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Power Combining of Semiconductor Lasers: A Review

J. Katz
Communications Systems Research Section

The subject of power combining of semiconductor lasers is reviewed. Several methods of coherent power combining are described and compared. A comparison is also made between coherent and incoherent power combining, and important operational characteristics are considered. It is found that in communication links with demanding requirements coherent power combining is necessary.

I. Introduction

The growing interest in optical communications for free space applications (e.g., deep space, intersatellite links) (Refs. 1-3) has increased the need for appropriate light emitting sources. As discussed in an earlier report (Ref. 4), semiconductor injection lasers are excellent candidates for this application, particularly because of their very long lifetimes, high efficiency and small size and weight. Their drawback is that in high power (about 1 watt average) applications, a single device cannot radiate all the power needed in a stable radiation pattern and frequency. In the above-mentioned report (Ref. 4) and in subsequent ones (Refs. 5, 6), several aspects of solving this problem via mutal phase locking of several lasers through overlapping fields were analyzed.

It is the purpose of this report to review the general problem of power combining of semiconductor lasers by coherent and incoherent methods. Section II compares several methods of coherent power combining, namely mutual coupling (discussed before), injection locking and amplification. Regenerative amplification is also mentioned. The various methods are briefly described and then compared on the basis of several important operational characteristics, such as locking range, power efficiency, thermal considerations, reliability, monolithic implementation, realization of two-dimensional configurations and the need for additional components. It is found that all the coherent methods are similar in their problems and performance, although coherent amplification might be somewhat better. Section III compares coherent and incoherent power combining. Again the two methods are briefly described and then compared on the basis of the spatial and spectral characteristics of their resulting radiation. It is found that although incoherent power combining is easier to implement, the significant advantages offered by coherent power combining seem to justify the additional efforts needed to realize devices based on these methods, especially in systems whose designs impose stringent requirements on beam directivity and optical background noise immunity.

II. Comparison Between Methods of Coherent Power Combining

In this section three methods for coherent power combining, namely mutual coupling, injection locking and amplification are discussed. The schematic configurations of these methods are shown in Fig. 1. The common feature of all these methods is the establishment of some coherent interaction between all the elements of the array.

In the case of mutual coupling (Fig. 1a), no laser in the array has a privileged status. There is a certain amount of coupling among the lasers, which, under certain conditions, results in their synchronization. This method has been analyzed (Ref. 5) and demonstrated (Refs. 4, 6). In particular, it was found that phase-locking requires that the following inequality be approximately satisfied:

$$2\left|\frac{\Delta\omega}{\omega_0}\right| \leqslant |\xi| \qquad (1)$$

$\Delta\omega$ is approximately equal to the rms deviation of the lasers' oscillation frequencies from the "center-of-mass" frequency ω_0 of the array and ξ is a dimensionless parameter describing the strength of the coupling interaction (Ref. 5). In the case of coupling due to field overlap of lasers which are in close proximity, ξ can assume in AlGaAs lasers the maximum value of (Ref. 5).

$$|\xi|_{max} \cong \frac{8 \cdot 10^{-4}}{d^2} \qquad (2)$$

where d is the distance between individual lasers of the array in micrometers. Coupling due to other mechanisms (e.g., diffraction) is also possible.

Injection locking of lasers (Fig. 1b) is obtained by similar physical mechanisms. In this case, however, there is a master laser oscillator. Portions of its emitted radiation are coupled simultaneously into all the other lasers in the array, forcing them to oscillate at its frequency. There is no coupling among the lasers in the array and no coupling from the array back into the master laser. Injection locking was analyzed in electrical oscillators (Ref. 7) and in lasers (Ref. 8), and has been experimentally demonstrated in lasers (Ref. 9). The condition for injection locking of two lasers can be expressed as (Ref. 7):

$$2\left|\frac{\Delta\omega}{\omega_0}\right| < \frac{\delta E_m}{QE} \qquad (3)$$

where $\Delta\omega$ is the difference between the (radian) frequencies of the master laser and the array element laser, E_m is the electric field strength of the master laser oscillator, δ is the fraction of it that is coupled to the array element laser whose electric field strength is E, and the figure of merit of its cavity is Q.

