H. Wieder
H. Werlich

Characteristics of GaAs Laser Arrays Designed for Beam Addressable Memories

Abstract: Four properties of GaAs laser arrays i.e., the efficiency, junction width, beam spread, and polarization, are important in assessing the usefulness of such devices in beam addressable memory applications. Measurements made on a series of arrays are presented. It is shown that the first two parameters closely approach the characteristics of an idealized array, while the latter two reduce the energy density at the storage plane to 25 percent of that at the junction surface. With existing devices, information has been written and recovered at a bit rate of 10 MHZ.

Introduction

A beam addressable memory (BAM) has been proposed[1] in which arrays of GaAs lasers are used as the transducer elements for READ-WRITE operations. The memory plane consists of a doped EuO film in which the local temperature is raised by an impinging laser beam to a level such that its coercive force can be overcome by a bias magnetic field. The reversed magnetic state of the "written" spot is then detected in the READ mode by its effect on the polarization state of the laser beam.

The performance of the laser arrays is important in the realization of such a memory system and, because of this, a program has been instituted to study and evaluate these experimental arrays. In this paper we present the results of these studies and compare the measured performance of several laser arrays with that of an idealized array.

Ideal characteristics of laser arrays for BAM

In the field of memory technology, optical techniques are particularly suited to applications involving high bit densities. Since optical cost considerations favor 1:1 imaging over other magnifications, this application can best be served by lasers having very small junction widths. This is a key requirement of the laser array package.

Some of the other requirements of these arrays stem from the characteristics of the storage medium and the configuration chosen for this type of memory. The geometry envisioned for an EuO memory is one in which a rotating disk carrying the memory material is addressed by a battery of laser arrays, each laser acting as transducer for several adjacent tracks. A bit is written thermomagnetically when a laser pulse of sufficient energy is projected onto the disk in the presence of a bias magnetic field. The readout is performed with the same laser in a subsequent scan of the track, using a magneto-optic effect. Since a bit is distinguished from background noise by a relatively small perturbation of the polarization state of the READ beam, it is important that this polarization difference be easily detectable. This requires an analyzer in the detection apparatus and, in the case of an array of closely spaced lasers, a unique polarization orientation for the entire array. Thus, a second characteristic of the idealized array is that all the lasers be well polarized and have a common plane of polarization.

The remaining criteria are associated with the need for achieving, in the most efficient and economic manner, the highest possible energy density at the memory plane during the writing mode. Thus, each laser should have very high energy conversion efficiency and should radiate its optical energy into a relatively narrow cone, so that all of the energy can be collected and relayed to the storage medium by means of simple optics. Although the criteria of small junctions and narrow beam spreads are mutually exclusive in their respective limits, an optimum junction size can be achieved by examining the various tradeoffs involved. Finally, the array must behave uniformly with respect to the properties that have been enumerated – efficiency, junction size, polarization and beam spread.

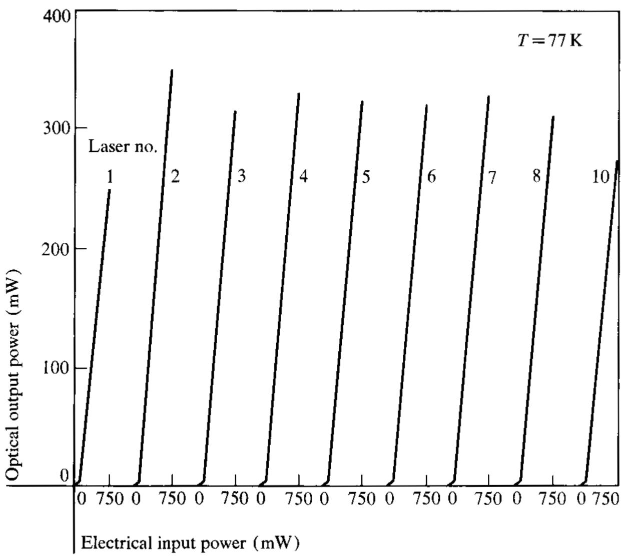

Figure 1 Efficiency (optical output power vs electrical input power) for nine of ten lasers in Array No. CD184-4. The horizontal axis terminates at 750 mW for each laser.

