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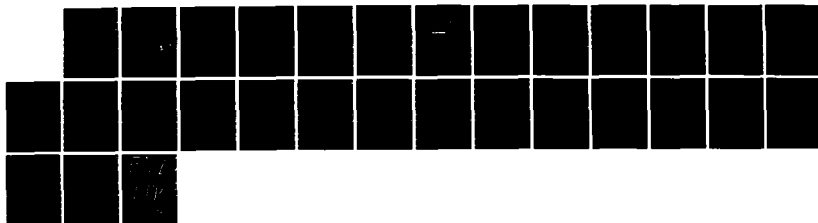
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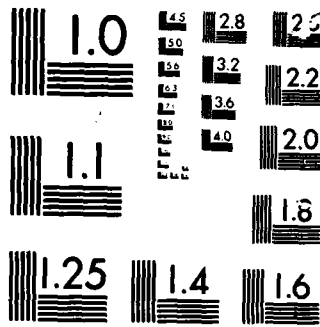
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FINAL REPORT

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Optoelectronic Devices and Related Physical Phenomena
in Thin Film Semiconductor Configurations

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INTRODUCTION

The following report summarizes the main findings of the research program in "Optoelectronic Devices and Related Physical Phenomena in Thin Film Semiconductor Configurations." The main areas of research were:

1. Laser Arrays
2. Unstable Resonator Semiconductor Lasers
3. Novel Laser Structures and Laser Physics
4. Theory and Measurement of Noise in Semiconductor Lasers

These are described in detail in what follows.

1. LASER ARRAYS

Until recently, almost all semiconductor laser phased arrays have suffered from undesirable double lobed far-field patterns. During the past several years we have, therefore, undertaken a thorough theoretical and experimental study of phased arrays which culminated in the demonstration of several new array structures which achieve the desired single lobe far-field operation.

Most of the published works on the subject of semiconductor laser coherent power combining have reported various configurations of laser arrays on common substrates. The lasers are placed in close proximity to each other so there is sufficient interaction to assure their phase-locking. An important feature of such arrays is that a single contact is applied to all the lasers, i.e., they are internally connected electrically in parallel. This has important consequences regarding the operation of the array, since individual diode elements

cannot be accessed independently and thus there is no control over the internal functioning of the device. In response to this problem we have designed, fabricated and tested a novel type of 8-element phase-locked semiconductor laser array where each diode laser has its own separate contact⁽³⁾ (Figure 1a), which provides an additional degree of freedom in the design of monolithic arrays which can be used for example, to compensate for device-to-device nonuniformities, tailor the near-field and far-field distributions and perform other functions.⁽⁴⁾ This array also serves as a small-scale "laboratory" for investigating the basic physical processes governing the coupling interactions among the integrated lasers.

Experimental results include the demonstration of control over the near-field (Figure 1b),⁽²⁾ the far-field^(4,5) distributions of several elements of the array. A reduction in the number of longitudinal modes and single longitudinal mode operation has been achieved.⁽⁴⁾ In addition, basic beam scanning has been demonstrated,⁽⁶⁾ and coupling mechanisms were investigated and found to be different in gain-guided lasers as compared to the evanescent wave coupling typically assumed for real index-guided lasers.^(7,8)

An eight element monolithic array of GaAlAs electroabsorption modulator has been demonstrated by reverse bias operation of the separate contact array.⁽⁷⁾ This device may be useful for intensity modulation in high spatial resolution applications.

Uniform semiconductor laser arrays tend to oscillate in a superposition of their supermodes, thus leading to large beam divergence and spectral spread. We have shown that supermode discrimination in gain-guided arrays, in favor of the desired

fundamental supermode, is made possible by the near-field interference patterns which result from the complex optical fields of the gain-guided lasers.⁽¹⁰⁾ We have also demonstrated a uniform array which utilizes diffraction effects to couple the lasers.⁽⁹⁾

The main impediment to fundamental mode operation uniform evanescently coupled arrays is the existence of strong absorption in the interchannel regions. This absorption favors the oscillation of the out-of-phase supermodes which best "avoid" these lossy regions.⁽¹⁵⁾ We developed a new array structure based on a square wave transverse modulation of the effective index in which the gain is uniform across the transverse dimension, thus removing the incentive for higher supermode oscillation and again leading to single lobed far-field operation.⁽⁹⁾

We proposed nonuniform structures⁽¹¹⁾ of phase-locked diode lasers, which make it possible to discriminate efficiently against all the higher order array supermodes. In these chirped arrays, the envelopes of the various supermodes, including the highest order one, differ significantly from each other. Thus, by proper tailoring of the gain distribution across the array, one can select the fundamental supermode. We then demonstrated a single contact tailored gain chirped array⁽¹²⁾ in which the gain profile across the array is made strongly asymmetric by varying the width of the contact stripes. The device exhibited single lobed operation close to the diffraction limit for a single supermode. Fabrication of this device is simple, and suited to large-scale processing techniques.

