Single contact tailored gain phased array of semiconductor lasers

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We demonstrate a single contact tailored gain-guided array in which the gain profile across the array is made strongly asymmetric by varying the width of the contact stripes. A proton isolated array of six (GaAl)As lasers with 5-μm separations and widths varying linearly between 3 and 8 μm had a single lobed far field 2° wide, close to the diffraction limit for a single supermode. Fabrication of this device is simple, and suited to large-scale processing techniques. We also show that in such an asymmetric gain-guided array the fundamental mode is favored over higher order modes, and that higher order modes can have single lobed far-field patterns differing only slightly from that of the fundamental.

Recently, there has been an increasing interest in phase-locked semiconductor laser arrays. Among other desirable properties, these arrays possess the potential of combining the outputs of the individual array elements into a single diffraction limited narrow beam, thus providing much higher beam power densities than may be obtained from a single semiconductor laser.[1] However, most arrays reported to date have shown double lobed far-field patterns whose angular divergence is often several times the diffraction limit.[1-3] This behavior is now understood to result from the lack of lateral supermode control in uniform arrays.[4] To achieve the desired diffraction limit without using external compensating optics single lobe operation in the fundamental supermode is necessary. In the present work, we point out the feasibility of using a nonuniform gain profile in order to favor the fundamental supermode and experimentally demonstrate a gain-guided phase-locked array incorporating this principle which shows nearly diffraction limited single lobe operation. Fabrication of this device is simple, and suited to large-scale processing techniques. We also show that a gain-guided array with an *asymmetric* lateral gain profile can have higher order modes which have single lobed far-field patterns almost identical with that of the fundamental and that such arrays can thus oscillate in a number of supermodes without an appreciable spread in the beam width, albeit at a sacrifice of temporal coherence.

In a uniform array, only the fundamental supermode has a single lobed far field; all the higher order supermodes have far-field patterns which are multilobed.[4,5] To achieve single lobe operation such arrays must lase in the fundamental supermode. All higher order supermodes must be suppressed. However, in a uniform array, the fundamental supermode does not have the highest modal gain, and hence is not the lasing mode.[4] This results in the commonly observed double lobed far-field patterns. It is therefore necessary to design a structure in which the fundamental supermode has the highest modal gain. One way in which this may be achieved would be to make the gain profile across the array nonuniform. We find, for example, that an asymmetric, ramped gain profile causes the fundamental supermode to be preferentially concentrated in the region of higher gain when compared to the higher order supermodes. This causes the fundamental supermode to possess the highest modal gain and to oscillate all alone. We therefore anticipate that such arrays will show the desired single lobed far-field patterns.

A previously demonstrated method for producing an arbitrary nonuniform gain profile made use of separate contacts in arrays utilizing multilayer metallizations.[6] If dynamic control of the gain profile is not needed, a simple way to tailor the gain profile across a proton isolated array would be to vary the widths of the stripe contacts. This effect is well known, and has been explained in terms of a leakage current.[7] The lasers under the wider stripes have lower leakage currents, and therefore higher gains than narrower lasers. The gain profile across the array may then be tailored by using contact stripes of different widths. In particular, an asymmetric ramped gain profile may be obtained by introducing a linear variation in contact widths across the array. We are thus led to the concept of a *single contact tailored gain* phased array laser.

To test these ideas, an asymmetric tailored gain-guided array was fabricated using conventional liquid phase epitaxy, and is illustrated schematically in Fig. 1. Four layers were grown on a n^+-GaAs substrate Si doped, 2×10^{18} cm^{-3}). The composition and thickness of the layers are as follows: n-$Ga_{0.6}Al_{0.4}As$ lower cladding layer 2.0 μm thick, Sn doped, 2×10^{17} cm^{-3}, undoped GaAs active region 0.15 μm thick, p-$Ga_{0.6}Al_{0.4}As$ upper cladding layer 1.8 μm thick, Ge doped, 3×10^{17} cm^{-3}, p^+-GaAs cap layer, 0.2 μm thick, Ge doped, 8×10^{18} cm^{-3}. Immediately after growth Cr/Au was deposited to form the p contact. Six laser stripes varying linearly from 3 to 8 μm and separated by 5 μm were formed by proton implantation through a photoresist mask. Several proton implant energies were used to vary the degree of electrical and optical isolation between the array elements. The remainder of the processing was conventional. The devices were finally cleaved into bars approximately 250 μm long

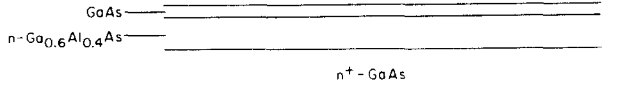

FIG. 1. Schematic diagram of the single contact tailored gain array with an asymmetric, ramped gain profile.

