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Gain broadening mechanism in various GaAlAs laser structures

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Coupling of an external grating to a GaAlAs laser results in a strong enhancement of the selected mode and a reduction of the nonselected modes. The spectral form of this reduction is measured with a new sensitive experimental arrangement for three types of laser structures: proton bombarded stripe geometry, V-groove and CSP lasers. This spectral form is determined by the gain curve of the laser only and is independent on the position of the selected mode, i.e., no spectral hole burning is observed at room temperature.

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I. INTRODUCTION

Some of the basic physical properties of semiconductor lasers are not yet cleared up. Among these is the question of whether the gain of the laser is broadened homogeneously, i.e., the carrier distribution in the oscillating laser still follows the Fermi-Dirac law, or, whether the main lasing modes do burn a spectral hole into the gain curve. Various approaches have been used to treat the problem theoretically[1-5] and, sometimes, predictions have been rather contradictory. The same holds for various experimental investigations of this problem.[6-11] Even in the same type of experiment as, e.g., the optical coupling of an external grating to one facet of a semiconductor laser,[6] both homogeneous gain broadening and spectral hole burning were observed.[7,8] This means, that either experimental accuracy or the different structures of the lasers are causing such discrepancies.

We repeated the experiment with the externally coupled grating using a more sensitive measurement technique and several different types of lasers. Our experiments show that the homogeneous broadening mechanism is dominant in all laser structures investigated. This is true even in the case when laser current is close to threshold where, at first sight, inhomogeneous gain broadening seems to appear.[7]

A comparison of the different laser structures shows that the laser with additional optical confinement reacts much more sensitively to external optical feedbacks, probably owing to the small spontaneous emission factor inherent to these laser structures.[12]

II. EXPERIMENTS

The lasers used are conventional proton bombarded stripe lasers with a stripe tilted by an angle of 2°, V-groove lasers[13] and CSP lasers.[14] The data of the lasers which were used for this publication are compiled in Table I. In the case of the first two types of lasers the gain is confined by current only, whereas in the case of the CSP laser an additional optical confinement is introduced. All lasers show a completely linear light-current characteristic without kinks and are oscillating in the fundamental transverse mode. dc excitation was used in all experiments. Far above threshold the lasers with only gain confinement show multilongitudinal mode emission whereas the CSP laser shows single longitudinal mode emission.[10]

Figure 1 shows a block diagram of the experimental setup. Using a lock-in and two boxcar amplifiers with appropriate gate position (see Fig. 1), the following three spectra could be recorded simultaneously: The spectra of the laser with and without grating (boxcar 1 and 2) and, very sensitively, the difference of the two spectra (lock-in). The simultaneous recording of these spectra is necessary, since alignment is rather critical and sensitive to external distortions.

The ruling of the grating (1200 lines/mm) was oriented parallel to the *pn* junction of the laser. Thus high resolution was achieved ($\simeq 0.2$ Å with a distance grating laser of about 40 cm; this value was checked experimentally).

Some spectra were taken more rapidly using a rotating diffraction plate at the entrance slit of the spectrometer.[15] The mode spectrum is then visualized on the screen of an oscilloscope from which pictures can be taken.[6]

The double spectrometer (1-m focal length, 1200 lines/mm) guaranteed high stray light suppression. Typical slit widths used were $10\,\mu m$, resulting in an optical resolution of about 0.1 Å.

Some low-temperature experiments were performed in a liquid-nitrogen dewar.

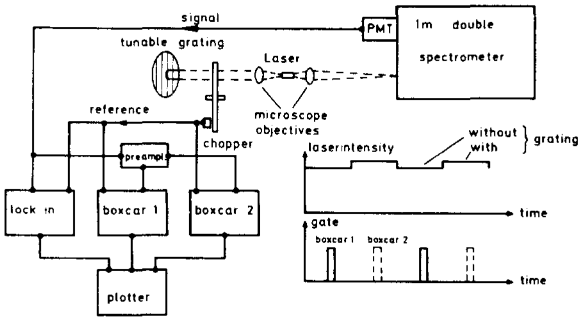

FIG. 1. Block diagram of the experimental setup. The position of the gates of the two boxcars is illustrated in the insert.

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TABLE I. Structure, origin, and threshold of the lasers used in our experiments.