Coherent amplification (Fig. 1c) is similar to injection locking: in both cases there is a master laser-oscillator. However, in the case of coherent amplification, the elements of the array are only gain-elements (i.e., amplifiers) without feedback. (This is accomplished by coating the laser mirrors with antireflection coating thus eliminating its feedback mechanism.) Light generated in the master laser-oscillator is split and fed simultaneously into all the gain elements, where a travelling-wave amplification is employed. The amplified outputs of the amplifiers are automatically phase-locked (provided, of course, that the output of the master oscillator is coherent over its near-field pattern). Amplification in semiconductors has been analyzed (Ref. 10), and the operation of coherently amplified GaAs homojunction devices has been demonstrated (Ref. 11).

An intermediate case between injection-locking and coherent amplification occurs when the gain elements in the array do have some amount of feedback, but it is insufficient to produce lasing; i.e., they operate as regenerative amplifiers (Ref. 12). Since the added complexity in implementing this method (the regenerative amplifier has to be biased very accurately just below the lasing threshold) does not yield improved performance over either regular amplification or injection locking, it will not be further considered here.

Schematic configurations of the above methods are shown in Fig. 1. In the following paragraphs they are compared from the aspects of locking range, power efficiency, thermal considerations, reliability, monolithic implementation, realization of two-dimensional configurations and the need of additional components.

A. Locking Range

We are considering the problem of the range of frequencies $\Delta\omega/\omega_0$ over which phase-locking can be maintained. In the case of mutual locking (Eqs. 1, 2), and for lasers that are spaced about $d \cong 5$ μm apart, the result is $2|\Delta\omega/\omega_0| \leqslant 3 \cdot 10^{-5}$. For injection locking (Eq. 3) with $E_m \cong E$, $Q \cong 10^4$ and $\delta = 0.1$, we obtain $2|\Delta\omega/\omega_0| \leqslant 10^{-5}$. Since the actual requirement for phase-locking in the case of mutual coupling can actually be somewhat more stringent than the one expressed in Eq. (1) (Ref. 5), both methods have basically the same locking range. (This result applies also in the case of regenerative amplifiers.)

B. Power Efficiency

Under optimized conditions, all the coherent phase-locking methods basically have the same power efficiency. The reason is that the photon density distribution in semiconductor lasers that are optimized for power efficiency is very similar to the photon density distribution in travelling wave amplifiers (Ref. 13). Second-order differences between the methods result from different coupling losses among the lasers or between the master-laser oscillator and the rest of the array.

C. Thermal Considerations

One of the problems in mutual coupling is that the lasers have to be put in close proximity (several micrometers) to one another so that sufficient coupling will be established among them (Ref. 5). This aggravates the problems of removing excess heat generated in the laser junctions and ohmic contacts. This problem can be mitigated by employing injection-locking or amplification, since in this case no mutual coupling has to be established among the elements of the array, and thus they can be placed further apart. However, doing that presents two new problems. First problem is that of efficient coupling from the master-laser to the array. Thus there is a tradeoff between thermal performance and the number of elements that can be locked, and the optimum configuration must be found in each case. The second problem is that as the array elements are further apart than in the mutual-coupling case, the increased separation causes the radiation pattern of the array to have more grating sidelobes (see next section).

D. Reliability

The mutual coupling approach is potentially more reliable than the other approaches since the performance of the entire array can, in principle, be designed in such a way that it is not critically affected by a failure of a single element. In the case of either injection-locking or amplification, failure of the master laser-oscillator means failure of the whole array. However, since the reliability of semiconductor laser devices is adversely affected at elevated temperatures, the actual advantage of the mutual coupling method can become insignificant because of its potentially inferior thermal characteristics.

