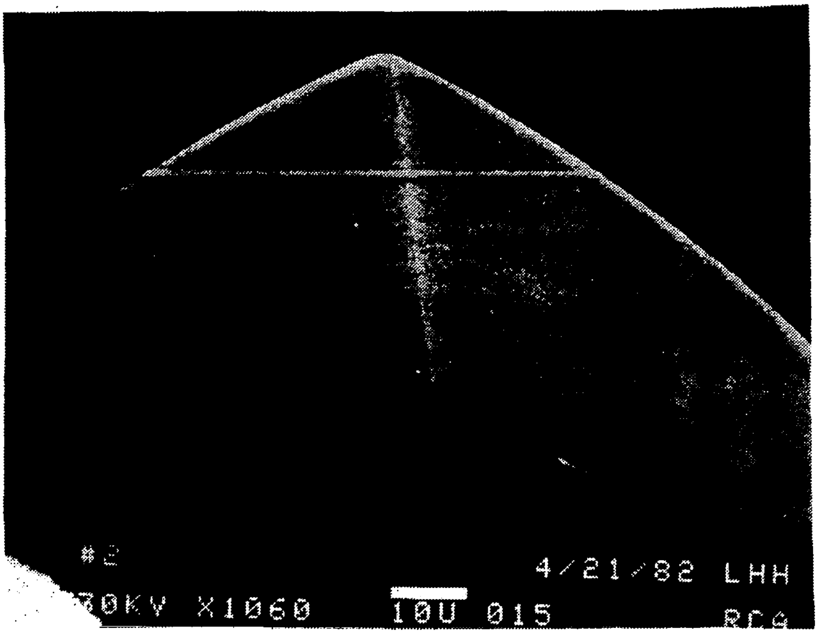


Figure 6. SEM photomicrograph of the polished wedge at the input end of the fiber.

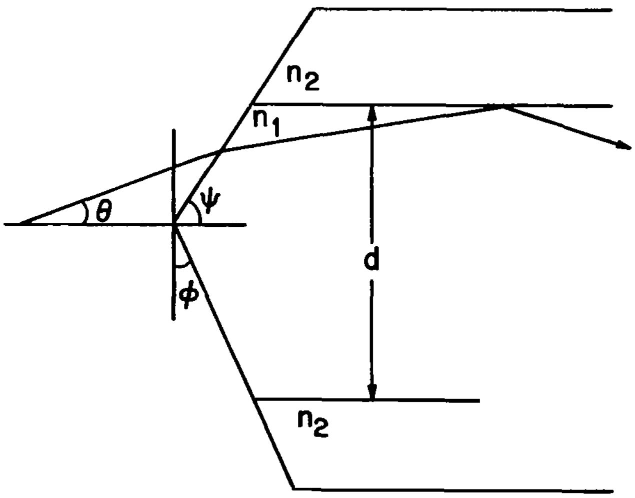


Figure 7. Geometry of the fiber acceptance angle.

time, onto one end of short sections of 0.2 N.A. graded index fibers with 50-μm core diameter. Using a CDH single-mode laser [1,22] with a beam full width at half maximum (FWHM) of 40° normal to the junction plane, at a distance of 15 μm, we obtained a coupling efficiency of 58%,[1] typical of values reported previously [20].

A convenient way of evaluating feedback is to record the spectrum of a single-longitudinal-mode laser directly and then compare it with the spectrum taken from a fiber driven by the same laser under identical conditions. Any feedback perturbs the laser and causes new spectral modes to appear [23]. Although not equal to that of Bludau and Rossberg [24] in detecting feedback, the method is sensitive; in the case of the channeled-substrate-planar (CSP) laser it was shown that [25] spectroscopy reveals feedback-induced modes at an external reflectivity of $2\text{-}4 \times 10^{-4}$. To make sure the observed feedback is not caused by other reflecting surfaces, it is essential that such other reflections be eliminated, especially at the far end of the fiber [26].

