Observation of Changes of Laser Beam Characteristics in Aged Oxide-Defined Narrow-Stripe Lasers

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Abstract—**Aged oxide-defined narrow-stripe lasers sometimes exhibit beam narrowing in both the near-field and far-field light distributions, accompanied by the development of sustained pulsations. The beam narrowing is found to correlate with the presence of a darkened area under the stripe viewed by cathodoluminescence imaging. We propose an explanation based on a thermal waveguiding effect resulting from increasing heat dissipation in the darkened area.**

THIS paper reports a study on changes of laser beam characteristics in aged oxide-defined narrow-stripe AlGaAs lasers. The changes are characterized by laser beam narrowing in both the near-field and far-field light distributions in some aged lasers, accompanied by the development of self-sustained pulsations. We have found a correlation between beam narrowing and the presence of a darkened area under the stripe in cathodoluminescence images viewed through the p-AlGaAs cladding layers. We propose an explanation based on a thermal waveguiding effect resulting from increasing heat dissipation in the center of the stripe. The fact that material defects cause sustained pulsations in semiconductor lasers is well established [1], [2]. However, changes in laser beam characteristics related to material degradation have not been reported before.

The oxide-defined narrow-stripe lasers we have studied are grown by liquid phase epitaxy. The lasing wavelength is around 8200 Å. The current isolation is provided by a 0.1-μm-thick SiO_2 film, and the stripe contact is made through 5-μm-wide openings in the oxide film. The wafer is cleaved into 250-μm-long bars and diced into chips which are indium-soldered onto a copper block heat sink. Before aging, the lasers are free from kinks and pulsations up to 15 mW, as expected for narrow-stripe lasers. The aging is carried out in a 70°C ambient at a constant light output of 7 mW/facet.

Fig. 1 shows an example of the CW near-field and far-field light distributions of a laser before and after aging. This laser has been under life test over 4000 h and has developed beam narrowing and sustained pulsations. The threshold current has risen from 100 to 130 mA. In most lasers, the far-field narrowing is more pronounced than the near-field narrowing. We note that the beam after narrowing, as shown in Fig. 1, remains symmetrical and well behaved, and the narrowing effect is not a result of kinks or bends in the light-current (*L-I*) characteristics, even though nonlinear *L-I* characteristics and beam movements often occur at high powers. The narrowed far field is not caused by wavefront distortion or multifilamentary operation resulting from facet damage, coating deterioration, or obstructions. These causes can be identified by inspecting the facet and by measuring the near-field light distribution.

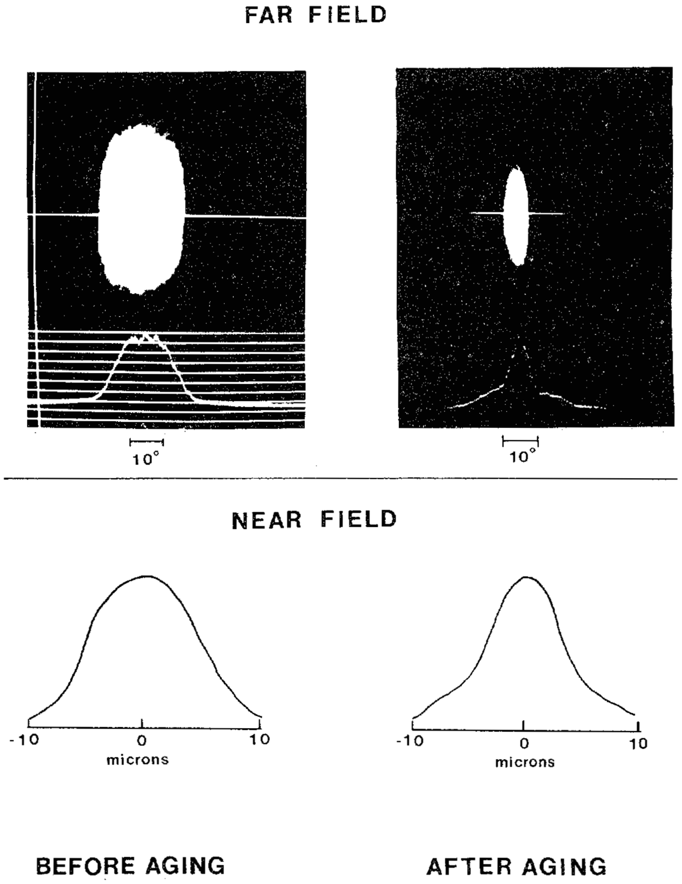

Fig. 1. Near-field and far-field light distributions of a laser before and after aging.