E. Monolithic Implementation

Because of their simpler configurations, arrays based on mutual coupling are somewhat more amenable to monolithic integration than arrays which use injection locking or coherent amplification.

F. Realization of Two-Dimensional Configurations

This parameter is important for achieving reduction of the far-field pattern of the array in both directions (see next section). Generally, arrays based on injection locking or on coherent amplification can be more readily arranged in two-dimensional configurations (with a probable penalty of increased losses in the coupling from the maser laser).

G. Additional Components

In all the coherent methods a phase-shifter in tandem with each array element is needed so that the individual phases (which are locked, but not necessarily at the desired values) can be modified to yield the desired radiation pattern. In addition, when employing injection locking or coherent amplification, there is also a need of optical isolators so that light that is generated by the array elements will not be coupled back into the master laser and thus interfere with the overall operation of the array. Such isolators can introduce some additional losses in the coupling from the master laser oscillator.

Before concluding this section it is important to note that the choice of the optimum method depends on the overall system parameters. Since there is no single coherent power combining method with decided advantages over the others, a detailed comparison between the coherent power combining method has to be carried out in any case of a particular system design. However, all other things being equal, it seems that the coherent amplification method is somewhat better than the other methods, delivering essentially the same performance without having to satisfy the additional and rather stringent requirement for synchronization of two (or more) oscillators.

III. Comparison Between Coherent and Incoherent Power Combining

In this section a comparison between coherent and incoherent methods of power combining of semiconductor lasers is carried out. In order to review the basic differences between the two approaches, a simplified one-dimensional analysis is first presented.

Assume a set of M identical lasers at locations $\{d_n\}$, $n = 1, 2, \ldots M$. The near-field pattern of each laser (i.e., the field distribution at its output facet) is denoted by $\mathscr{E}(x)e^{i\phi_n}$ where $\mathscr{E}$ and ϕ are the field amplitude and phase, respectively. The near-field of the whole array $\mathscr{E}_t$ is thus given by

$$\mathscr{E}_t(x) = \sum_{n=1}^{M} \mathscr{E}(x - d_n)e^{i\phi_n} \tag{4}$$

In the case of coherent power combining, the ϕ_n's in Eq. (4) are fixed numbers. The far-field intensity distribution of the array (i.e., its radiation pattern), I_{coh}, is approximately given by (Ref. 14, 15)

$$I_{coh}(\theta) = |\mathscr{F}\{\mathscr{E}(x)\}\cos\theta|^2 \cdot \left|\sum_{n=1}^{M} e^{i\left(\frac{2\pi}{\lambda} d_n \sin\theta + \phi_n\right)}\right|^2 \tag{5}$$

where θ is the far-field angle and $\mathscr{F}\{\circ\}$ denotes a Fourier-transform operation.

In the case of incoherent power combining, the ϕ_n's in Eq. (4) are random variables. We can assume that over all the relevant time periods, the random fluctuations of the ϕ_n's are fast enough so that the cross terms that appear when calculating the intensity average to zero (for example, even wavelength separation of 1Å at $\lambda = 1$ μm corresponds to 30 GHz, which is much faster than typical detector bandwidths). The far-field intensity pattern in this case is

$$I_{inc}(\theta) = M\,|\,\mathscr{F}\{\,\mathscr{E}(x)\}\cos\theta\,|^2 \qquad (6)$$

As expected, no cross-interference terms are present, and the far-field pattern of the incoherent array is an amplified version of the far-field pattern of its elements.

In the following paragraphs a comparison between coherent and incoherent power combining of semiconductor lasers will be made. In two important aspects, namely, improved radiation pattern and spectral distribution, coherent power combining has a significant advantage over incoherent power combining. Several advantages of incoherent power combining will also be presented.

A. Far-Field Pattern

From Eq. (5), which describes the case of coherent power combining, it is anticipated that by a judicious choice of the d_n's and adjustment of the ϕ_n's, the resulting beam pattern can become narrower, in a similar fashion to microwave phased arrays. The reduction of the angular extent of the beam pattern is an important feature of coherent power combining, since narrower beams make the task of subsequent beam narrowing for high-directivity free-space transmission much easier. (It should be emphasized that two-dimensional arrays are needed to obtain a reduction of the far-field beam pattern in both the horizontal and vertical planes.)

