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Controlled fundamental supermode operation of phase-locked arrays of gain-guided diode lasers

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Uniform semiconductor laser arrays tend to oscillate in a superposition of their supermodes, thus leading to large beam divergence and spectral spread. Discrimination among the supermodes in phase-locked arrays is discussed theoretically. It is shown that supermode discrimination in gain-guided arrays, in favor of the fundamental supermode, is made possible by the near-field interference patterns which result from the complex optical fields of the gain-guided lasers. A fundamental supermode operation is demonstrated, for the first time, in GaAlAs/GaAs gain-guided laser arrays. This is achieved by control of the current (gain) profile across the array by means of individual laser contacts.

Phase-locked arrays of semiconductor lasers provide a promising approach to the realization of high power diode lasers with stable radiation patterns.[1-4] However, phase-locked laser arrays, being multichannel waveguide devices, support several lateral modes (supermodes). These supermodes generally oscillate at different frequencies and their far-field patterns differ significantly.[5,6] The extraction of diffraction limited beams from phase-locked arrays thus requires the excitation of primarily a single supermode. Such a single supermode oscillation of the array would also result in a minimal spectral width of its longitudinal modes. In this letter we discuss and demonstrate the discrimination among the supermodes of gain-guided laser arrays by control of the gain distribution across the array. We demonstrate, for the first time, single fundamental supermode oscillation of such arrays. This is achieved with a phase-locked array incorporating separate laser contacts.

An array consisting of N (weakly coupled) single spatial mode lasers supports N supermodes (i.e., eigenmodes of the composite array waveguide). In the case of identical lasers with uniform nearest neighbor coupling, the relative field amplitude E_l^ν of the νth supermode in the l th array channel is[5,6]

$$E_l^\nu = \sin\left(l\,\frac{\pi\nu}{N+1}\right) \quad \begin{array}{l}\nu = 1,2,\cdots N\\ l = 1,2,\cdots N\end{array}. \tag{1}$$

The near field of the supermodes is given by

$$E^\nu(x,y) = \sum_{l=1}^{N} E_l^\nu \mathscr{E}_l(x,y), \tag{2}$$

where $\mathscr{E}_l(x,y)$ is the near field of the l th laser in the array. (The propagation is along the z axis.)

Figure 1 shows, as an example, the calculated near-field intensity patterns of the four supermodes ($\nu = 1,2,3,4$) supported by a gain-guided laser array with four identical elements and uniform, nearest neighbor coupling. The near field of each individual laser was calculated assuming a $\cosh^{-2}$ gain distribution in the junction plane.[7] The parameters used correspond to GaAs/GaAlAs gain-guided array with $\sim$4-μm-wide laser stripes. The near-field patterns shown in Fig. 1 are considerably more involved than those of coupled index-guided lasers.[5] The numerous intensity lobes arise from the interference between the gain-guided optical fields, which are characterized by curved phase fronts.[8] Note that the pattern of the $\nu = 4$ supermode exhibits essentially zero intensity below the laser stripe centers, whereas, the pattern of the $\nu = 1$ mode has its main lobes below the stripes. In contrast, the only significant difference between the intensity patterns of the $\nu = 1$ and $\nu = 4$ supermodes of *index-guided* arrays is that the latter one exhibits intensity nulls *between* the laser stripes. This occurs because the com-

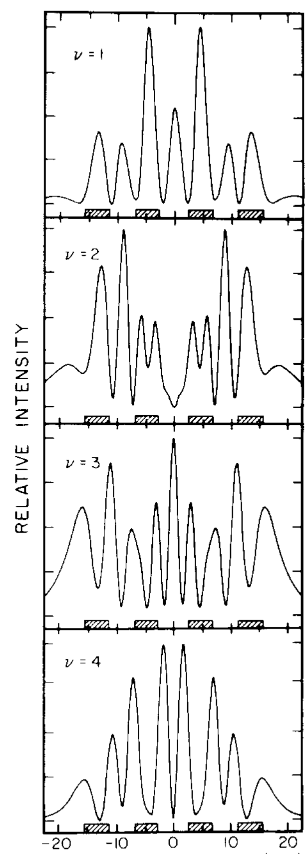

FIG. 1. Calculated near-field patterns of the supermodes in a four-element gain-guided array with 9-μm period. The field of each coupled laser was calculated assuming 300 cm^{-1} gain difference between the peak gain and the loss in the umpumped regions, gain profile width of $\sim 6\,\mu$m ($y_3 = 6\,\mu$m was used, where y_3 is defined in Ref. 7), antiguiding factor $b = 3$, and wavelength $\lambda = 0.9\,\mu$m. The positions of the laser stripes are indicated by the crossed regions.

