High Power Semiconductor Lasers for Deep Space Communications

J. Katz
Communications Systems Research Section

The parameters of semiconductor lasers pertaining to their application as optical emitters for deep space communications are discussed. Several methods to overcome their basic disadvantage, which is the low level of powers they emit, are reviewed. Most of these methods are based on a coherent power combining of several lasers.

I. Introduction

The DSN is currently considering optical frequencies for far deep space communications. In (Ref. 1) it was shown that optical wavelengths in the 0.85 μm region appear to be the most desirable, primarily due to the facts that quantum detectors exist for such wavelengths and the optical signals can be generated by AlGaAs semiconductor injection lasers. It is the purpose of this report to present the basic operational characteristics of semiconductor injection lasers, discuss their basic limitation, namely, the low power levels that they emit, and finally, to outline various possible methods to mitigate this problem. For reference purposes, three tables are given in the Appendix which list the semiconductor laser devices that are commercially available today. Further details on semiconductor lasers can be found in one of the following textbooks (Refs. 2-4).

II. Advantages and Disadvantages of Semiconductor Laser Devices

Semiconductor injection lasers have many inherent advantages, which loom significantly in our application. First, they have a high overall efficiency. An efficiency of 35 percent was demonstrated for a particular device at room temperature (Ref. 5), and efficiencies of over 20 percent can be expected for most device structures. Furthermore, an additional improvement can be expected at lower temperatures (see next section).

Semiconductor lasers are also small in size, rugged and reliable solid state devices. Projected room temperature operation lifetimes exceeding 10^5 hours have been demonstrated (Refs. 6 and 7). Finally, semiconductor lasers can be easily and directly modulated at high rates up to the GHz region (Ref. 8).

The primary drawback of these types of lasers is that a single laser cannot supply the amount of optical power needed for far deep space communication. For this reason, combined operation of several lasers must be accomplished. This topic will be discussed in Section IV of this article.

Semiconductor laser operation has been demonstrated in many atomic systems. Among these, lasers based on the (Al,Ga)As system are an attractive choice because the technology of this system is the most mature, compared to other candidates. These lasers emit their radiation in the 0.8-0.9 μm (near IR) region.

Other current research is conducted mainly in systems which produce lasers with longer wavelengths (1.3–1.5 μm). Such wavelengths are optimum for fiber-optic communication, but not for space applications, where shorter wavelengths are desirable because of their smaller beam divergence.

III. Operational Parameters of Semiconductor Injection Lasers

A semiconductor injection laser is basically a p-n diode where the dominant recombination process is radiative, thus enabling—under the conditions of high injection (necessary for sufficient population inversion) and optical feedback—a laser operation. The population inversion is established directly via the current passing through the device, and the optical feedback is usually supplied by the mirrors formed naturally by the cleavage planes of the semiconductor crystal itself. A schematic view of an injection laser is shown in Fig. 1.

The most important characteristic of the injection laser is the light vs current (L-I) curve. A typical curve for a good laser is shown in Fig. 2. The important parameters shown in this figure are:

(1) I_{th} — threshold current. Below this current the light output consists of multimode, incoherent and weak spontaneous emission. For currents above I_{th}, lasing occurs.

(2) L_{max} — Maximum amount of light that can be extracted from the laser before a failure occurs.

(3) $\eta_d = (e\lambda/hc)(\Delta L/\Delta I)$ differential quantum efficiency (e is the electron charge, λ is the emission wavelength, h is Planck's constant and c is the velocity of light). Values exceeding 30 percent per facet have been achieved (Refs. 9–13).

The overall operational efficiency of the laser at an operating point (I,L) is

$$\eta = \frac{\eta_d}{2}\left(1 - \frac{I_{th}}{I}\right) \tag{1}$$

The factor of 1/2 is due to the fact that in most applications, light from only one of the two laser facets is utilized. Ohmic losses in the contacts of the diodes have not been included in Eq. (1).

In the following paragraphs, some of the laser parameters will be described in more detail.