As a simple illustrative example, we describe the near-field profile of a single device by

$$\mathscr{E}(x) = \begin{cases} E_0 & |x| < a \\ 0 & |x| > a \end{cases} \qquad (7)$$

The incoherent far-field intensity pattern is calculated from Eqs. (6) and (7) to be

$$I_{inc}(\theta) = 4\frac{2}{a}E_0^2\,M\cos^2\theta\,\mathrm{sinc}^2\left(2\pi\frac{a}{\lambda}\sin\theta\right) \qquad (8)$$

where $\mathrm{sinc}(Z) \equiv (\sin Z)/Z$. The far-field intensity of the coherent array is calculated in a similar fashion from Eqs. (5) and (7). For the case of $\phi_n \equiv 0$ and $d_n = n \cdot d$, the result is

$$I_{coh}(\theta) = I_{inc}(\theta)\cdot M\cdot\left[\frac{\sin\left(2\pi\frac{d\cdot M}{\lambda}\sin\theta\right)}{M\sin\left(2\pi\frac{d}{\lambda}\sin\theta\right)}\right]^2 \qquad (9)$$

The distributions described by Eqs. (8) and (9) are shown in Fig. 2a for the following values of parameters: $\lambda = 0.9$ μm, $a = 2$ μm, $d = 9$ μm and $M = 10$.

The three important features of the far-field patterns, as deduced from Eqs. (8), (9) and shown in Fig. 2a, are:

(1) The intensity of the radiation in the forward direction ($\theta = 0$) is increased by a factor of M by using coherent instead of incoherent power combining.

(2) Under the same conditions, the angular extent of the forward direction radiation lobe is reduced by a factor of $(Md/2a)$.

(3) Coherent power combination is accompanied by the presence of grating lobes. Some of the problems of energy waste and pointing ambiguity associated with them can be mitigated by randomizing the locations of the array elements (Refs. 16–18). A calculated example is shown in Fig. 2b. All the parameters of the array are the same as before, but now the location of each element is randomly distributed within ±2 μm of its deterministic location. (In the case of mutual coupling, sufficient coupling should be maintained also in the new random locations.) It is clearly seen that the level of sidelobes is significantly reduced. The improvement increases with the number of elements of the array and with the amount of randomization allowed in their locations.

B. Spectral Characteristics

Semiconductor laser materials have wide gain linewidths, and thus they can support lasing modes over the range of many angstroms (Ref. 19). When we have an incoherent array of lasers, then even though each of them has an (almost) identical spatial beam pattern, the lasing wavelength will differ from one laser to another, due to minor differences in their lengths, currents, etc. In order for the receiver to collect all the spectral content (i.e., energy) of the received signal, a wide optical filter has to be used, with the unavoidable consequences of admitting more background radiation noise into the system. Systems employing phase-locked arrays, on the other hand, can use much narrower optical filters at the receiver – provided, of course, that the array elements and the array itself oscillate in a single longitudinal mode (i.e., a single spectral line). Single longitudinal mode operation has been demonstrated in many types of laser diodes (Ref. 20) and in laser diodes placed in external cavities (Ref. 21), and it is conceivable that when these diodes are used as elements in the array, it will oscillate in a single longitudinal mode. The narrower optical filter bandwidths which can be used in conjunction with coherent arrays can result in a significant reduction (up to several orders of magnitude) in the amount of background noise radiation detected by the receiver.

It is also worthwhile to mention some practical considerations pertaining to the use of operation of optical filters. Although the inherent laser linewidth is very narrow – less than 10^{-3} Å (Refs. 20, 22) – such narrowband optical filters cannot be implemented yet. As of today, the best demonstrated filters have bandwidths of the order of 10^{-1} Å (Ref. 23). They can also be electronically tuned, which is necessary for compensating wavelength drift due to doppler shifts and temperature variations at the transmitter. (AlGaAs semiconductor injection lasers have wavelength temperature variations of the order of 0.5 to 4Å/K.)