Finally, we have carried out a rate equation analysis of phase-locked semiconductor laser arrays.⁽¹³⁾ It was found that for given

(laser) current densities, the photon density distribution in the array elements is that particular one which maximizes the total photon density. The results of this analysis were then combined with the waveguiding properties of the laser array waveguide, yielding a basic model of phase-locked diode laser arrays. This model explains the effects of the variation of the current combination through the array elements on its mode structure that were observed recently.

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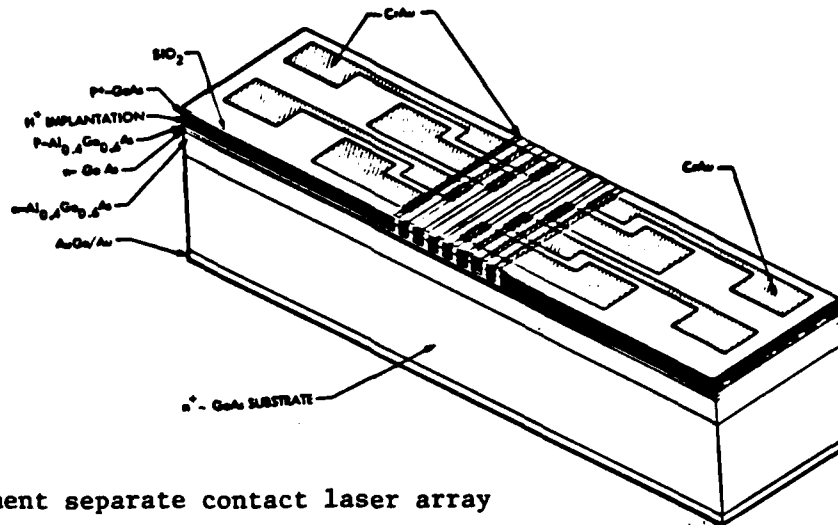


Fig. 1(a): 8 element separate contact laser array

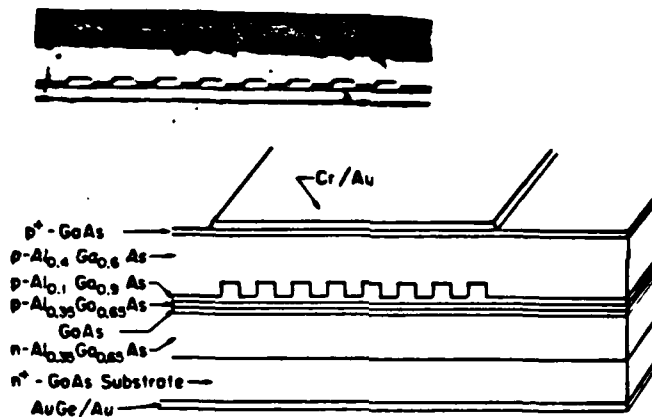


Fig. 1(b): Buried ridge phased array

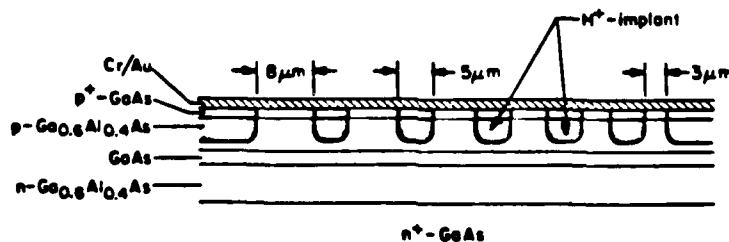


Fig. 1(c): Single contact tailored gain chirped array of proton implanted lasers.

2. UNSTABLE RESONATOR SEMICONDUCTOR LASERS

Laser cavities of the unstable resonator (UR) type have been shown to exhibit many advantages when combined with a lasing medium characterized by a high single-pass gain.⁽¹⁷⁻²⁰⁾ The most prominent of these advantages is the potential for increasing the mode volume of a laser oscillator while maintaining high discrimination between transverse modes. As a result, the cavity is relatively insensitive to inhomogeneities in the lasing medium. These properties make UR geometries very attractive for semiconductor lasers,⁽²¹⁾ since they may provide an optimal solution to the task of increasing the lateral dimension of the laser and avoiding multi-lateral mode operation and filamentation.