A. Threshold Current (I_{th})

For commonly used heterojunction lasers (see below), the threshold current density (J_{th}) ranges from about 1-3 KA/cm^2 at room temperature (depending on the laser type), leading to threshold currents of few tens to a few hundreds of milliamperes for typical device dimensions. The formula for calculating J_{th} can be found in (Ref. 3). An important feature of I_{th} is its rather strong dependence on temperature. As the laser temperature is decreased (by ΔT) the threshold current is reduced, according to (approximately) exp $[-\Delta T/T_0](T_0 \sim 120°$ K), thus increasing the overall device efficiency. (It is worth mentioning that there is also a ten-fold improvement in reliability for every 30° K cooling). This property of semiconductor lasers is an added advantage, since in deep space missions it is possible to cool the optical emitter passively (i.e., without investing power) down to temperatures of about 120° K.

B. Limitations on the Power Output

The maximum power that can be reliably extracted from a laser diode depends both on the type of laser (with cleaved mirrors or distributed feedback) and on the mode of operation (pulsed or CW).

For lasers with cleaved mirrors (which are the most commonly used), the ultimate limit in pulsed operation is reached when the light intensity at the laser facet exceeds a certain limit. This failure mechanism, known as catastrophic degradation, is somewhat analogous to dielectric breakdown. The light intensity at the failure is about 10 MW/cm^2 although this value depends inversely on the square root of the pulse width (Ref. 2). Special laser structures (Ref. 14), (Ref. 15), or special laser coating (Ref. 16), have been demonstrated where the catastrophic damage occurs at much higher intensities. The catastrophic degradation limit may be a function of the operating temperature, but this dependence is as yet unknown. As an example, assume that the safe working limit of a specific device is 5 MW/cm^2. Then, an emitting area of 200 (μm)^2 is needed to achieve a peak power of 10 watts.

When the laser is operated in a CW fashion, which is not likely to be the case in our application, the limiting factor is usually due to thermal effects. This limit is lower than the catastrophic damage limit (e.g., 10 mW for CW operation vs. ~100 mW for pulsed operation).

As a final remark, we should mention that for lasers without mirror feedback (e.g., Distributed Feedback (DFB) and Distributed Bragg Reflector (DBR) lasers), the limiting mechanism is not known. The ultimate limit—the dielectric breakdown of the material—occurs above 1 W/$(\mu m)^2$, which is about one to two orders of magnitude higher than the catastrophic facet damage. It is possible, however, that other mechanisms will prevent one from achieving this limit. Although mirrorless lasers are more amenable to integration, they usually have a higher threshold current and a lower differential quantum efficiency than the ones with cleaved mirrors. Thus lasers without mirror feedback are less attractive for our application, although their possible application must not be completely ruled out.

C. Radiation Pattern of a Laser

Due to the small dimensions of the laser active region cross-section, the light output is emitted into a large solid angle: up to $50°$ in a direction perpendicular to the junction plane and about $10°$ in the direction of the junction plane. This large angle can interfere with subsequent efficient light processing (collimating, etc.).

D. Single Spatial Mode Operation

For deep space applications one needs more power than a single laser diode can supply. We have seen before that the limiting device parameter is the light intensity at the laser facet. One could ask why is it not possible to get higher power levels simply by increasing the cross-section area of the device active region. The answer is that this is not a good solution since by doing so, the active region cross-section dimensions become much larger than the radiation wavelength (~ 0.9 μ), and such a structure cannot support a stable radiation pattern. Thus, the use of a single large emitting area would cause the transmitted beam to vary spatially in an unpredictable fashion, a situation which is unacceptable for deep space applications. Possible methods to overcome this problem are discussed in the next section.

IV. Possible Approaches for Obtaining High Power Semiconductor Laser Emitters

It has been noted that a single commercially available semiconductor injection laser, operating in the fundamental transverse mode, can deliver a few milliwatts in a CW operation, and at the most, a few hundred milliwatts in pulsed operation. This amount of power is far below that needed for space communications, which is about 1 W average power and with peak powers as large as possible.

There are several approaches to partly or totally overcome this problem, as outlined in the following.

A. Optimization of the Parameters of Single Laser Diodes

This is done by modifying the cross-section shape of the active region, which results in a better mode selection (Refs. 17 and 18). By using this approach, it seems feasible to obtain devices that maintain a single mode behavior up to power levels of 100 mW.

B. Phase Locking of Several Lasers by Placing Them in a Common External Cavity

The cavity includes optical elements which cross-couple the radiation fields of the individual lasers. Under certain conditions, the amount of coupling is sufficient to obtain phase-locking (Refs. 19 and 20). An example of such a device is shown in Fig. 3.