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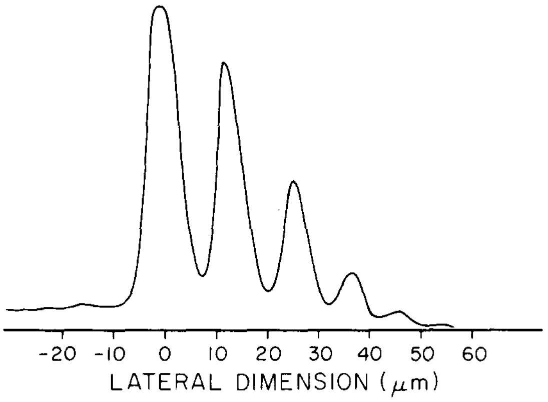

FIG. 2. Near-field pattern just below threshold of a deeply implanted array. The considerably greater intensity under the wider stripes indicates that the gain is greater there than it is under the narrower stripes, thus making visible the asymmetric gain profile across the array.

and tested under low duty cycle pulsed conditions.

To demonstrate the gain tailoring effect resulting from varying the contact stripe widths, a deep implantation was performed so that the array elements would be optically isolated from each other. The spontaneous emission pattern just below threshold then follows the gain profile. Figure 2 shows the near-field pattern of a deeply implanted array just below the threshold current of 325 mA. It is clearly seen that the lasers under wider stripes emitted considerably more light than the narrower ones, indicating that the gain was greater under the wider array elements.

Other devices were fabricated using a shallow proton implant depth to allow stronger optical coupling between the individual lasers. These arrays had thresholds of about 250 mA. The near-field and far-field patterns of such a device operated at $1.6I_{\text{th}}$ are presented in Fig. 3. The near-field pattern exhibits the asymmetric envelope expected from an asymmetric gain distribution, and also shows the secondary intensity peaks characteristic of gain-guided arrays.[8] The intensity far-field pattern shows that almost all of the array's power is radiated into a single lobe 2° wide which was slightly more than the calculated diffraction limit of 1.8°. The asymmetric gain distribution causes this lobe to be directed 3½° off axis. This single lobed far-field pattern was stable up to about twice threshold. Arrays with somewhat deeper implants (i.e., more well defined channels) had essentially single lobed far fields 3° wide at twice threshold which broadened to 5° when operated at four times their threshold current of 275 mA. However, the increased modulation of the near-field intensity pattern due to the deeper implant in these latter arrays (which were very similar to that of Fig. 2) caused more power to spill into the secondary lobes.

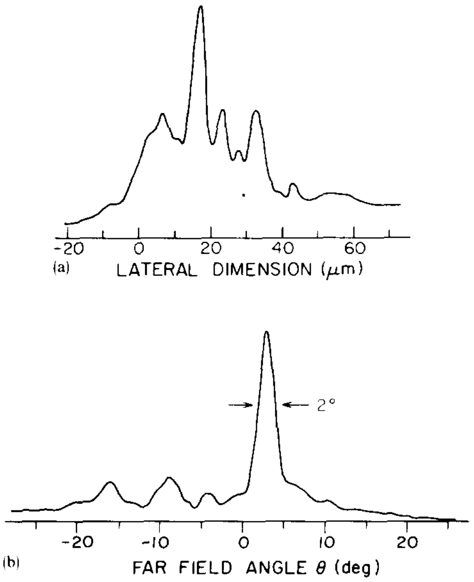

FIG. 3. (a) Near-field and (b) far-field intensity patterns of a shallowly implanted array operated at $1.6I_{\text{th}}$ in which the coupling between the lasers produces phase locking as indicated by the narrow beam divergence. The off-axis location of the peak is characteristic of an asymmetric gain profile. The beamwidth of approximately 2° is close to the theoretical value of 1.8° for single supermode operation.

To analyze these results, we employed a simple waveguide model of an asymmetric gain-guided array operated near threshold using realistic parameters. The channel gain was varied linearly between 70 cm^{-1} under the widest stripe to just above transparency under the narrowest. Dips of 20 cm^{-1} below the gain envelope were introduced between the channels to take account of current spreading due to the shallow implant depth. The absorption of the unpumped lossy region on each side of the array was estimated to be 100 cm^{-1}. The free carrier and band edge effects of the gain on the real part of the index were included by setting the antiguiding factor $b = 3.0$.[9] The eigenmodes and unsaturated modal gains were then obtained by numerical solution of Maxwell's equation.