These criteria are all related to the goal of achieving the highest possible energy density within the area of a bit during the writing process, while also attaining the highest possible bit density. Except for its influence on the polarization requirements, the reading process has been neglected in this discussion. Treves[2] has shown that the achievable signal-to-noise ratio in a magneto-optic readout is proportional to the square root of the power level of the READ beam. However, since this power level must be well below the level at which accidental erasure is effected, the READ requirements do not pose a restrictive criterion for laser operation. The ability to deliver sufficient energy in a short pulse to write bits on the storage medium thus remains the principal criterion for evaluation of laser array performance.

Experimental methods

• *Fabrication*
The arrays have been fabricated by somewhat different methods in two laboratories. The methods are discussed in detail in the accompanying papers[3,4]. The junctions are about 17 μm wide and from 2 to 4 μm deep. The geometrical cavity length ranges from 0.2 to 0.3 mm, and the spacing between junctions is about 0.1 mm. In one package the heat sink was copper and in the other, sapphire. Each array consisted of either 10 or 20 separate junctions.

• *Measurements*
The array properties were measured with the heat sink held at 77 K, using a cold finger mount. The mount rested on a 3-ball support, rather than being suspended, to avoid vibration of the laser during the measurements. Each laser was individually addressed, and its properties were studied only after it was determined that there were no electrical leaks to neighboring lasers.

The near-field distribution of a laser was measured by scanning the magnified image of the junction in directions along and perpendicular to the junction plane, using a slit whose width was one-tenth the narrow dimension of the junction image. The far-field distribution was measured in two ways—first with an aperture scanning angularly through two orthogonal circles centered at the laser, and second by measuring sequentially the relative power passing through a series of apertures placed at a fixed distance from the laser. The former method measures the detailed distribution along the principal axes of the pattern, while the latter measures the relative useful power collected by an optical system having an adjustable numerical aperture.

Measurements of a set of output power vs. input power curves (Fig. 1) were used to calculate pulsed efficiency.

The properties of the laser that affected their usefulness as BAM devices were not sensitive functions of the operating power level of the laser. Nevertheless, the data presented in Figs. 2, 3 and 4 were taken at a power level for which thermomagnetic writing could be achieved (750 mW input current). The spectra in Fig. 5 were taken at about twice threshold, where modes are well resolved.

Properties of individual lasers and of arrays

• *Efficiency*
One of the better laser arrays made for a BAM has the pulsed efficiency characteristics that can be derived from Fig. 1. Threshold for pulsed operation at 77 K is about 75 mW, which corresponds to 1000 A cm^{-2}. Thus, while the threshold current density is about the same for these lasers as for those with much larger junctions, the total driver current needed to reach a given output power density level at the junction face is considerably reduced. Laser efficiency in this particular array deviates from the average by only $\pm$ 15 % (omitting the one junction that was defective), which represents about the best uniformity achieved to date. The linear portion of the efficiency curve extends well above the upper level shown in the figure, often reaching about 3 W input. Over this region some of the best lasers have indicated quantum efficiencies[5] of about 40 percent, as measured from one end of a cleaved and uncoated crystal, although scattered light from the concealed end of the laser may have contributed somewhat to this measurement. Nevertheless, the high efficiency of these lasers remains one of their most favorable properties.

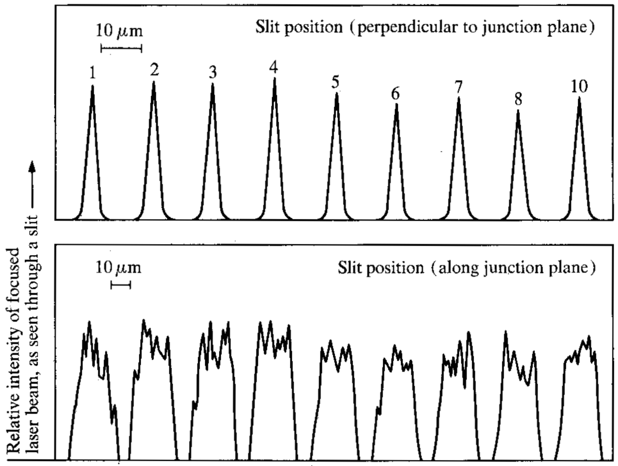

Figure 2 Near-field patterns for nine of ten lasers in Array No. CD184-4. The upper trace is for a scan taken perpendicular to the junction plane, and the lower trace is a scan parallel to the junction plane.