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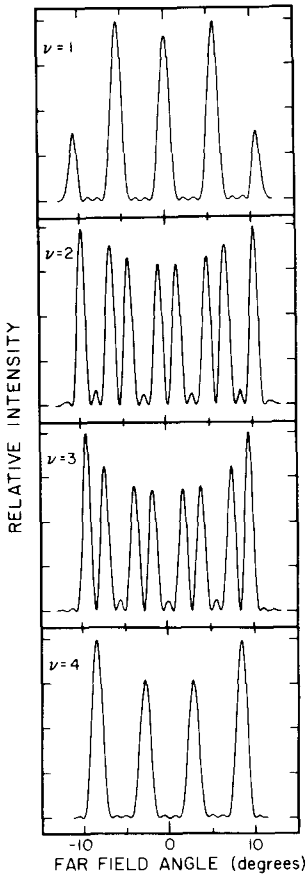

FIG. 2. Calculated far-field patterns for the supermodes of Fig. 1.

ponents of the fundamental supermode ($\nu = 1$) in adjacent channels are in phase, whereas those of the highest order supermode ($\nu = 4$) are π radians out of phase from each other [see Eq. (1), and Fig. 2 in Ref. 5]. These features have an important impact on the supermode discrimination, as discussed below.

The calculated far-field patterns (in the junction plane) of the four supermodes of Fig. 1 are shown in Fig. 2. These patterns closely resemble the ones obtained for index-guided arrays,[5] except for the central dip in their envelopes. This is a consequence of the curved phase fronts of the coupled optical fields.[7,9] Each supermode oscillates, generally, at a different frequency. Therefore, it is clear that the excitation of several supermodes would result in far-field patterns with broad lobes and a broadening of the longitudinal mode linewidths.[5]

Differences in the supermode modal gains are brought about by their different near-field patterns. In an array of N lasers, the intensity pattern of the fundamental supermode $\nu = 1$ differs significantly from those of the supermodes $\nu = 2,3, \ldots N - 1$ in the relative excitation of the various channels [see Eq. (1)]. This means that one can discriminate against these higher order supermodes by tailoring the lateral gain distribution (across the array) such that it matches the intensity distribution of the fundamental supermode. However, in index-guided arrays it is more difficult to discriminate against the highest order supermode $\nu = N$ because it differs from the fundamental one mainly in its intensity *between* the array channels [see Eq. (1), and Fig. 2 in Ref. 5]. As shown by Fig. 1, the situation with gain-guided arrays