C. Advantages of Incoherent Power Combining

Incoherent power combining is much easier to implement than coherent power combining, and that is its basic advantage. No effort has to be made in order to synchronize the lasers, no external optical components (e.g., phase-shifters, isolators) are needed for the array implementation, the thermal performance is potentially better, and two-dimensional configurations are easier to construct. The design of an incoherent array is free from the many constraints imposed by the requirement of phase-locking. However, although incoherent power combining is easier to implement, the significant advantages offered by coherent power combining (namely, improved power directivity and narrower spectral extent) seem to justify the additional efforts needed to realize devices based on these methods.

IV. Conclusions

Methods of coherent and incoherent power combining of semiconductor lasers have been described. It was found that although incoherent power combining is easier to implement, the significant advantages offered by coherent power combining seem to justify the additional efforts needed to realize devices based on this method. This conclusion is true, particularly in systems which require very high beam directivity and narrow spectral range of the transmitted radiation.

References

1. Pierce, J. R., "Optical Channels: Practical Limits with Photon Counting," *IEEE Trans. Comm.*, COM-26, pp. 1819-1821 (1978).

2. Lesh, J. R., Katz, J., Tan, H. H., and Zwillinger, D., "2.5 Bit/Detected Photon Demonstration Program: Description, Analysis and Phase I Results," *TDA Progress Report 42-66*, pp. 115-132, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1981.

3. Gagliardi, R. M., Vilnrotter, V. A., and Dolinar, S. J., Jr., "Optical Deep Space Communication via Relay Satellite," Publication 81-40, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1981.

4. Katz, J., "High Power Semiconductor Lasers for Deep Space Communications," *TDA Progress Report 42-63*, pp. 40-50, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1981 (and references therein).

5. Katz, J., "Phase-Locking of Semiconductor Injection Lasers," *TDA Progress Report 42-66*, pp. 101-114, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1981.

6. Katz, J., "Phase Control and Beam Steering of Semiconductor Laser Arrays," *TDA Progress Report 42-68*, pp. 42-49, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1982 (and references therein).

7. Adler, R., "A Study of Locking Phenomena in Oscillators," *Proc. IRE*, 34, pp. 351-357, 1946.

8. Tung, C. L., and Statz, H., "Phase-Locking of Laser Oscillators by Injected Signal," *J. Appl. Phys.*, 38, pp. 323-324 (1967).

9. Stover, H. L., and Steier, W. H., "Locking of Laser Oscillators by Light Injection," *Appl. Phys. Lett.*. 8, pp. 91-93, 1966.

10. Stern, F., "Saturation in Semiconductor Absorbers and Amplifiers of Light," in *Proc. Physics of Quantum Electronics Conf.*, McGraw-Hill, N.Y., 1966, pp. 442-449.

11 Vuillenmier, R., Collins, N. C., Smith, J. M., Kim, J. C. S., and Raillard, H., "Coherent Amplification Characteristics of a GaAs Phased Array," *Proc. IEEE*, 55, pp. 1420-1425, 1967.

12. Chang, M. B., and Garmire, E., "Amplification in Cleaved-Substrate Lasers," *IEEE J. Quant. Electron.* QE-16, pp. 997-1001, 1980.

13. Katz, J., "Power Efficiency of Semiconductor Injection Lasers," *TDA Progress Report 42-66*, pp. 94-100, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1981.

14. Casey, H. C., Jr., and Panish, M. B., *Heterostructure Lasers*, Academic Press, New York, 1978, Chapter 2.

15. Parrent, C. B., Jr., and Thompson, B. J., "Physical Optics Notebook," SPIE, Redondo Beach, California, 1971, Chapter 3.