The method used here to avoid end reflections is to bevel the output end (fig. 8). The bevel angle ω must satisfy the inequality

$$\cos^{-1}(1/n_1) + \cos^{-1}(n_2/n_1) < \Omega < \sin^{-1}(n_2/n_1) \qquad (5)$$

The upper limit arises from the requirement that no light rays travel backwards within the core, and the lower limit assures that angles of incidence at the exit surface are less than critical. It is desirable to make ω as small as possible in order to get maximum attenuation of backwards reflected rays, but one should not design the bevel to be too close to the lower limit either, as that would cause reflection losses greater than 4% at the exit end. Most of the bevels used were in the vicinity of 55°, close to the critical angle for the fiber used. The output beam with such terminations is inclined toward the bevel, and the angle δ between the beam direction and the fiber axis is given by

$$\delta = \sin^{-1}(n_1 \sin \rho) - \rho \qquad (6)$$

where ρ is the complement to the bevel angle ω.

[1]We have not observed any significant reduction of coupling efficiency when the fiber was coated along a portion of its length with a mode-stripping compound. The efficiency measured here was lower than the 78% maximum reported in reference 20.

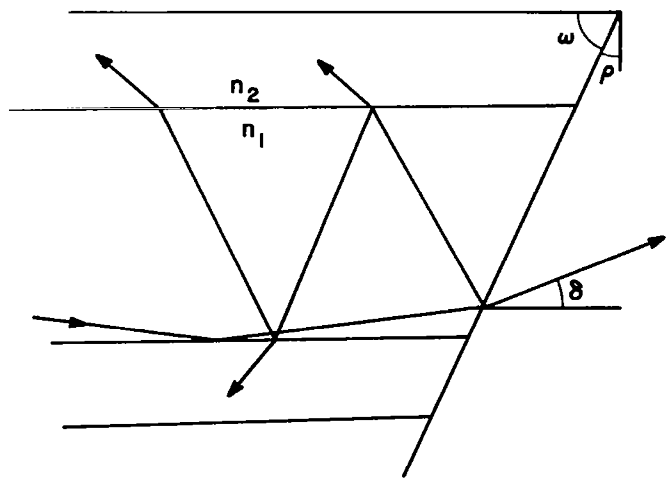


Figure 8. Geometry of the fiber output bevel.

A CDH single-longitudinal-mode laser was mounted on a temperature-stabilized block, and operated at a constant current with an output of about 3 mW. After the spectrum was recorded, a wedged fiber with beveled output end and a length of 30 cm was interposed between the laser and the spectrometer; then the spectrum was recorded again. Figure 9 shows that the two spectra are in close agreement. Thus, any optical feedback must be less than that causing spectral changes in CDH lasers.

The operating principles of the CDH laser and the CSP laser are different, and it is not known whether their sensitivity to feedback effects is similar. Assuming that they are not much different in this respect, we may conclude that the arrangement used, i.e., a wedge at the input end and a bevel at the output end, maintains the reflected power below the $\sim 10^{-4}$ level. Even lower reflectivities were reported in reference 24, although the authors do not make clear how they avoided reflections from the far end of the fiber. Thus 5 km of fiber with 2 dB/km attenuation may not be sufficient to prevent far-end reflections from dominating front-end reflections. In the present case, it appears that the bevel used at the end of a quite short section (30 cm) of fiber was effective in bringing the back-end reflections below the aforementioned ($\sim 10^{-4}$) level.

Equations (3) to (6) can only be taken as rough approximations for the case of parabolic-index fibers, the acceptance half-angle in that case being