The disadvantages of this method are that it relies heavily on mechanical structures, which makes it inherently less stable, and it is larger in size. The advantage of such a structure, however, is that the powers of individual diodes can be combined coherently, thus providing a more finely defined radiation beam. This is similar to the fine pointing characteristics of phased arrays.

C. Monolithic Phase Locking: One Dimensional Array

In this method the power of several lasers is also combined coherently. However, unlike the last method, in this scheme all the lasers are grown monolithically on a common substrate, and all the lasers in this array are electrically operated in parallel (Refs. 21–24). In this case, the coupling mechanism leading to phase locking is achieved via overlapping the electromagnetic fields of adjacent lasers. To achieve this, the lasers must be in close proximity ($\lesssim 10$ μ) to one another. With such a device, there is no need for an external cavity. This method has been used to produce devices consisting of 10 phase locked diodes and which are capable of delivering up to 900 mW of peak power in 100 ns 1 percent duty cycle pulses.

D. Monolithic Phase Locking: Two Dimensional Array

In this method, each laser diode in the parallel monolithic array described above is replaced by either a vertical combination of several diode lasers (Fig. 5), or by a laser diode that can emit higher power levels (for example, diodes of the types described in paragraph A. of this section). Operation of a

device with a vertical combination of several active regions has already been demonstrated (Ref. 25). Basic potential problems expected in the fabrication and operation of a two-dimensional array are maintaining the uniformity of the emitted radiation patterns and the coupling required for locking, as well as the removal of heat generated within the device structure.

E. Hybrid Device

Hybrid combinations of the above approaches have also been recently suggested (Ref. 26). The proposed device would consist of many injection lasers put on a common substrate in a common DBR resonator which supplies the cross-coupling between the lasers (see Fig. 6). The proposed device is expected to emit 0.1-1 W average power from an emitting area of about 10 mm^2.

V. Conclusion

The basic properties of semiconductor injection lasers were described and their advantages discussed. The primary disadvantage of these devices (i.e., low single spatial mode output power) was then identified and several methods for overcoming this limitation were discussed. The technologies for solving the power limited emitter problem are just now emerging, but with so many independent approaches in progress, one can be quite confident that commercial devices capable of delivering the requisite power will soon be available.

References

1. Katz, J., and Lesh, J. "Optical Communication for Deep Space Missions Using Integrated Semiconductor Injection Lasers," Technical Report (in preparation), Jet Propulsion Laboratory, Pasadena, Calif.

2. Kressel, H., and Butler, J. K., *Semiconductor Lasers and Heterostructure Leds*, Academic Press, 1977.

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

4. Thompson, G. H. B., *Physics of Semiconductor Laser Devices*, Wiley Interscience, Chichester, 1980.

5. Chinone, N., et al, "Highly Efficient (GaAl)As Buried Heterostructure Lasers with Buried Optical Guide," *Appl. Phys. Lett.* 35, pp. 513-516, Oct. 1, 1979.

6. Hartman, R. L., Schumaker, N. E., and Dixon, R. W., "Continuously Operated (Al,Ga)As Double-Heterostructure Lasers with 70°C Lifetimes as Long as Two Years," *Appl. Phys. Lett.* 31, pp. 756-759, Dec. 1, 1977.

7. Nita, S., Namizaki, H., Takamiya, S., and Sugaki, W., "Single Mode Junction-Up TJS Lasers with Estimated Lifetime of 10^6 Hours," *IEEE J. Quant. Electron.* QE-15, pp. 1208-1209, 1979.

8. Arnold, G., and Russer, P., "Modulation Behavior of Semiconductor Injection Lasers," *Appl. Phys.* 14, pp. 255-268, 1977.

9. Tsang, W. T., and Logan, R. A., "GaAs-Al$_x$Ga$_{1-x}$As Strip Buried Heterostructure Lasers," *IEEE J. Quant. Electron.* QE-15, pp. 451-469, June 1979.

10. Aiki, K., et al, "Transverse Mode Stabilized Al$_x$Ga$_{1-x}$As Injection Laser with Channeled-Substrate-Planar Structure," *IEEE J. Quant. Electron.* QE-14, pp. 89-94, Feb. 1978.

11. Burnham, R. D., and Scifres, R., "Etched Buried Heterostructure GaAs/GaAlAs Injection Lasers," *Appl. Phys. Lett.* 27, pp. 510-511, Nov. 1, 1975.