The calculated near fields of the three modes with the highest modal gains are presented in Fig. 4.[10] The fundamental supermode ($v = 1$) has the highest modal gain and therefore is the mode most favored to lase. The other two supermodes have modal gains 89%($v = 2$) and 79%($v = 3$) of the fundamental. It is quite a striking feature of these modes that

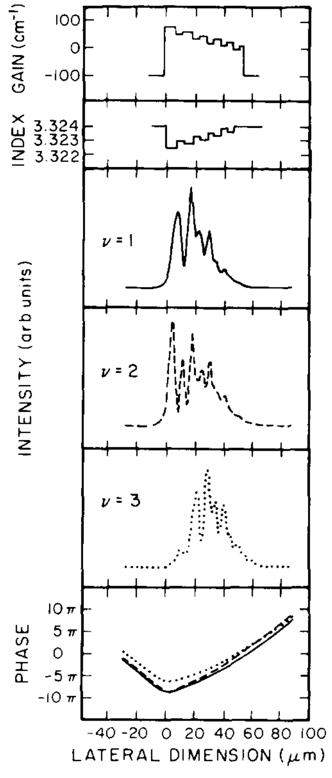

FIG. 4. Calculated near-field patterns of the simple model used to analyze the asymmetric gain guided array. The upper part of the figure shows the distribution of the complex dielectric constant used in the model. Only the three modes with the highest modal gains are shown. The fundamental ($v = 1$) mode has the highest modal gain; the other two supermodes have modal gains 89% ($v = 2$) and 79% ($v = 3$) of the fundamental.

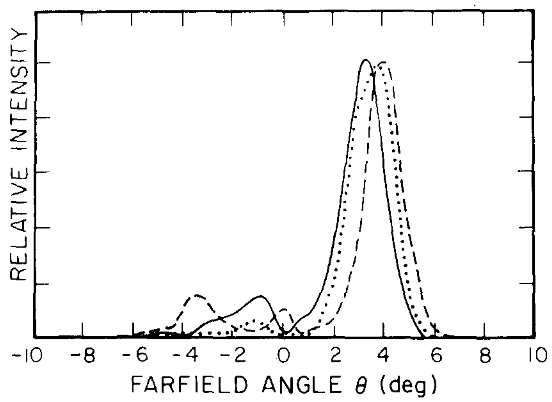

FIG. 5. Calculated far-field intensity patterns of the supermodes of Fig. 4. The solid line corresponds to $v = 1$, the dashed line $v = 2$, and the dotted line $v = 3$. The result that the higher order modes are so similar to the fundamental is characteristic of asymmetric gain-guided structures.

although the near-field intensities are quite dissimilar, the *phase fronts* of the modes are virtually identical, and exhibit nearly linear variations where the mode power is appreciable. The tilted phase fronts of the near field result in most of the array's power being radiated into a single lobe of angular extent 1.8° approximately $3\frac{1}{2}$° off axis which is in fair agreement with the experimental results (note that the beam may be made even narrower by merely increasing the size of the array).

Figure 5 illustrates a useful property of *asymmetric gain-guided* arrays. In any laser which is operated well above threshold, gain saturation effects cause the excitation of several transverse modes. In uniform arrays, single lobed far fields are exhibited only by the fundamental supermode; the excitation of several supermodes results in multilobed far-field patterns.[4,5] In the asymmetric gain-guided structure of Figs. 4 and 5, the supermodes with the highest modal gains are characterized by single lobed far fields with similar radiation patterns. This is a direct result of the lack of left-right inversion symmetry in the array and the complex valued electric field due to gain guiding.[11] As the example of Fig. 5 shows, the excitation of several supermodes leaves the far field single lobed, albeit with a somewhat larger beamwidth. This consideration is especially important for applications not requiring the spectral purity made possible by single transverse mode operation but requiring only narrow beamwidths. For example, the equal excitation of all three of the supermodes illustrated in Figs. 4 and 5 would result in the broadening of the main lobe from 1.8° to 2.8°. Such broadening of the main lobe was indeed observed in the radiation patterns of the more deeply implanted devices described above.

Although the model used here is simple, the agreement between the calculated near and far-field patterns for the fundamental mode and the experimental results of Fig. 3 is quite good. It should be noted, however, that it is difficult to determine the exact values of the many parameters which comprise the model. Nevertheless, extensive analysis shows the important result that although the near-field patterns are very sensitive to changes in the parameters, the single lobed nature of the far fields is much less sensitive to parameter variations as long as there is an asymmetric gain profile.

We note in passing that these results are similar to, and may be a possible explanation of, the experimental observation of the narrow single lobed off axis far-field patterns reported in Ref. 12 if unexpected contact effects were to introduce unintentional asymmetric gain profiles across the array.

In conclusion, we have demonstrated a single contact tailored gain-guided array with an asymmetric lateral gain profile which emits most of its power into a single, narrow beam. We also show that such an asymmetric gain-guided array has the desirable property that the fundamental supermode is favored over all other supermodes.

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