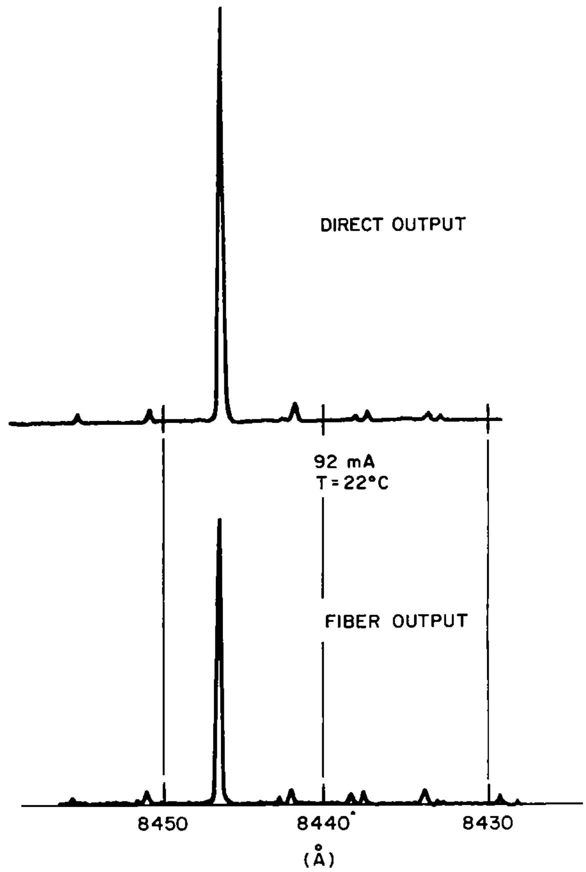


Figure 9. Spectra from a CDH single-mode laser. Upper figure: Direct output from laser. Lower figure: Output from fiber end.

smaller than predicted by equation (3). In general, the coupling efficiency of parabolic-index fibers is about equal to that of step-index fibers for laser sources, but is half for Lambertian radiators [27], where the error in these equations may be expected to be the greatest.

Wedged fibers of the kind described above are now being used for coupling single-mode lasers into multimode fibers, and some of these fibers were delivered to NASA for study and evaluation.

IV. HIGH-POWER LOC-TYPE SINGLE-MODE LASERS

Aside from single-mode stability under accelerated aging conditions and/or coupling-to-fiber conditions, objectives of the program were to improve both the high-power capability of single-mode devices as well as the rejection ratio between the main mode and the satellite modes in a single-mode device. Below we show results of spectral measurements on decibel (dB) scales for high-power single-mode CDH-LOC lasers, and describe the structure and results for a new type of high-power laser: the terraced-heterostructure large-optical-cavity (TH-LOC) laser.

A. SINGLE-MODE SPECTRA OF HIGH-POWER CDH-LOC DEVICES

By using high-power (i.e., ∿30 mW cw) single-mode CDH-LOC lasers and spectral measurements on decibel scales, we have studied the modal purity of CDH-LOC devices. We have reported previously [2] that above 20-mW output power levels we could not distinguish any longitudinal-mode satellites for spectra recorded on a linear scale: to better resolve the spectra we had to record them on decibel scales (fig. 10). At 10-mW output power the ratio between the main mode and its satellites is 20 dB. As the power is increased the ratio increases as well (i.e., the devices become more purely single mode). At 30-mW cw output power the main mode is 1000 times (i.e., 30 dB) stronger than its nearest satellites (fig. 10). The improvement in rejection ratio with increasing power agrees with the most current theories [4] on single-longitudinal-mode behavior in diode lasers. Results similar to the ones shown in figure 10 have been reported for CSP lasers, but only at power levels below 20 mW cw [28]. That is, CDH-LOC lasers have provided the highest power in a virtually pure (i.e., 30-dB rejection ratio) single mode. From a comparison of CDH with CDH-LOC devices it appears that the latter are better suited to achieving a rejection of satellite modes of 30 dB or better.

B. THE TH-LOC LASER

As part of the contract research effort we have investigated alternative approaches to the CDH-LOC laser structure for obtaining high-power single-mode operation. Our previous studies of LPE growth over channeled substrates [1] indicated that the relative position of the substrate-misorientation direction

