Chirped arrays of diode lasers for supermode control

E. Kapon, C. Lindsey, J. Katz,[a] S. Margalit, and A. Yariv
California Institute of Technology, Pasadena, California 91125

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We propose nonuniform structures of phase-locked diode lasers, which make it possible to discriminate efficiently against all the higher order array supermodes (lateral modes). In these nonuniform arrays, the effective mode index in each channel varies across the array. Consequently, 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 conveniently select the fundamental supermode. Such fundamental supermode oscillation is essential in order to obtain single lobe, diffraction limited beams and minimal spectral spread from phase-locked laser arrays.

Phase-locked arrays of diode lasers, which are multichannel waveguide devices, support several lateral modes (supermodes).[1] In conventional phase-locked arrays several such supermodes are usually excited, and this results in relatively broad far-field patterns as well as broad spectral linewidths.[1-5] Thus, it is desirable to discriminate among the supermodes and enforce a single supermode operation in order to achieve the optimal phase coherent performance of the array. In particular, oscillation in the *fundamental* supermode would result in a single-lobe, diffraction limited beam directed parallel to the array channels. Suppression of the higher order supermodes can be achieved generally by tailoring the lateral gain distribution across the array such that it matches the near-field pattern of the fundamental supermode.[6] However, in uniform arrays, i.e., arrays with identical channels, the envelopes of the intensity patterns of the fundamental and the highest order supermodes are similar,[1] which makes their discrimination more difficult to accomplish. Moreover, since the interchannel regions are usually lossy, the highest order supermode, with a two-lobe far-field pattern, is often the favored mode which oscillates.[1-5]

In this letter we introduce the concept of *nonuniform* laser arrays, in which the channels are made purposely nonidentical. It is shown that in such arrays, the near-field envelopes of the fundamental and the highest order supermodes can differ appreciably. By employing a proper gain distribution, one can then conveniently suppress *all* higher order supermodes.

Figure 1 shows the near-field patterns of the five supermodes which are supported by an index-guided array of five identical channels. (The channels are 3 μm wide and are on 5-μm centers). The lateral distribution of the effective index (in the junction plane) was taken, for definiteness, as that corresponding to an array of typical GaAs/GaAlAs ridge-waveguide lasers. The supermode patterns were calculated by solving Maxwell's equations numerically. The supermodes designated by $\nu = 1,2,3,4,5$ correspond to $(+\;+\;+\;+\;+)$, $(+\;+\;0\;-\;-)$, $(+\;0\;-\;0\;+)$, $(+\;-\;0\;+\;-)$, and $(+\;-\;+\;-\;+)$ field distributions in the various array channels, respectively.[1] ($+$, $-$, and 0 indicate whether the field is positive, negative, or zero in the corresponding channel.) It is clear that the near-field envelopes of the $\nu = 1$ and the $\nu = 5$ supermodes are very similar. (In fact, in the limit of very weak coupling between the channels, they become identical.[1]) Therefore, for a given gain distribution, the difference in their modal gain is due mostly to their interchannel intensities, which often results in oscillation of the highest order supermode.[2-5] This illustrates the deficiency of the uniform array structure.

In order to design improved array structures, the key point is to realize that the envelopes of the supermodes are given, approximately, by the eigenmodes of the fictitious waveguide formed by the envelope of the modal effective index in each channel.[7] As an example, the supermode envelopes of a uniform array (see Fig. 1) can be approximated by the (confined) eigenmodes of a slab waveguide whose width is that of the entire array. These modes are, to a good approximation, sinusoidal functions having zero amplitudes at the array boundaries. The similar result is also obtained by using coupled-mode theory.[1] Thus, it becomes clear that a difference in the envelopes of the fundamental and the highest

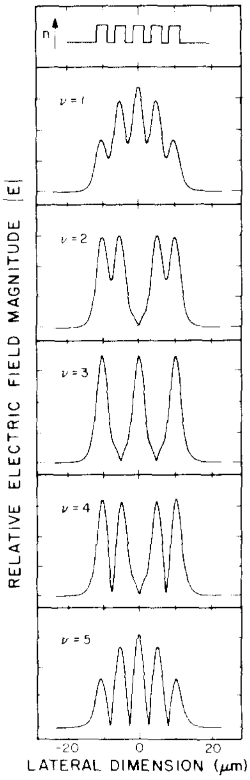

FIG. 1. Near-field patterns of the supermodes in a five-element uniform array. The insert shows the effective-index distribution across the array. The index in the channels is 3.4149; between and outside the channels it is 3.4118. The channel widths are 3 μm, the spacings are 2 μm, and the wavelength is 0.9 μm.

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[a] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109.