Fig. 2(a) shows the light output of the laser driven by two successive 1-μs-long square current pulses at 1.05 I_{th} and separated by 200 ns. There is considerable pulse distortion over a 1-μs period within each pulse. (The onset of sustained pulsations occurs at 1.1 I_{th}.) The unusual feature is that the light emission efficiency appears to increase with time. In addition, the intensity of the second pulse is strongly influenced by the presence of the first pulse. The interaction between pulses has been observed for pulse separations of up to 400 ns. The positive influence exerted by the first pulse on the second pulse is in contrast with a negative interaction observed in degraded index-guided lasers [2]. Fig. 2(b) shows the results of a time-

Manuscript received September 13, 1982.
The authors are with Optical Information Systems Inc., Elmsford, NY 10523.

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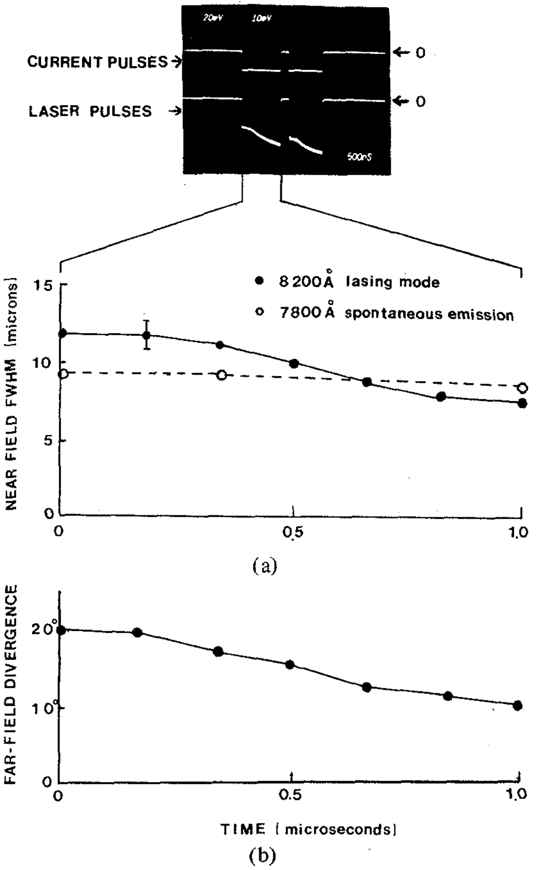


Fig. 2. (a)Waveforms of current pulses (upper trace) and laser pulses (lower trace) of an aged laser. (b)Near-field and far-field beamwidths measured as a function of time.

resolved lateral near-field and far-field measurement. One can see that a large beamwidth reduction of the lasing mode takes place over a microsecond period. In the meantime, the spontaneous emission profile at 7800 Å experiences only a slight reduction from 9 μm at time zero to 8.5 μm at 1 μs. The changes in beam characteristics of the lasing mode cannot be explained in terms of changes in gain- and carrier-induced refractive index profiles inferred from the spontaneous emission profile; an additional index-guiding mechanism must be included.

Based on the time scale of the beam narrowing, we propose an explanation based on the formation of index guiding due to a thermally induced refractive index distribution across the stripe. A similar thermal waveguiding effect has also been observed in oxide-defined narrow-stripe large-optical-cavity lasers [3]. The formation of index waveguiding concentrates the mode power to the center of the stripe. As a result, the modal absorption loss averaged over the beam cross section decreases, causing the pulse distortion shown in Fig. 2. In certain extreme cases, the onset of beam narrowing during a feedback-controlled constant-power life test results in a temporary decrease in laser current. The narrowing of the lasing mode also enhances carrier depletion in the center of the gain profile. It has been shown that the carrier-depletion-induced self-focusing acts to reduce the damping of relaxation oscillations, and thus promotes sustained oscillations [4], [5].