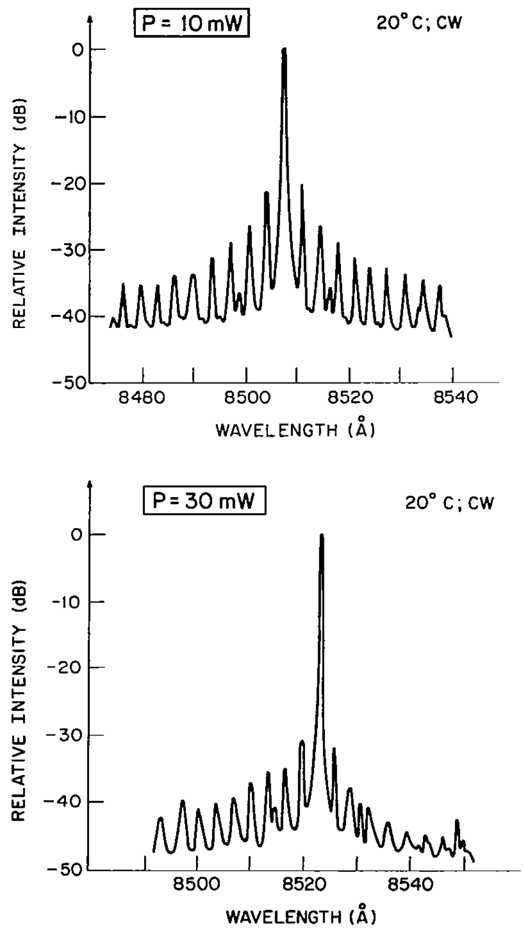


Figure 10. Typical cw spectra of CDH-LOC lasers at 10 mW per facet and 30 mW per facet, on a decibel (dB) scale.

with respect to the direction of the channels can affect the grown-structure geometry. Thus, when the substrate misorientation direction is parallel to the direction of the channels the grown structure is symmetrical; otherwise, the grown-structure geometry is asymmetrical. The definition of substrate misorientation and the influence of that misorientation on LPE growth over channeled substrates are shown schematically in figure 11. In this example the substrate is misoriented α degrees off the (100) plane toward the arbitrary direction [hkl]. Not only the amount of substrate misorientation is important, but also its relative position with respect to the direction of the channels. In figure 12, β, the angle between the channels' axis (i.e., [011]) and the [hkl] direction, is defined. Asymmetry in growth was observed for CDH-LOC structures

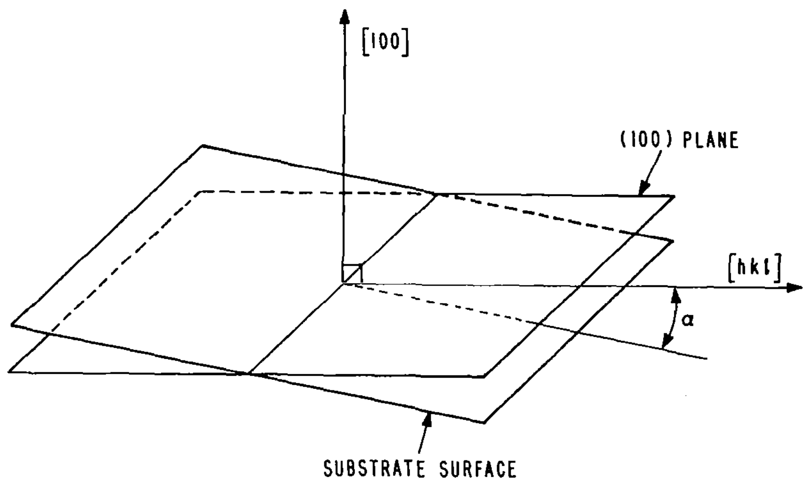


Figure 11. Diagram showing the effects of substrate misorientation on liquid-phase epitaxy over channels. The substrate is misoriented α degrees off the (100) plane and toward the [hkl] direction.

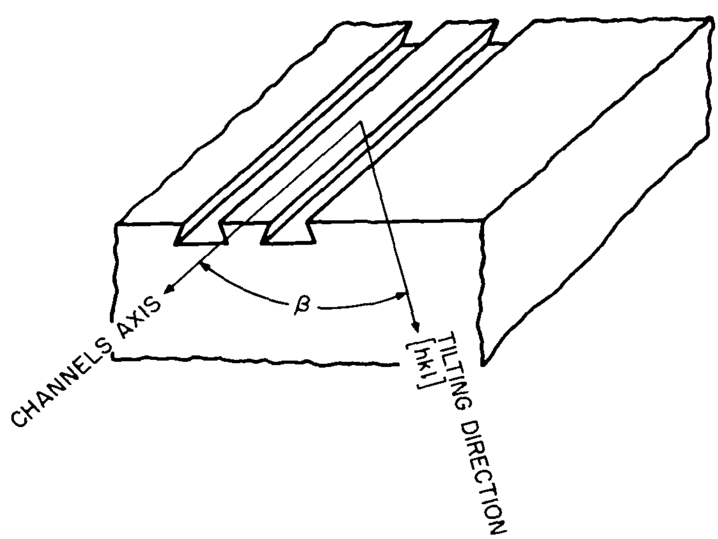


Figure 12. Diagram showing the definition of β, the angle between the substrate-misorientation direction (the tilting direction) and the axis of the channels.