16. Lo, Y. T., "A Mathematical Theory of Antenna Arrays with Randomly Spaced Elements," *IEEE Trans. Ant. Prop.*, AP-12, pp. 257-268, 1964.

17. Lo, Y. T., and Simcoe, R. J., "An Experiment on Antenna Arrays with Randomly Spaced Elements," *IEEE Trans. Ant. Prop.*, AP-15, pp. 231-235, 1967.

18. Corcoran, V. J., and Crabbe, I. A., "Electronically Scanned Waveguide Laser Arrays," *Applied Optics*, 13, pp. 1755-1757, 1974.

19. Yariv, A., *Quantum Electronics*, 2nd Edition, Wiley, New York, 1975, Chapter 10.7.

20. Nakamura, M., "Single Mode Operation of Semiconductor Injection Lasers," *IEEE Trans. Circuits and Systems*, CAS-26, pp. 1055-1062, 1979 (and references therein).

21. For example, Rediker, R. H., Scloss, R. P., Mooradian, A., and Welford, D., "External Cavity Controlled Operation of a Semiconductor Diode Gain Element in Series with an Optical Fiber," Topical Meeting on Integrated and Guided Wave Optics, Jan. 6-8, 1982, Pacific Grove, Calif.

22. Takakura, T., Iga, K., and Tako, T., "Linewidth Measurement of a Single Longitudinal Mode AlGaAs Laser with a Fabri-Perot Interferometer," *Japan. J. Appl. Phys.*, 19, pp. L725-L727, 1980.

23. Title, A. M., and Rosenberg, W. J., "Tunable Birefringent Filters," *Optical Engineering*, 20, pp. 815-823, 1981.

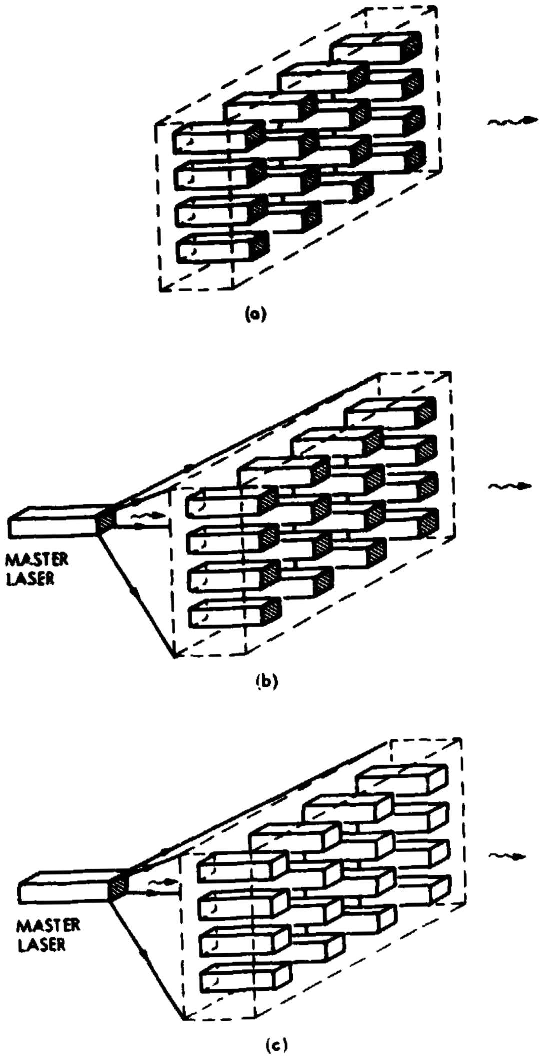

Fig. 1. Schematic configuration of coherent power combining methods: (a) mutual coupling, (b) injection locking (the array elements are lasers), (c) coherent amplification (the array elements are amplifiers).