One might expect the thermal waveguiding to increase with aging, possibly because of deterioration of the thermal contact [6], [7]. However, unaged lasers with high thermal impedance (due to improperly done indium soldering) do not exhibit any beam-narrowing effect. This seems to rule out poor thermal contact as a major cause of thermal waveguiding. The reason for this is the magnitude of thermal impedance is not an indicator of the temperature gradient under the stripe relevant to thermal waveguiding. It has been suggested that, in oxide-defined narrow-stripe lasers, the lateral temperature distribution has maxima occurring outside the stripe [8] and, therefore, would not favor thermal waveguiding.

Increasing nonradiative recombination is another possible cause of thermal waveguiding. We have examined a number of aged lasers, with and without beam narrowing, using a cathodoluminescence imaging technique. The p-metallization, oxide film, and the p$^+$-GaAs capping layer of these lasers are removed chemically, and the emitted light is viewed through the p-AlGaAs layer. An example of a cathodoluminescence image of an aged laser showing beam narrowing is shown in Fig. 3(a). There is a dark band running along the stripe and covering most of the stripe region. Outside the stripe area is a relatively bright region extending ~50 μm from each side of the stripe. For comparison, the cathodoluminescence image for an aged laser without beam narrowing is shown in Fig. 3(b). In this case, there is no darkening under the stripe. Such correlation between stripe darkening and beam narrowing has been found in all lasers we have studied. Similar dark bands in photoluminescence and cathodoluminescence images have also been found by other workers in aged AlGaAs lasers [9], [10] and in InGaAsP LED's [11], and they have been attributed to defect migration under the strain field induced by oxide films [9] or the p-contact [11]. It is interesting to note that the stripe regions adjacent to the mirrors appear to be brighter than those in the middle of the stripe, presumably due to a modified strain field near the cleaved edges. The mirror darkening effect, which has been identified as a common feature of aged proton-delineated stripe-geometry lasers [12] and aged stripe buried-heterostructure lasers [1], has not been observed in these lasers. The dark bands in cathodoluminescence images represent a higher nonradiative recombination rate which can cause localized heating. Since the width of the dark bands (~5 μm) is narrower than that of the carrier profile (~10 μm), the temperature gradient thus produced should be larger than in normal lasers. Increasing heat dissipation in the center of the stripe can modify the bandgap and cause more current to flow through the center [13]. This interdependence of temperature and current distributions may lead to a runaway situation.

The magnitude of the peak value of the refractive index change Δn_T due to localized heating can be estimated from the observed beamwidth reduction. We assume that the dielectric constant variation in the junction plane has a form similar to that used in [14]:

$$\epsilon(x) = \epsilon_0 + (\Gamma(2n\Delta n_c + ign/k) + 2n\Delta n_T)\operatorname{sech}^2(x/w) \quad (1)$$

where Γ is the vertical confinement factor, g is the gain constant, n is the refractive index of GaAs, Δn_c is the free-carrier-induced refractive index change, and w is the width parameter.

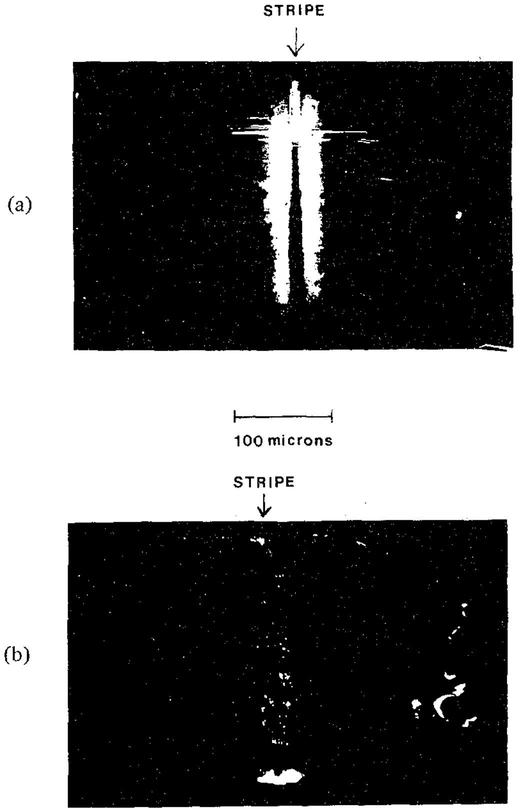


Fig. 3. Cathodoluminescence image viewed through the p-AlGaAs layer of aged lasers (a) with and (b) without beam narrowing. The large dark spot to the left of the stripe in (b) is due to a drop of epoxy for electrical contact.