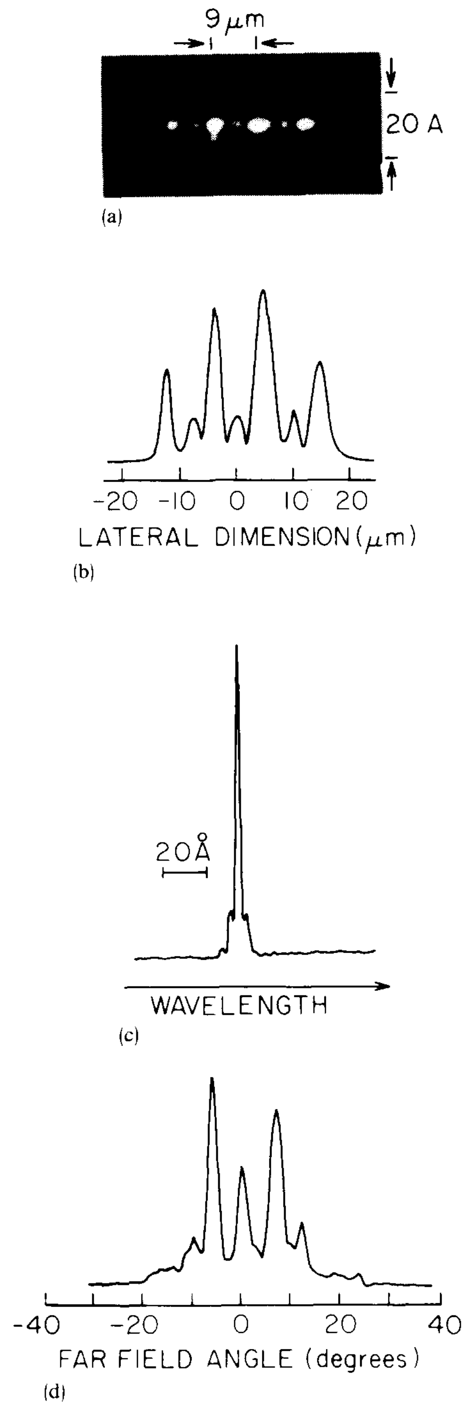

FIG. 3. Single supermode oscillation of a four-element, separate contact GaAs/GaAlAs laser array: (a) spectrally resolved near field, (b) near-field pattern, (c) spectrum ($\lambda = 0.87\ \mu$m), (d) far-field pattern.

is different, owing to the peculiar interference patterns in their near fields. It is clear, from Fig. 1, that in gain-guided arrays the highest order supermode can have considerably lower modal gain than the fundamental one, when its intensity minima are located below the laser stripes. However, this can be achieved only if the lateral gain distribution across the array is controllable.

One practical way for accomplishing the control of the lateral gain distribution is by incorporating a separate contact to each of the array lasers.[10] The gain distribution can then be controlled, to a large extent, by tailoring the individual laser currents. Our separate-contact array consisted of gain-guided GaAs/GaAlAs lasers whose stripes were delineated by proton implantation. Each laser stripe was $\sim 4\,\mu$m wide and the center-to-center separation was $9\,\mu$m.

The mode structure of the array was studied, under pulsed conditions, by examining its spectrally resolved near fields. For a general current combination through the array lasers, multilongitudinal mode operation was obtained, with different spatial mode patterns at different lasing frequencies. However, for specific current combinations single longitudinal mode operation was obtained, with a lateral intensity pattern which depended on the current combination. Figure 3 shows such a single mode operation of a four-element array with 9-μm center-to-center separation and approximately equal laser currents. The lateral near-field pattern, Fig. 3(b), and the spectrum, Fig. 3(c), were obtained by scanning the spectrally resolved near field shown in Fig. 3(a). The far-field pattern in the junction plane, Fig. 3(d), was measured under the same lasing conditions.

The measured near-field and the far-field patterns, Figs. 3(b) and 3(d), are similar to the calculated ones, shown in Figs. 1 and 2 ($\nu = 1$). Since the field patterns of the higher order supermodes ($\nu > 1$) are significantly different from those of the fundamental one, it is clear that oscillation in the fundamental supermode at a single longitudinal mode was achieved. This fundamental supermode oscillation is attributed to the control of the gain distribution in the separate contact array. This control makes it possible to obtain phase matching among the coupled, gain-guided lasers, since by changing the laser currents one can vary the phase velocities in the array channels.[11] Under phase-matching condition, with approximately equal currents through the lasers, the near-field patterns of the supermodes appear as in Fig. 1. At the same time, the gain distribution best matches the intensity distribution of the fundamental supermode, as discussed above. Thus, oscillation in the fundamental supermode results. This fundamental supermode oscillation is very susceptible to variations in the laser currents, because such variations change the near-field patterns of Fig. 1, on which the supermode discrimination relies. This explains why it is so difficult to accomplish fundamental supermode oscillation in single-contact laser arrays. Finally, the far-field pattern of the fundamental supermode shown in Fig. 4(d) exhibits several main lobes. This is due to the fact that the far-field pattern of each individual laser in the array is relatively broad. A single lobe (directed parallel to the array channels) could be obtained by increasing the near-field spot size of each laser (e.g., by using shallow proton implantation), thereby decreasing the angular divergence of the far-field envelope.

In summary, we discussed and demonstrated supermode discrimination in phase-locked arrays of gain-guided diode lasers. Such discrimination, in favor of the fundamental supermode, is desirable in order to obtain optimal performance of phase-locked arrays. Controlled oscillation of phase-locked arrays in the fundamental supermode was demonstrated, for the first time, using arrays with separate laser contacts.

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