where the angle β was between 20° and 45°. This asymmetry is a reflection of the LPE growth tendency to reconstruct the low-surface-energy (100) plane.

We grew on substrates where β took a maximum value (i.e., β = 90°), making the direction of the substrate misorientation perpendicular to the direction of the channels. The difference in growth was dramatic (fig. 13). Instead of the concave-shaped lasing cavity characteristic of the CDH-LOC structure, we obtained a large terrace-like cavity. The terrace is formed away from the originally etched substrate mesa, thus reflecting the strong tendency of LPE for reconstructing the (100) surface. The lasing cavity occurs on the terrace slope as a result of lateral variations in active- and guide-layer thicknesses. Due to its geometry, the novel structure was named terraced-heterostructure large-optical-cavity (TH-LOC) laser [29].

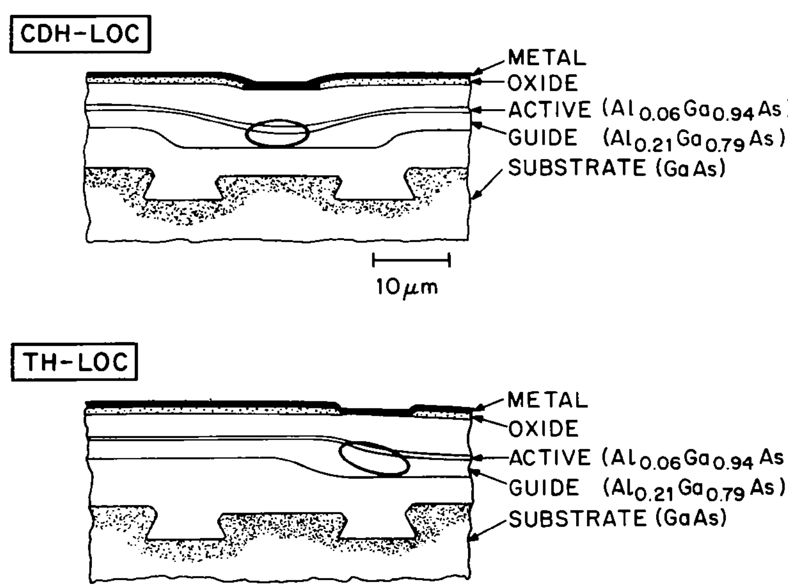


Figure 13. Schematic representations of the CDH-LOC and TH-LOC laser structures and their respective lasing areas.

From 5° angle-lapped cross sections it was found that both the active and the guide layers went through a maximum on the terrace slope. Thus, the active layer increases in local thickness from 0.12 to 0.16 μm over 7 μm in the lateral direction, while the guide layer reaches a maximum thickness of 2.25 μm at the terrace shoulder. The variations in active- and guide-layer thicknesses are illustrated in figure 14. The thickness variations are plotted with respect to the active-guide-layer interface. In the lateral direction everything is plotted with respect to the shoulder on the top surface of the guide layer. The various thickness variations combine to provide a weak lateral positive-index waveguide ($\Delta n \cong 3 \times 10^{-3}$) [fig. 14(c)], which allows a wide fundamental mode: 6.5 μm at $1/e^2$ points in intensity. Since the device is of the LOC type, the spot size in the plane perpendicular to the junction is wide as well: 2 μm at $1/e^2$ points in intensity.