In order to fabricate UR semiconductor lasers, a technique for etching curved facets into the GaAs/GaAlAs was developed by us.⁽²²⁾ As a first application, double heterostructure lasers were fabricated in which one of the laser facets was produced by a hybrid wet and reactive-ion-etching technique. This technique is suitable for GaAs/GaAlAs heterostructure lasers and utilizes the selectivity of Freon-12 plasma in preferentially etching GaAs over GaAlAs. Lasers fabricated by this technique are compatible with optoelectronic integration and have threshold currents and quantum efficiency comparable to lasers with both mirrors formed by cleaving. The technique enables the use of relatively higher pressures of noncorrosive gases in the etch plasma resulting in smoother mirror surfaces and further eliminates the nonreproducibility inherent in

the etching of GaAlAs layers. Then, GaAs heterostructure lasers with unstable resonator cavities were demonstrated for the first time with both curved mirrors fabricated by etching. Typical output powers of 0.35 Watts were observed in a stable, highly coherent lateral mode. The laser operated stably in a single longitudinal mode over a large range of injection currents. The external quantum efficiency was 70% that of a similar laser with both cleaved mirror facets implying good output coupling of the energy from the entire region.⁽²³⁾ In these lasers, single lateral mode operation was demonstrated by measuring the spatial degree of coherence of the laser output.⁽²⁴⁾ If the highly astigmatic beam is corrected by appropriate external optics, the focusing capability of these lasers may lead to power densities in a single mode higher than that emitted by any other semiconductor sources reported until now.⁽²⁴⁾

In order to reduce the cavity losses in UR lasers, an unstable resonator semiconductor laser with a real index lateral waveguide has been also fabricated. Output powers in excess of 400 mW were observed with a stable, highly coherent lateral field distribution. The incorporation of a lateral real index waveguide with the unstable resonator configuration results in a substantial increase in the external quantum efficiency and a decrease in the threshold current of the UR laser.⁽²⁵⁾

The successful fabrication of semiconductor lasers with curved mirrors indicates that laser cavities of different geometries can be designed as well and the cavity design can be tailored to specific needs in the output beam characteristics. As examples of other cavity design, and eventual applications, we demonstrated a

tilted mirror semiconductor laser,⁽²⁶⁾ a confocal unstable resonator semiconductor laser,⁽²⁷⁾ and an array of phase locked unstable resonator lasers.⁽²⁸⁾

3. NOVEL LASER STRUCTURES AND LASER PHYSICS

A variety of new lasers have been demonstrated in GaInAs/InP. Low Threshold InGaAsP/InP injection lasers on semi-insulating InP substrates have been developed with mirrors fabricated by the microcleavage technique. Miniature suspended bridges containing the laser channels have been formed and then microcleavage has been accomplished by the use of ultrasonic vibrations. Lasers with current thresholds as low as 18 mA with 140 μ m cavity length and 35-45% differential quantum efficiency have been obtained.⁽²⁹⁾

Mode stabilized terrace-large optical cavity (TR-LOC) lasers have been fabricated on semi-insulating (SI) InP substrates. The fabrication process involves a single-step liquid phase epitaxial (LPE) growth and a lateral Zn diffusion. The laser operates in a stable single transverse mode and is capable of delivering a power exceeding 300 mW/facet (at pulsed operation) with very smooth far-field pattern.⁽³⁰⁾

Inverted strip buried heterostructure lasers have been fabricated. These lasers have threshold currents and quantum efficiencies that are comparable to those of conventional buried heterostructure lasers. The optical mode is confined by a weakly guiding strip loaded waveguide which makes possible operation in the fundamental transverse mode for larger stripe widths than is possible for conventional buried heterostructure lasers. Scattering of the laser light by irregularities in the sidewalls of the waveguide, which can be a serious problem in conventional buried heterostructure lasers, is also greatly reduced in these lasers.⁽³²⁾

Very low threshold InGaAsP terrace lasers on semi-insulating (SI) InP substrate have been fabricated using the mass transport technique. The fabrication process involves a single-step liquid phase epitaxial (LPE) growth followed by a mass transport of InP at -675°C in the presence of an InP cover wafer. Lasers operating in the fundamental transverse mode with smooth far-field patterns and threshold currents as low as 9.5 mA have been obtained.⁽³³⁾