Laser number	Laser structure	Origin	Threshold mA at 295 K
T 1155	Proton bombarded stripe geometry	Hewlett-Packard	105
T 1303	Lasers (7-μm stripe tilted by 2°)	Hewlett-Packard	91
ZH A4	V-groove laser	AEG-Telefunken	83
4682	Channelled substrate planar	Hitachi	73
4683	Stripe lasers (CSP)	Hitachi	74

III. RESULTS AND DISCUSSION

Figure 2 shows three spectra taken simultaneously of a proton bombarded stripe laser: a) spectrum with grating, b) spectrum without grating, and c) difference between spectrum a) and b) measured with lock-in technique. Obviously the reduction of the nonselected modes in spectrum c) is directly correlated to the peak heights of these modes in spectrum b). In particular, the modes close to the selected mode are not especially reduced. A tuning of the selected mode in a wavelength range of ± 40 Å was possible with this type of laser, always resulting in a reduction of the modes directly correlated to their original peak height, i.e., if the peak height of the two modes is identical the reduction is the same no matter whether it is directly besides the strong, selected mode or 60 Å away. Exactly the same result is obtained for various currents as well for the proton bombarded stripe as for the V-groove laser. A direct comparison with the CSP laser can be made only in a region where it is oscillating in several longitudinal modes, i.e., at currents close to threshold. Corresponding spectra taken just below threshold are shown in Fig. 3.

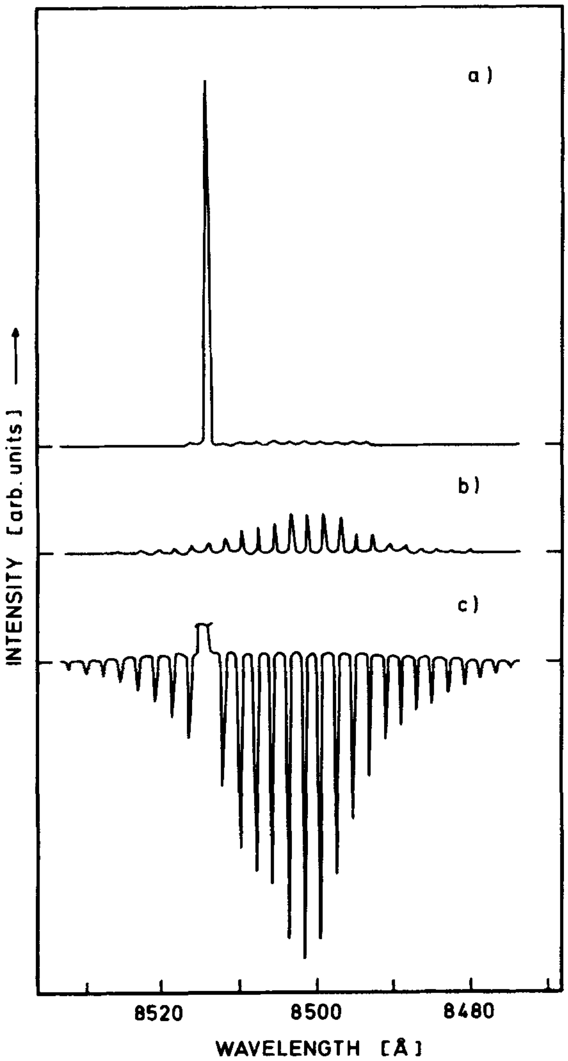

FIG. 2. Simultaneously recorded spectra of laser T 1155 (295 K, 119 mA): a) with grating, b) without grating—same scale as a), and c) difference a)–b) in enhanced scale.

Now, the peak height of the modes is directly correlated to the gain of the active region at the corresponding wavelength.[16] Therefore all these data show that homogeneous gain broadening is by far the dominating mechanism in all these laser structures. Any spectral hole burning effect would be visible strongly enhanced, since the peak height of the modes reacts rather sensitively to any changes in the gain curve.[10,11]