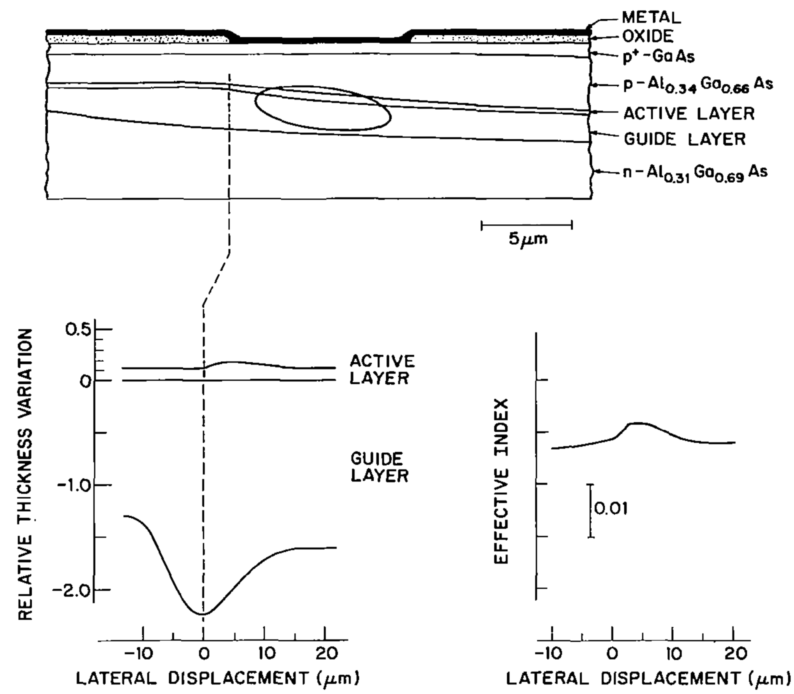


Figure 14. TH-LOC laser. Top: Schematic representation; the structure is drawn to scale with the exception of the active layer. The lasing spot is shown at $1/e^2$ intensity. Lower left: Active- and guide-layer thickness variations with respect to the active-guide layer interface. Lower right: Relative lateral variation of the effective refractive index corresponding to the thickness variations of the active and guide layers.

TH-LOC lasers were operated in cw operation and found to have thresholds in the 60- to 80-mA range (fig. 15). A notable characteristic of these threshold currents was their relative insensitivity to ambient-temperature variations,

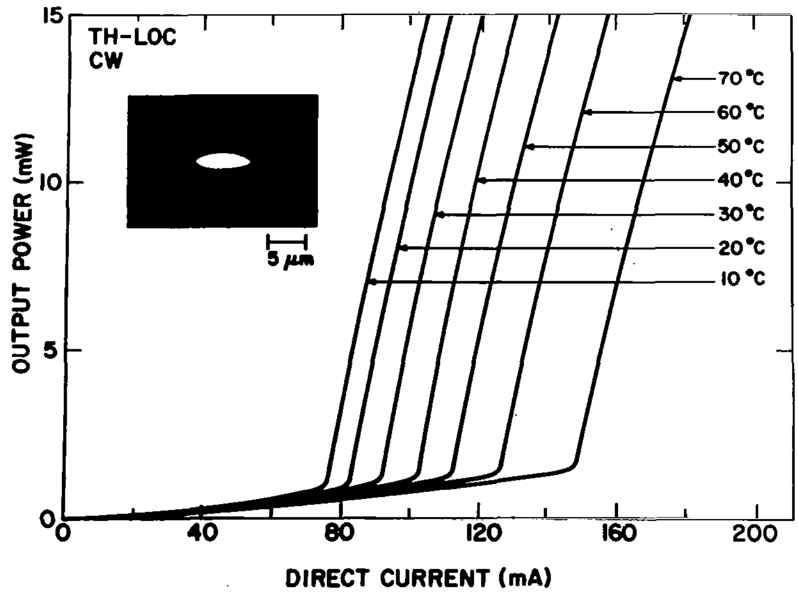


Figure 15. cw light-current characteristics of TH-LOC lasers at various ambient temperatures. Inset: High-resolution photograph of typical near-field pattern of TH-LOC lasers.

compared with the behavior of threshold currents in the CDH-LOC device. Specifically, while the threshold-current temperature coefficient T_0 is found to be 70-80°C in CDH-LOC lasers [2], in TH-LOC lasers T_0 has values of 190°C to room temperature and 105 to 50°C ambient temperature (fig. 16). We believe this enhancement in T_0 to be caused by temperature-dependent current focusing in the very same way in which this occurs in CDH lasers [1]. The current focusing effect in the TH-LOC structure is favored by the fact that the high-resistivity p-AlGaAs layer varies in thickness by a factor of two (i.e., from 1.5 to 3 μm) across the lasing cavity. The relatively high T_0 value as well as low thermal resistance values (R_{th} = 20-30°C/W) have allowed TH-LOC laser operation to 60 mW cw at room temperature and to 15 mW cw at 70°C ambient temperature.