12. Wittke, J. P., and Laddany, I., "Lateral Mode Selection in Semiconductor Injection Lasers," *J. Appl. Phys.* 48, pp. 3122-3124, July 1977.

13. Tsang, W. T., and Logan, R. A., "Lateral Current Confinement by Reverse-Biased Junctions in GaAs-Al$_x$Ga$_{1-x}$As DH Lasers," *Appl. Phys. Lett.* 30, pp. 538-540, May 15, 1977.

14. Yonezu, H. O., Veno, M., Kamejima, T., and Hayashi, I., "An AlGaAs Window Structure Laser," *IEEE J. Quant. Electron.* QE-15, pp. 775-781, 1979.

15. Takamiya, S., et al, "One Order Power Improvement of Single Mode TJS Laser Diodes by Crank Structure," in the *7th IEEE Intl. Semicond. Laser Conf.*, (Paper P8).

16. Namizaki, H., Takamiya, S., Ishii, M., and Susaki, W., "High-Power-Density Single Mode Operation of GaAs-GaAlAs TJS Lasers Utilizing Si$_3$N$_4$ Plasma Deposition for Facet Coating," *J. Appl. Phys.* 50, pp. 3743-3745, 1979.

17. Botez, D., "CW High Power Single Mode Operation of Constricted Double Hetero-junction AlGaAs Laser with a Large Optical Cavity," *Appl. Phys. Lett.* 36, pp. 190-192, 1980; Botez, D., Butler, J. K., and Connolly, J. C., "Mode Control in High-Power CDH-LOC Diode Lasers: the W-Shaped Lateral Waveguide," in the *3rd Intl. Conf. Integrated Optics and Optical Fiber Commun.*, (Paper MB-5), 1981.

18. Streifer, W., Scifres, D. R., and Burnham, R. D., "Above Threshold Analysis of Double-Heterostructure Diode Lasers with Laterally Tapered Active Regions," *Appl. Phys. Lett.* 37, pp. 877-879, 1980.

19. Crowe, J. W., "External Cavity Coupling and Phase Locking of Galium Arsenide Injection Lasers," *IEEE J. Quant. Electron.* QE-4, pp. 169-174, Apr. 1968.

20. Philipp-Rutz, E. M., "Single Laser Beam of Spatial Coherence from an Array of GaAs Lasers: Free Running Mode," *J. Appl. Phys. 46*, pp. 4552-4556, Oct. 1975.

21. Scifres, D. R., Streifer, W., and Burnham, R. D., "High-Power Coupled-Multiple-Stripe Phase-Locked Injection Laser," *Appl. Phys. Lett. 34*, pp. 259-261, Feb. 15, 1979.

22. Ripper, J. E., and Paoli, T. L., "Optical Coupling of Adjacent Stripe-Geometry Junction Lasers," *Appl. Phys. Lett. 17*, pp. 371-373, Nov. 1, 1970.

23. Scifres, D. R., Burnham, R. D., and Streifer, W., "Phase-Locked Semiconductor Laser Array," *Appl. Phys. Lett. 33*, pp. 1015-1017, Dec. 15, 1978.

24. Tsang, W. T., Logan, R. A., and Salathe, R. P., "A Densely Packed Monolithic Linear Array of GaAs-Al$_x$Ga$_{1-x}$As Strip Buried Heterostructure Laser," *Appl. Phys. Lett. 34*, pp. 162-165, Jan. 15, 1979.

25. Katz, J., Bar-Chaim, N., Margalit, S., and Yaris, A., "Large Optical Cavity AlGaAs Injection Lasers with Multiple Active Regions," *J. Appl. Phys.* 51, pp. 4038-4041, 1980.