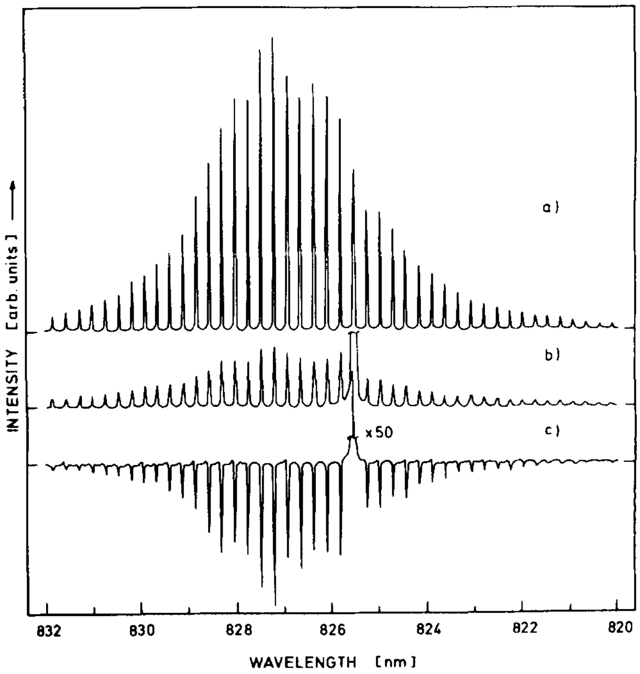

FIG. 3. Spectra of laser 4683 just below threshold (295 K, 73.8 mA): a) without grating, b) with grating, and c) difference b)–c).

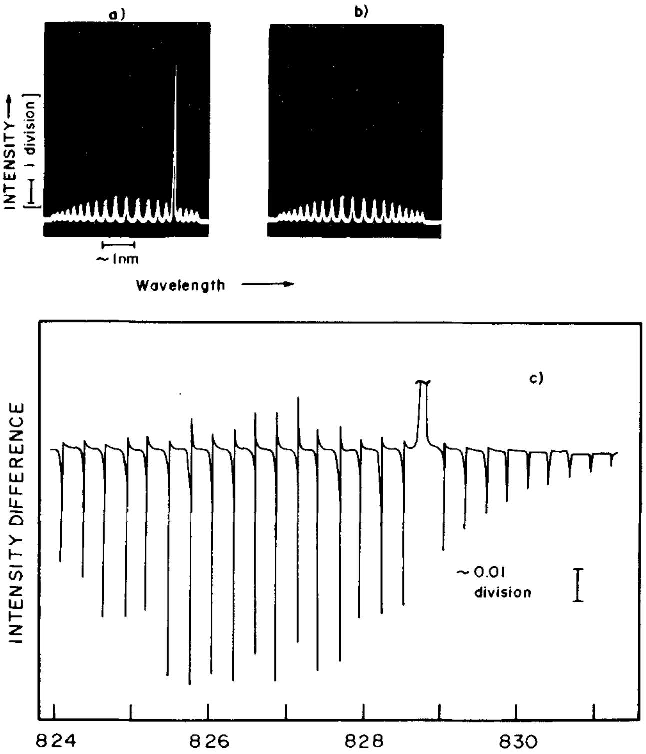

FIG. 4. Spectra of laser 4683, further below threshold (295 K, 72.4 mA): a) with grating, b) without grating, and c) difference a)–b) in strongly enhanced scale (see corresponding bars).

A quantitative estimate can be made: With a peak to valley ratio of about 300 a change in gain of 1% would alter the externally observable peak intensity by about 10%.[11] Since our experimental accuracy is certainly better than these 10%, we conclude that spectral hole burning effects in our experiments are certainly smaller than 1%.

At a power of about 10 mW in the single longitudinal mode one can compare this experimental value with the gain suppression as it is calculated for different intraband relaxation times by Yamada and Suematsu.[5] Even with a cautious estimate we conclude that either the relaxation time in our lasers must be faster than 2×10^{-13} sec or one of the assumptions in the theory (as, e.g., validity of the k-selection rule) is invalid.

Let us now demonstrate that the apparent spectral hole burning effect as it was observed in the experiments on InGaPAs lasers by Wright *et al.*[7] probably is simply due to lack of sensitivity. In Fig. 4, parts a) and b), two spectra of a CSP laser are shown with, a), and without, b), grating. In this experiment current was further below the threshold (without grating) than in Fig. 3. Apparently, no reduction of the nonlasing modes is observed, i.e., the experimental result is the same as in Ref. 7. Using, however, the more sensitive lock-in technique, as shown in part c) of Fig. 4, a small reduction of all the other modes is clearly seen. Once more the reduction follows the gain curve of the laser, i.e., the broadening is homogenous. Thus the conclusion is wrong that no visible reduction in the original spectrum means that inhomogeneous broadening takes place. The explanation for the small reduction is simple: Owing to the low intensity of the selected mode only few carriers are needed for stimulated emission. Since these carriers are drawn homogeneously from all energies, the reduction of gain at all energies is small. The absolute value of gain being just below threshold small, too (note the small peak to valley ratio in Ref. 7), the reduction of the external visible intensity is expected to be even smaller. Therefore it might not be visible if a sensitive technique is not used.