(In general, the temperature variation in the junction plane may be approximated by $\mathrm{sech}^2(x/D)$ with $D \neq w$. In this case, the dielectric constant variation in the vicinity of the center of the stripe can be expressed in the form of (1) by replacing Δn_T with $\Delta n_T(w/D)^2$.) We use $g = 450$ cm^{-1}, $\Delta n_c = -3\ g/k$ [14], and $w = 6.5$ μm. The calculated near-field and far-field light distributions for different Δn_T are plotted in Fig. 4. Without thermal waveguiding, the far-field pattern has a slight depression in the center with a FWHM divergence of 22°. In order to explain a 50 percent reduction in the far-field beam divergence (or a ~20 percent reduction in the near-field beamwidth), we need $\Delta n_T = 0.003$. Using $dn/dT = 5 \times 10^{-4}/°\mathrm{C}$ [15], the index difference translates into a temperature increase of 6° C.

The material degradation induced beam-narrowing effect described in this paper is undesired in applications using optical fibers. It has been suggested [9], [10] that the material degradation is caused by the strain field introduced during device fabrication. We believe that the material quality is also an important factor since some wafers fabricated by the same technique are substantially more resistant to this type of degradation. Further study is needed to understand the effect of material defects and laser fabrication processing on device reliability.

ACKNOWLEDGMENT

The authors wish to thank OIS LPE and processing groups for laser fabrication, J. Duda and R. Bertaska for valuable technical assistance, and S. R. Chinn and P. S. Zory for comments and suggestions.

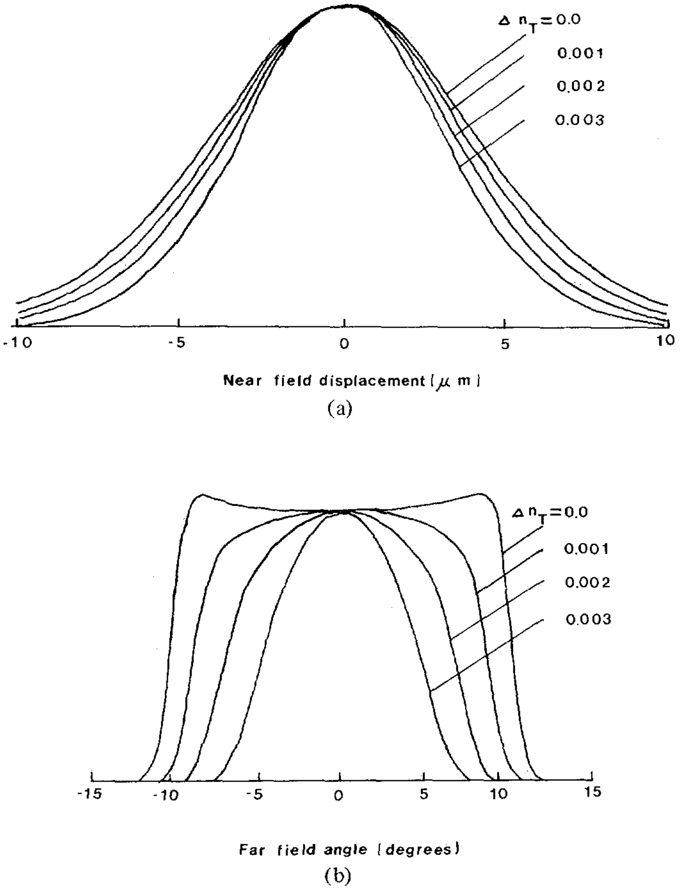


Fig. 4. Calculated near-field and far-field light distributions for different thermally induced refractive index change Δn_T.