26. Evans, G. A., et al, "Progress Toward a Monolithically Integrated Coherent Diode Laser Array," (Interim report prepared by the Aerospace Corporation under Contract F04701-79-C-0080).
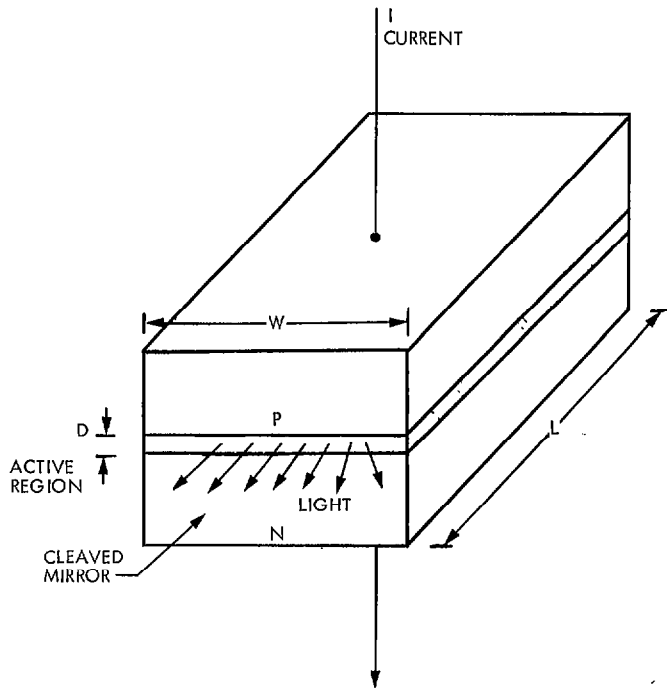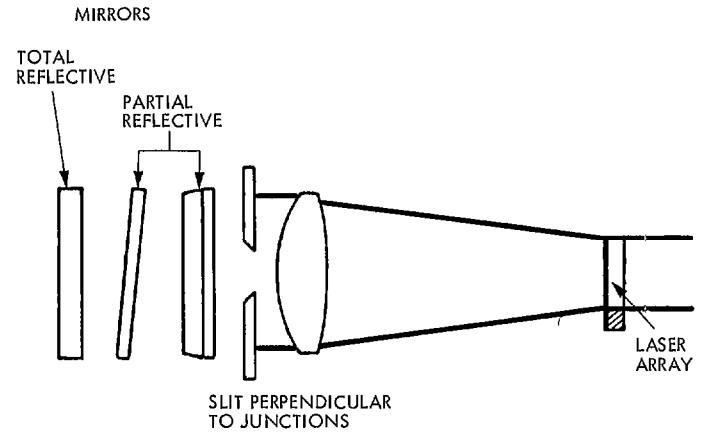
Fig. 1. Schematic view of an injection laser

Fig. 3. Locking of discrete devices with external optical cavity (Adapted from Fig. 4 in Ref. 19)
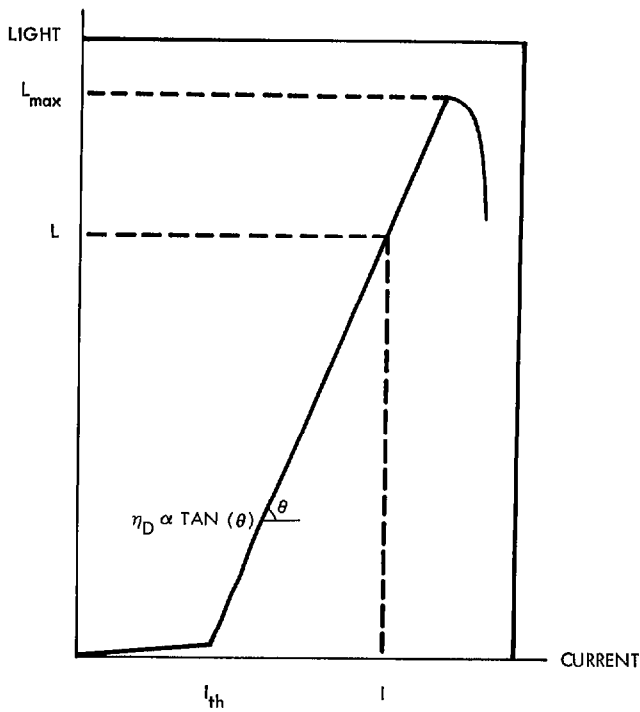

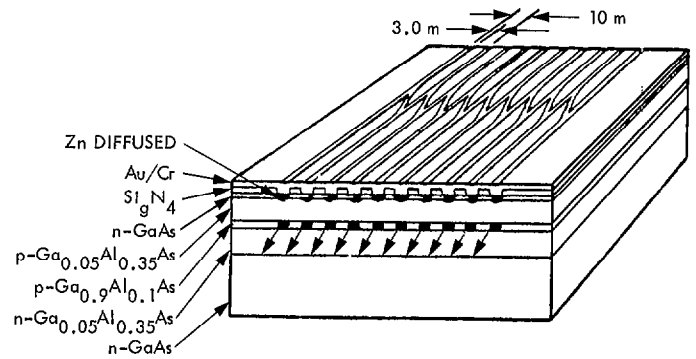**Fig. 2. Light-current curve of an injection laser**