Fundamental-mode cw operation has been obtained to a power level of 50 mW per facet (fig. 17). The beams are narrow ($\theta_{||}$ = 6°; $\theta_{\perp}$ = 23°) as a result of the large near-field spot size. Furthermore, the device operated in a single longitudinal mode to 50 mW cw (fig. 18). The 50-mW value is of importance as it represents the highest power into a single longitudinal mode ever reported from semiconductor diode lasers. The fact that a record-high single-mode power

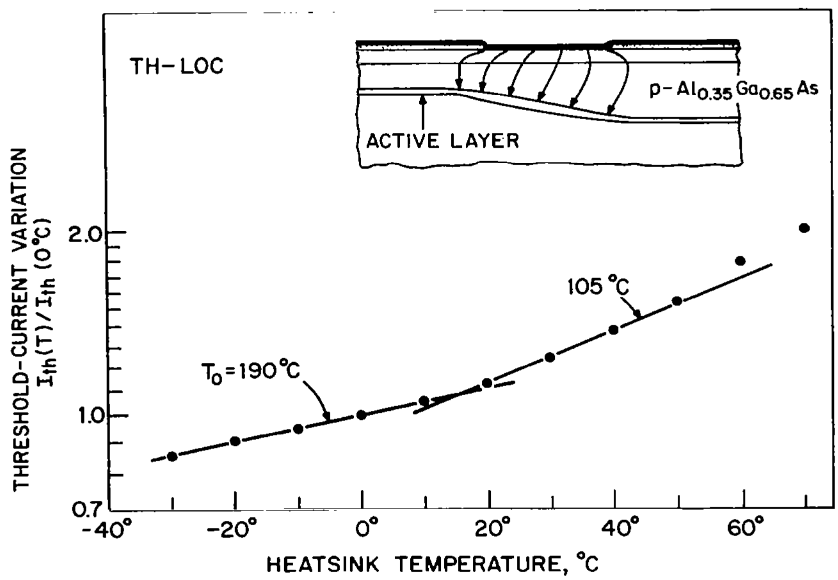


Figure 16. Threshold-current temperature dependence for TH-LOC lasers. Inset: Schematic representation of current focusing in TH-LOC structures.

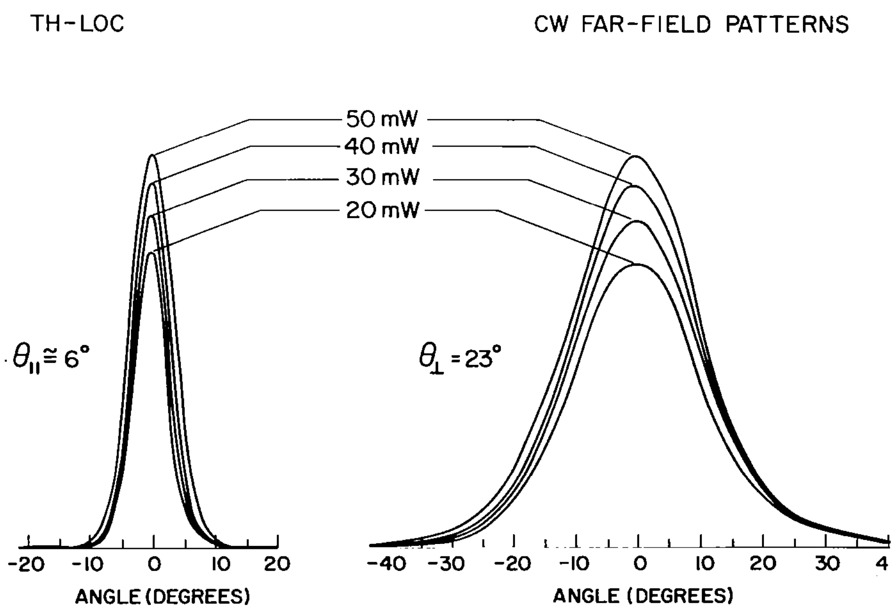


Figure 17. cw spectra of TH-LOC lasers at elevated power levels. At 50 mW from one facet, the diode is driven at 2.5 times threshold current. Spectrometer resolution: 0.15 Å.