REFERENCES

[1] R. L. Hartman, R. A. Logan, L. A. Koszi, and W. T. Tsang, "Pulsations and absorbing defects in (Al, Ga) As injection lasers," *J. Appl. Phys.*, vol. 50, pp. 4616-4619, 1979.

[2] C. H. Henry, R. A. Logan, and F. R. Merritt, "Pulsations in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ buried heterostructure lasers caused by the heating of defects," *J. Appl. Phys.*, vol. 52, pp. 1560-1573, 1981.

[3] Y. C. Chen, A. R. Reisinger, and S. R. Chinn, "Thermal waveguiding in oxide-defined, narrow-stripe large-optical-cavity lasers," *Appl. Phys. Lett.*, vol. 41, pp. 129-131, 1982.

[4] R. Lang, "Intensity pulsation enhancement by self focusing in semiconductor lasers," *Japan. J. Appl. Phys.*, vol. 19, pp. L93-L96, 1980.

[5] J. P. van der Ziel, "Self-focusing effects in pulsating $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ double-heterostructure lasers," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 60-68, Jan. 1981.

[6] H. Kressel, M. Ettenberg, and I. Ladany, "Accelerated step-temperature aging of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ heterojunction laser diodes," *Appl. Phys. Lett.*, vol. 32, pp. 305-308, 1978.

[7] K. Fujiwara, T. Fujiwara, K. Hori, and M. Takusagawa, "Aging characteristics of $\mathrm{Ga}_{1-x}\mathrm{Al}_x\mathrm{As}$ double heterostructure lasers bonded with gold eutectic alloy solder," *Appl. Phys. Lett.*, vol. 34, pp. 668-670, 1979.

[8] J. S. Manning, "Thermal impedance of diode lasers: Comparison of experimental methods and a theoretical model," *J. Appl. Phys.*, vol. 52, pp. 3179-3184, 1981.

[9] B. Wakefield, "Strain-enhanced luminescence degradation in GaAs/GaAlAs double-heterostructure lasers revealed by photoluminescence," *J. Appl. Phys.*, vol. 50, pp. 7914-7916, 1979.

[10] M. J. Robertson, B. Wakefield, and P. Hutchinson, "Strain-related degradation phenomena in long-lived GaAsAs stripe lasers," *J. Appl. Phys.*, vol. 52, pp. 4462-4466, 1981.

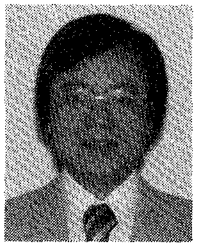
[11] A. K. Chin, M. A. DiGiuseppe, and W. A. Bonner, "Stress-induced defect migration in InP/InGaAsP double-heterostructure wafers," *Mater. Lett.*, vol. 1, pp. 19-21, 1982.

[12] R. L. Hartmann and L. A. Koszi, "Characterization of (Al, Ga)As injection lasers using the luminescence emitted from the substrate," *J. Appl. Phys.*, vol. 49, pp. 5731-5744, 1978.

[13] T.J.S. Mattos, N. B. Patel, and F. D. Nunes, "Calculation of the threshold current of stripe-geometry double-heterostructure GaAs-$Ga_{1-x}Al_xAs$ lasers, including a self-consistent treatment of the current-temperature dependence," *J. Appl. Phys.*, vol. 53, pp. 149-155, 1982.

[14] P. M. Asbeck, D. A. Cammack, and J. J. Daniele, "Non-Gaussian fundamental mode patterns in narrow-stripe-geometry lasers," *Appl. Phys. Lett.*, vol. 33, pp. 504-506, 1978.

[15] T. L. Paoli, "Waveguiding in a stripe-geometry junction laser," *IEEE J. Quantum Electron.*, vol. QE-13, pp. 662-668, Aug. 1977.



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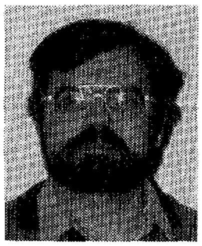

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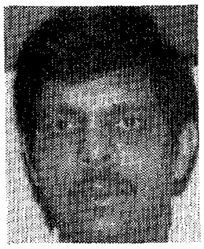

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