Coupling a grating to a CSP laser at currents far above threshold is a case which must be considered separately, since then the spectrum already consists of a single longitudinal mode without the external grating. Figure 5 shows schematically the intensity distribution of the lasing and nonlasing modes without grating, a), and with the grating tuned to different wavelengths, b) and c). With this laser the lasing wavelength can be changed up to 60 Å without substantial loss in intensity. The fact that the externally selected mode suppresses the inherent single longitudinal mode even at a distance of 60 Å shows that no spectral hole burning takes place.

On the other hand, the intensity of the nonlasing modes increases when the intensity of the lasing mode is reduced [compare parts a)–b) of Fig. 5]. This holds also for the modes which are close to the externally selected mode, although their intensity increase is much smaller owing to the smaller gain at these wavelengths. No anomaly in the intensity dis-

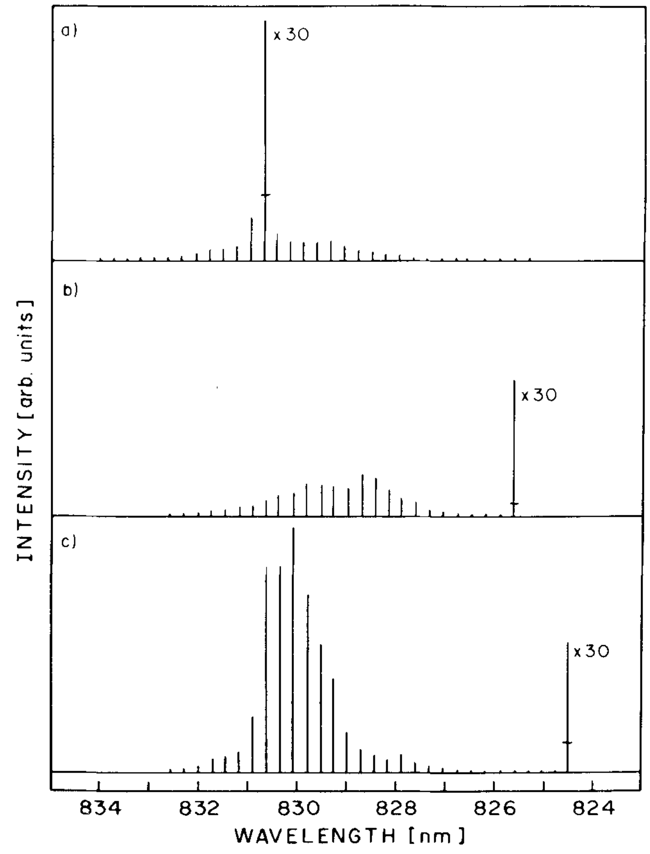

FIG. 5. Intensity distribution of the modes of laser 4682 (295 K, 118.1 mA): a) without grating, b) and c) with grating tuned to different wavelengths.

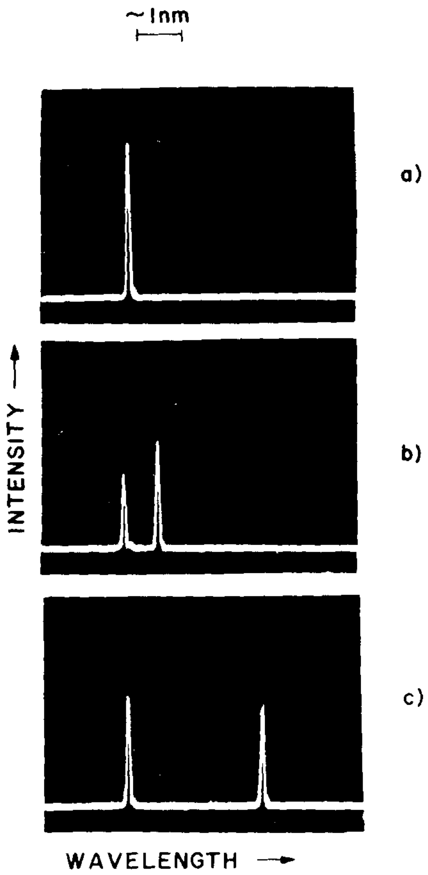

FIG. 6. Spectra of laser 4682 (295 K, 129.9 mA): a) without grating, b) and c) with horizontally slightly misaligned grating tuned to two different wavelengths.

tribution of the nearest and next nearest nonlasing modes is observed in contrast to the case of the inherent single mode [see Fig. 6(a) and Fig. 4 of Ref. 10]. These observations might lead to the conclusion that other effects than spectral hole burning cause the reduction of the nonlasing modes with increasing current in the case of the CSP laser.