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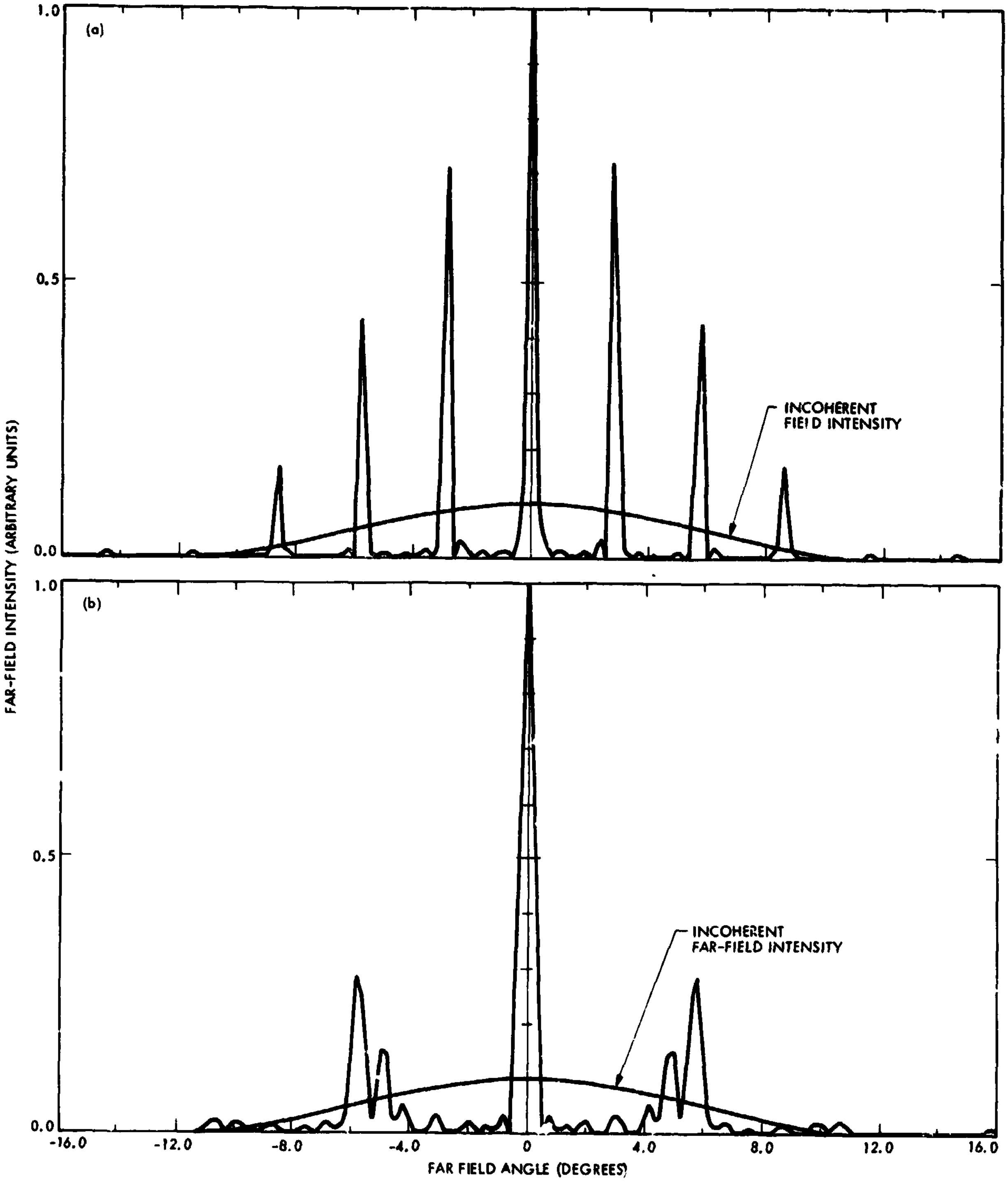

Fig. 2. Approximate far field pattern of a 10-element diode laser coherent array (laser aperture: 4 μm; wavelength: 0.9 μm): (a) array elements are regularly spaced 9 μm apart, (b) array elements are randomly distributed within ± 2 μm of their deterministic location in (a) (also shown is the far-field pattern in the case of an incoherent array)