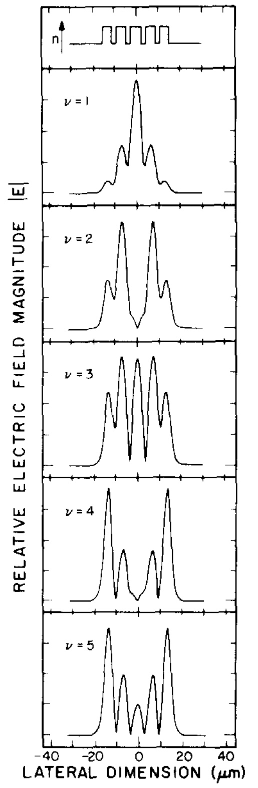

FIG. 2. Near-field patterns of the supermodes in a five-element inverted "v" chirped array. The channel widths are 4, 4.5, 5, 4.5, and 4 μm, from left to right. All other parameters are the same as in Fig. 1.

order supermodes can be brought about by proper tailoring of the effective indices in the array channels. This variation in the effective channel indices can be accomplished, for instance, by changing the effective index step or the width of those channels.

Figure 2 and 3 show the calculated supermodes supported by two nonuniform array structures, each with varying channel widths.[8] In Fig. 2, the channel widths are reduced from 5 μm in the center channel to 4 μm in the outer channels, symmetrically, in steps of 0.5 μm (inverted "v" chirp). In Fig. 3, the widths are chirped linearly from 3 to 5 μm, across the array. In both examples the channel spacings are uniform (2 μm). It is clear that the variation in the channel widths resulted in significantly different envelope patterns of the supermodes $\nu = 1$ and $\nu = 5$, in contrast to the case of uniform arrays (compare with Fig. 1). This is a consequence of the particular envelopes of the modal effective index in the array channels, which arises from the channel width variations. For instance, approximating the effective channel index envelope of the inverted "v" chirped array (Fig. 2) by a parabola shows at once that the supermode envelopes can be approximated, in this case, by Gauss–Hermite functions.[7] The higher order Gauss–Hermite functions are pushed against the boundaries of the (effective) array waveguide, which is just the feature desired in order to obtain efficient supermode discrimination. Similarly, the linear chirp gives rise to supermode envelopes which are related to Airy functions.[7]

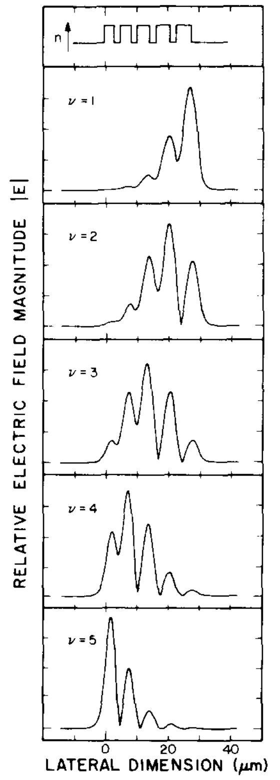

FIG. 3. Near-field patterns of the supermodes in a five-element linearly chirped array. The channel widths are 3, 3.5, 4, 4.5, and 5 μm, from left to right. All other parameters are the same as in Fig. 1.

Obviously, one can now suppress all the higher order supermodes in these chirped arrays by concentrating the gain at the peak of the near-field envelope. This can be achieved, for example, by employing separate laser contacts[9] or by putting a stripe contact located above the peak of the fundamental supermode envelope and using a highly conductive upper cladding layer. To examine the achievable supermode discrimination more quantitatively, we calculated the modal gains of each supermode (near threshold), when the envelope of the gain distribution in the array channels was assumed to be proportional to the intensity envelope of the fundamental supermode. The resulting relative modal gains are presented in Fig. 4. It is clear that the chirped array structures allow for a very large discrimination against the highest order supermode, in contrast to the uniform structure. In addition, the discrimination against the other higher

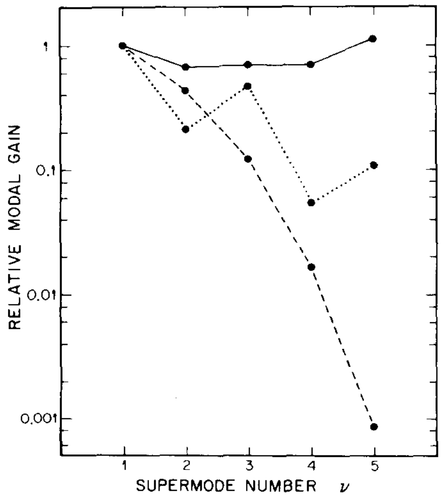

FIG. 4. Relative modal gain of the supermodes shown in Fig. 1 corresponding to (envelope) gain distributions which are proportional to the (envelope) intensity distributions of the fundamental supermodes. Uniform array—solid line; inverted "v" chirped array—dotted line; linearly chirped array—dashed line.