For reasons of completeness, a few other effects observed with the CSP laser are to be mentioned: (i) Coupling of the external grating results in a mode broadening. (ii) By slightly misaligning the grating in a horizontal direction, operation in two longitudinal modes is possible. This effect is demonstrated in Fig. 6. (iii) A strongly misaligned grating causes multilongitudinal mode emission even far above threshold. (iv) Using the chopper introduces instabilities in the single mode operation due to the on- and off-switching of the reflection from the grating.

(i)–(iv) might be explained with the assumption that the spontaneous emission factor into the lasing modes which is especially small for CSP lasers[12] is enhanced by the external (misaligned) grating. However, a more detailed comparison of experiment and the theory of Petermann[12] is not yet possible due to the still rather qualitative nature of both works.

Although the behavior with respect to the broadening mechanism is rather identical for the different types of lasers, they differ drastically in the absolute value of "sensitivity" on the external optical coupling: The V-groove laser shows only a very small enhancement of the single selected mode combined with a small (nevertheless homogeneous) reduction of the other modes. The effect is two to three orders of magnitude larger for the CSP laser. The proton bombarded stripe laser (with tilted stripe) is situated in between these extremes.

It appears that this sensitivity to external perturbations is correlated with the spontaneous emission factor into the lasing modes. Perhaps the reduced spontaneous emission factor in case of the additional optical confinement is the reason for the single longitudinal mode emission of the CSP and BH laser[12] and not the excess gain suppression of the neighboring modes.[5]

Finally, Fig. 7 demonstrates the influence of temperature: With the proton bombarded stripe laser only a small enhancement of a selected mode was possible. The reduction of the other modes seems to be inhomogeneous in the sense that it is larger on the high-energy side and no more determined by the peak height only. However, further investigations are needed in order to decide whether indeed inhomogeneous gain broadening takes place or whether the expressed reduction on the high-energy side is due to other

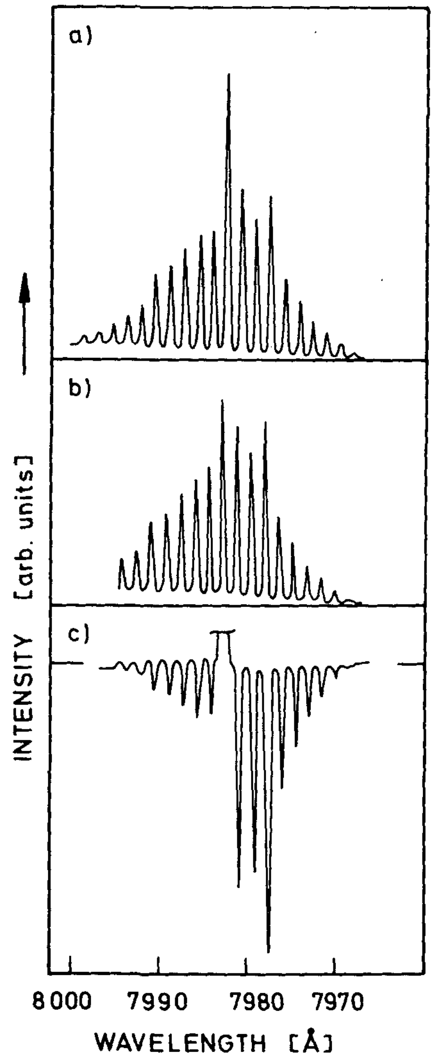

FIG. 7. Spectra of laser T 1155 at low temperatures (77 K, 45 mA): a) with grating, b) without grating, and c) difference a)–b).

effects. Unfortunately, this low-temperature experiment is not possible with the other two types of lasers: The V-groove laser, which at room temperature already shows a small enhancement, does not show any effects at low temperatures. The CSP laser, which we have, cannot be operated at liquid-nitrogen temperature (for unknown reasons we observed a parallel resistance at 77 K).

In conclusion, we have shown that at room temperature the broadening mechanism in proton bombarded stripe, V-groove, and CSP lasers is predominantly homogeneous. There is no evidence for any kind of spectral hole burning. This result is in agreement with the result of Bachert *et al.*[8] It appears that some of the effects which are observable with the CSP laser as, e.g., reduction of the nonlasing modes, jumpy changes in the emission spectra with increasing currents, and the hysteresis behavior in the mode wavelength-current diagram[10] are due to other effects than spectral hole burning.

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