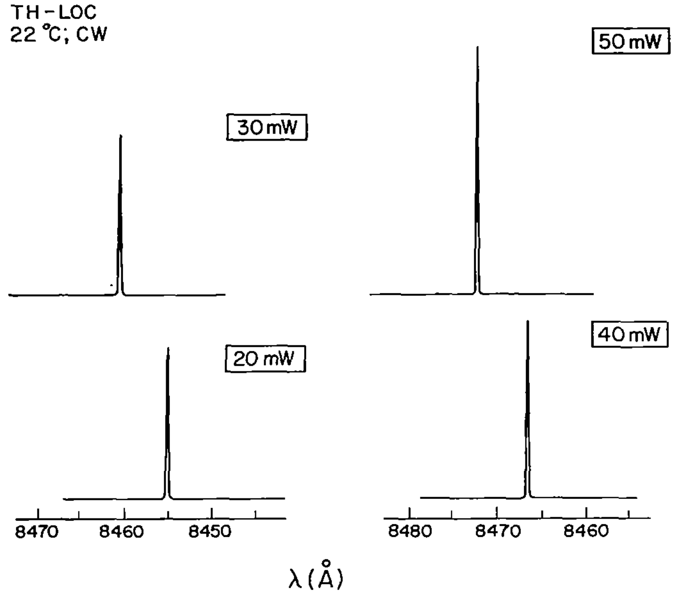


Figure 18. Typical cw far-field patterns of TH-LOC lasers in planes parallel and perpendicular to the junction.

is associated with a very large spot size tends to indicate that the upper limit of the single-mode operating regime in AlGaAs lasers depends directly on the emitted power flux density, as has been experimentally observed for GaAs TJS lasers at 77 K [30]. Our observations are also in agreement with current theories of longitudinal-mode behavior, which predict that the single-mode regime is limited by spatial hole burning [31] and/or intraband relaxation times [32].

In conclusion, we have realized a new type of high-power single-mode diode laser, one that provides the highest power into a single mode ever achieved. The TH-LOC structure is grown similarly to the CDH-LOC structure, the only difference being that the substrate is misoriented perpendicular to the direction of the channels.

V. CONCLUDING REMARKS

During the past year we have essentially fulfilled all the requirements of the program. Long-term reliability has been demonstrated for the CDH laser, as has its ability to maintain single-mode cw operation after long times (5000 to 10,000 h) on lifetest at elevated temperatures. The problems associated with the coupling of single-mode lasers to multimode fibers have been virtually eliminated by the use of wedge-shaped optical fibers.

As to high-power single-mode diode-laser operation, we have demonstrated 30-dB rejection ratios from CDH-LOC lasers operated around the 30-mW cw output power level. A novel LOC-type high-power device, the terraced-heterostructure LOC (TH-LOC), has been developed. The new structure exploits the properties of LPE over substrates misoriented perpendicular to the direction of the channels. Up to 50 mW cw has been obtained in single-mode operation; this is the highest single-mode power ever reported from diode lasers.

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16. Abstract

A study of single-mode spectral behavior with aging in CDH lasers is presented. CDH lasers have demonstrated excellent reliability ($\geq 10^6$ years extrapolated room-temperature MTTF) and single-mode operation after 10,000 hours of 70°C aging. The deleterious effects of laser-fiber coupling on the spectra of the diodes have been eliminated through the use of wedge-shaped fibers. A novel high-power LOC-type laser has been developed: the TH-LOC laser, which provides the highest power into a single-mode (i.e., 50 mW cw) ever reported.

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