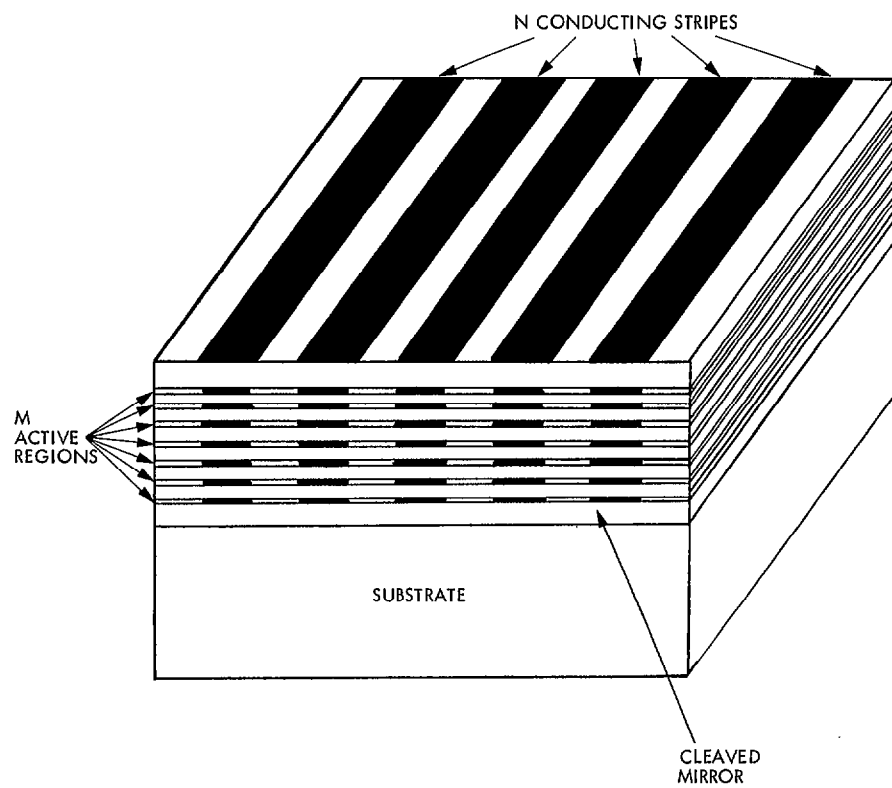**Fig. 4. High-power phase locked injection laser array (Fig. 1 in Ref. 21)**

N CONDUCTING STRIPES

M
ACTIVE
REGIONS

SUBSTRATE

CLEAVED
MIRROR

Fig. 5. Schematic view of proposed two-dimensional phase-locked laser array

(a)

(b)

BRAGG
DEFLECTOR
CASCADE

DISTRIBUTED
BRAGG
REFLECTOR (DBR)