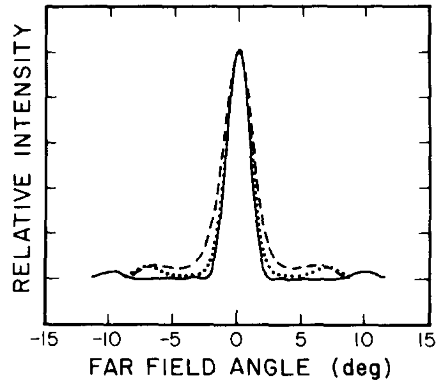

FIG. 5. Far-field patterns of the fundamental supermodes. Uniform array—solid line; inverted "v" chirped array—dotted line; linearly chirped array—dashed line.

order supermodes increases as well. This is an additional advantage, since, above threshold, the higher order supermodes tend to oscillate due to gain saturation in the array channels.[1,10]

Finally, Fig. 5 compares the far-field patterns (in the junction plane) of the fundamental supermodes of the three array structures discussed above. The main difference between these far fields is in the structure of the side lobes. However, it should be noted that these far fields were calculated without accounting for the gain in the array channels. Thus the asymmetric gain distribution required for the selection of the fundamental supermode in the linearly chirped array (Fig. 3), would result in a deflection of the main lobe for this case. The angular beam divergence in the far field can be reduced by increasing the width of the fundamental supermode near field. This can be achieved, for instance, by reducing the separation of the outermost channels of the symmetrically chirped array (Fig. 2). This variation of the channel spacing, which does not effect the supermode discrimination significantly,[1] is an additional degree of freedom in designing nonuniform array structures.

In conclusion, it was shown that by properly varying the effective indices of the channels in laser arrays it is possible to discriminate against *all* higher order supermodes. This can be realized, for example, by employing array structures with chirped channel widths. Such nonuniform arrays would oscillate in the fundamental supermode, yielding single-lobe, diffraction limited beam and minimal spectral spread.

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[1] E. Kapon, J. Katz, and A. Yariv, Opt. Lett. **9**, 125 (1984).
[2] D. R. Scifres, W. Streifer, and R. D. Burnham, J. Quantum Electron. **QE-15**, 917 (1979).
[3] D. R. Scifres, C. Lindstrom, R. D. Burnham, and T. L. Paoli, Electron. Lett. **19**, 169 (1983) and references therein.
[4] D. E. Ackley and R. W. H. Engleman, Appl. Phys. Lett. **39**, 27 (1981).
[5] D. Botez and J. C. Connolly, Appl. Phys. Lett. **43**, 1096 (1983).
[6] E. Kapon, J. Katz, S. Margalit, and A. Yariv, Appl. Phys. Lett. (to be published).
[7] E. Kapon and A. Yariv (unpublished).
[8] The wider channels in the structures of Fig. 2 and 3, when isolated, support higher order modes. However, in reality these higher order modes are more lossy due to scattering at the channel boundaries and because of the gain distribution beneath each channel. Therefore, the supermodes presented in Figs. 2 and 3 are only those arising from the coupling of the fundamental channel modes. Of course, in theory, the higher order channel modes could be eliminated by selecting a smaller index step.
[9] J. Katz, E. Kapon, C. Lindsey, U. Shreter, S. Margalit, and A. Yariv, Appl. Phys. Lett. **43**, 521 (1983).
[10] J. Katz, E. Kapon, S. Margalit, and A. Yariv, IEEE J. Quantum Electron. (to be published).

Reactively sputtered TeN_x optical recording media

M. A. Bösch, H. R. Haller, L. M. Schiavone, and J. L. Shay
AT & T Bell Laboratories, Holmdel, New Jersey 07733

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The optical recording characteristics of TeN_x films are described. Te-nitride formation has been achieved by reactive sputtering. The optical writing properties vary drastically with increasing nitrogen incorporation. Films with moderate nitrogen content maintain good hole and rim forming properties while enhancing the sensitivity of the medium. These layers show a considerable resistance against rapid environmental stress.

Pure Te films have good ablative optical recording properties but are not suitable as a stable recording medium. Several methods have been devised to "passivate" tellurium to achieve archival lifetime of the medium. Alloying Te with other chalcogenides or with pnictides led to commercial products with a estimated lifetime of 10 years.[1-3] Intentionally oxidizing Te to a suboxide produced a phase change medium.[4] A carbon "alloyed" Te medium has also been reported having good environmental stability.[5] Finally, hydrogenating Te provides a means to produce a stable Te medium.[6]