Short cavity length ($38\mu\text{m}$) lasers have been fabricated in GaInAsP/InP using a recently developed microcleavage technique. SiO_2 -amorphous Si multilayer coatings have been evaporated on the lasers to obtain high reflectivity mirrors. The lasers have current thresholds as low as 3.8 mA with 85% reflecting front mirror and high reflectivity rear mirror and 2.9 mA with two high reflectivity mirrors. Single longitudinal mode operation is observed over a wide range of driving currents and temperatures.⁽³⁴⁾

An undercut mesa laser is fabricated on an n^+ -InP substrate using a single step liquid phase epitaxy growth process and a planar structure is obtained by using a polyimide filling layer. The lasers operate at fundamental transverse mode due to a scattering loss mechanism. Threshold currents of 18 mA and stable single transverse mode operating at high currents are obtained.⁽³⁵⁾

The effects of the doping level in the P-cladding layer on the T_0 as high as 90 K has been observed. A new laser structure which involves a simple modification scheme applicable to most laser structures with improved temperature sensitivity has been demonstrated.⁽³⁶⁾

Carrier leakage over the heterobarrier in an InGaAsP/InP laser is measured directly in a laser-bipolar-transistor structure. Experimental results indicate a significant amount of carrier leakage under normal laser operating conditions.⁽³⁷⁾

The interband Auger recombination lifetimes of two Auger processes have been calculated to correlate measured threshold current densities and carrier lifetimes for InGaAsP and InGaAsSb lasers. Good agreement with experimental data was obtained for lasers with low nominal threshold current densities. These results demonstrate the importance of Auger recombination in the threshold characteristics of InGaAsP/InP lasers.

4. THEORY AND MEASUREMENT OF NOISE IN SEMICONDUCTOR LASERS:

In this work we have explained theoretically and accounted for experimentally a variety of basic stochastic properties of the electric field emitted from a semiconductor laser. In particular, properties related to the spectral purity of this field. This work is important to a number of potential applications of these devices which are now under intensive study. This includes coherent systems and certain sensing applications such as the fiber ring gyro. These applications require sources which exhibit extremely good frequency stability as gauged by their field spectrum linewidth.

Until very recently it was believed that the spectral purity of a single mode semiconductor laser was governed by physics similar to that found in other lasers. A few years ago it was believed that the fundamental linewidth of these devices was given by an equation known as the modified Schawlow-Townes linewidth formula. It was not until measurements were performed by Aram Mooradian's group at Lincoln Laboratories that this belief came under question.⁽³⁹⁾ They performed the first careful measurements of fundamental linewidth in a semiconductor laser. Their results indicated broadening some 20 to 40 times larger than predicted by the Schawlow-Townes formula (e.g., measured linewidths of 100 MHz at 1 milliwatt of output power versus a predicted 3 MHz at 1 milliwatt). Our initial interest in this field was sparked by these results.

Our ensuing work and that of others showed that, in fact, the linewidth in these devices was governed by an equation of the form⁽⁴⁰⁻⁴²⁾

$$\Delta\omega = \Delta\omega_{ST}(1 + \alpha^2)$$

Where $\Delta\omega_{ST}$ is the Schawlow-Townes linewidth and α is referred to as the linewidth enhancement factor. α is given by,

$$\alpha = \frac{\partial\chi_r/\partial n}{\partial\chi_i/\partial n}$$

where χ_r and χ_i are the real and imaginary components of the complex susceptibility function and n is a parameter describing the overall excitation level of the active medium, for instance, the carrier density. α results from the fact that semiconductor lasers, as a subset of the class of all regenerative oscillators, operate in a detuned mode. The result is that amplitude and phase fluctuations of the field are coupled together. This, in turn, allows components of quantum noise which will normally only influence the intensity noise of the device to now have a channel in the phase. This channeling of these fluctuations causes a degradation of lasing field spectral purity.

The value of α lies in the range -4 to -6 as inferred from linewidth versus power measurements conducted by our group and others. We have also calculated α from first principles for bulk material, finding values which also fall within this range.⁽⁴³⁾ In addition, we were able to establish a relation between this phase noise enhancement and the presence of chirping in the output of directly modulated semiconductor lasers. Our theory showed that besides enhancing the field spectrum linewidth of a semiconductor laser, the parameter α

also controls the apportioning of modulation energy into FM and AM components. We then used this formalism to achieve an independent measurement of the α parameter by measuring the ratio of FM to AM in several devices under direct current modulation.⁽⁴⁴⁾ The results gave α values which were in close agreement with values inferred from linewidth measurements.

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in semiconductor lasers has resulted in a new quantum formulation which takes into account the amplitude to phase coupling. This coupling is characterized by a new dispersive parameter α . Direct measurement of α were performed. *Keywords:*

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