OUTPUT
GRATING
COLLIMATOR
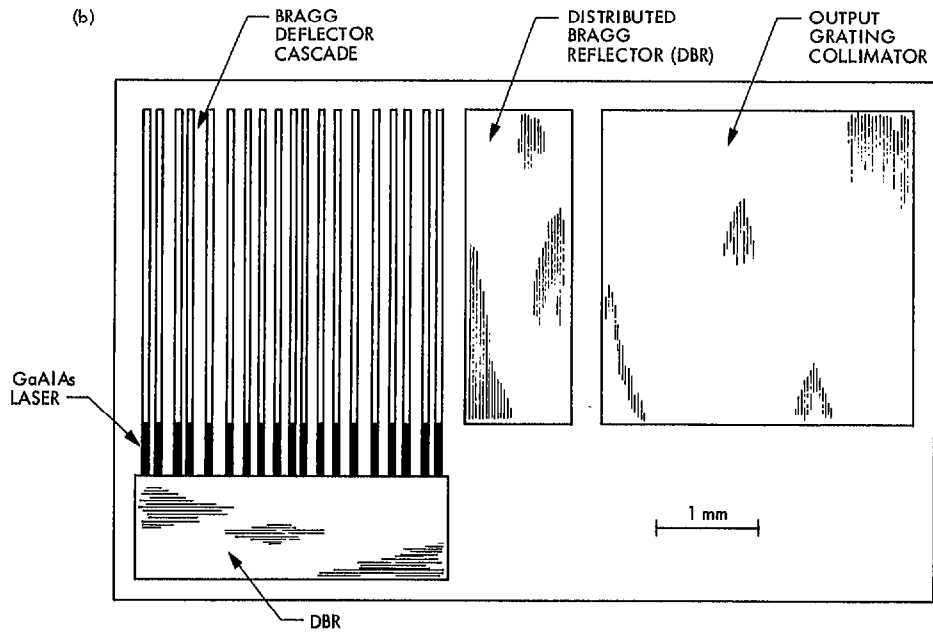
3 mm

GaAlAs
LASER

1 mm

DBR
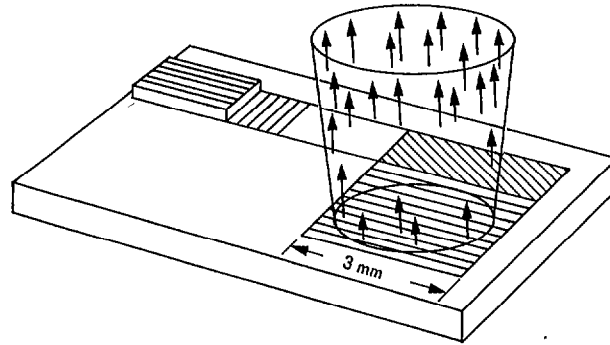
Fig. 6. High brightness GaAs laser array: (a) Schematic view, (b) Top view and details of the structure from Ref. 26

Appendix

Devices Available on the Market

The next three tables summarize the parameters of GaAlAs lasers and laser arrays that are available on the market. Table A-1 lists double heterostructure diodes, which have high reliability and operate at low power levels. Table A-2 lists diodes intended for high peak power pulsed operation. These diodes have lower reliability and less controlled beam pattern. Table A-3 lists laser arrays, made of diodes of the type listed in Table A-2. In each table, only the best device in each category of each manufacturer is listed.

Table A-1. AlGaAs injection lasers: CW low power double heterostructure diodes (available on the market, March 1981)

Company	Country	Model	Type	Nominal Output Power [mW]	Operating Electrical Power [mW]	Power Efficiency %	Single Transverse Mode	Source Size [μ^2]	Beam Divergence [deg^2]
Hitachi	Japan	HLP3000	Buried Optical Guide	6	81	7.4	Yes		20 × 35
LDL	U.S.	SCW-20	CSP	7.5	170	4.4	Yes	0.2 × 7	10 × 35
Mitsubishi	Japan	ML-2200	TJS	3	72	4.1	Yes	0.4 × 2	10 × 40
RCA	U.S.	C86014E	Double Dovetail	7	200	3.5	Yes	2 × 6	
General Optronics	U.S.	GOLS	Proton Bombard-ment	5	200	2.5	Yes		10 × 45
Exxon/OIS	U.S.	OL3150Z		5	220	2.3	Yes	1 × 12	20 × 45
ITT	U.K.	LS7737		7	320	2.2	Yes		
		LS7735	Broad Area-DH	20	360	5.5	No		

Table.A-2. AlGaAs injection lasers: pulsed, high peak power diodes
(available on the market, March 1981)

Company	Country	Model	Type	Nominal Peak Output Power [W]	Duty Cycle (max) %	Power Efficiency %	Source Size [μm^2]
LDL	U.S.	LD 68	Single Hetero-Structure	20	0.1	3.3	2 × 400
RCA	U.S.	SG 2012	Single Hetero-Structure	20	0.1	1.7	2 × 600
ITT	U.K.	LA 15	Single Hetero-Structure	15	0.2	1.9	2 × 230
		LB 1	Double Hetero-Structure	0.2	15	4.4	0.5 × 100

Table A-3. AlGaAs injection laser arrays (available on the market, March 1981)

Company	Country	Model	No. of Diodes	Nominal Peak Output Power [W]	Duty Cycle (max) %	Power Efficiency %	Source Size [μm^2]	Remarks
LDL	U.S.	LA 410	120	1000	0.01	3	3900 × 4600	
		MH 167	5	80	0.03	5	400 × 400	
		LDF 167	5	80	0.04	4	500 × 500	Array with fiber integrator
RCA	U.S.	C 30042	6	100	0.01		500 × 500	
		C 30009	60	300	0.02	3	1500 × 4000	
ITT	U.K.	LS 7728	40	300		3	500 × 3800	