Near field

One of the most reproducible properties of the lasers is their near-field pattern. With shallow diffusion ($\approx 2\ \mu$m) the problems of "winging" and of junction curvature are avoided[3,4]. However, the near field of these lasers is always filamentary, which leads to strongly divergent far-field patterns. A typical laser measures 17 μm along the junction width and 3μm at the half-power points perpendicular to the junction plane. As can be seen in Fig. 2, the differences in the near fields of an entire array are usually restricted to variations in the structure as measured along the junction plane. Because of thermal spreading in the storage medium, it is doubtful that this would lead to a structured bit. No such structure has been detected in written bits.

Referring to the efficiency and near-field data, we see that a good laser yields about 10 mW of power from each square micrometer of emitting surface per ampere input to the laser. Only a fraction of this power density is available at the storage plane, principally because of losses encountered in two main areas: 1) the divergent far-field pattern and 2) the polarization nonuniformity of the array.

Polarization

As discussed earlier, the idealized array is well polarized and has a common plane of polarization. To the extent that the actual array deviates from this, some of the power radiated from the lasers cannot be used. A polarizer must be inserted in front of the array to provide a reference for observing magneto-optical effects introduced by the storage medium. This polarizer absorbs all the laser light emitted along the orthogonal polarization. Figure 3 is a composite of the polarization properties of one of the more uniformly polarized arrays, measured at a power level normally used in writing bits. The average polarization orientation of the array, indicated by the vertical dashed line in the figure, is very nearly along the junction plane (the origin in the figure). Most of the lasers are polarized within 15 percent of this average value. The relative loss in intensity sustained for any laser because of the insertion of the polarizer is given by

$$L_p = \frac{P + (1 - P)\cos^2\theta_M}{P + 1},$$

where θ_M is the angular mismatch between the polarizer and the peak intensity of light from the laser, and P is the polarization ratio (the ratio of maximum to minimum intensity of the laser as seen through a rotating polarizer). For the array considered in Fig. 3 the worst loss, 36 percent, is suffered by laser No. 1, shown at the top of the figure. Losses tabulated for entire arrays are given in terms of the average loss, which for this array is only 24 percent. Although the laser showing the worst loss is the one which limits the usefulness of the array, the average is considered more descriptive of the typical performance of the lasers and is the value listed in Table 1. It should be noted that, even for completely random polarization, losses can be limited to 50 percent by inserting a quarter-wave plate in front of the polarizer used in the system. The polarization nonuniformity in these arrays accounts, on the average, for a 25 percent reduction in the power density of the laser beam as seen in the memory plane.

Far field

Each laser consists of from three to seven closely spaced filaments which fill the junction width. The filamentary nature of these lasers results in a divergent far-field pattern (0.4 rad) which depends on the size of an individual filament ($\approx 4\ \mu$m), rather than the junction width ($\approx 17\ \mu$m)[6]. The radiation pattern shown in Fig. 4 for an entire array is plotted, not in terms of the intensity at a given angle with respect to the laser axis, but in terms of the relative amount of the total emitted power that appears in a solid angle of specified numerical aperture. A numerical aperture of 0.4 or greater is needed to avoid severe losses due to vignetting of the beam by the optics. The use of relatively inexpensive optics (N.A. = 0.15) introduces about a 65 percent reduction in the power density at the storage plane. The large beam spread of these arrays is their most significant limitation.

Bandwidth

Variations as great as 50 Å have been observed in the bandwidths and in the band positions of lasers belonging

Table 1 Measured and calculated properties of some experimental laser arrays.

Array No.	*Efficiency* (Measured from one end)*	*Junction size*	*Average polarization loss*	*Vignetting loss for N.A. = 0.15*	*Energy density at storage plane for (0.5 A) × (50 ns) pulse*
LA0131	0.26	3.0 × 14 μm	0.14	0.60	0.08 nJ/μm²
LA0132	.25	3.5 × 13	.22	.67	.05
LA0133	.25	3.5 × 17	.16	.66	.04
LA0143	.39	3.0 × 17	.24	.66	.07
LA0147	.39	3.5 × 17	.29	.68	.06
CD152-2	.33	2.5 × 16	.33	.59	.08
CD184-1	.40	2.5 × 18	.36	.66	.07
CD184-4	.40	3.0 × 17	.28	.63	.08

*Optical power output ÷ electrical power input

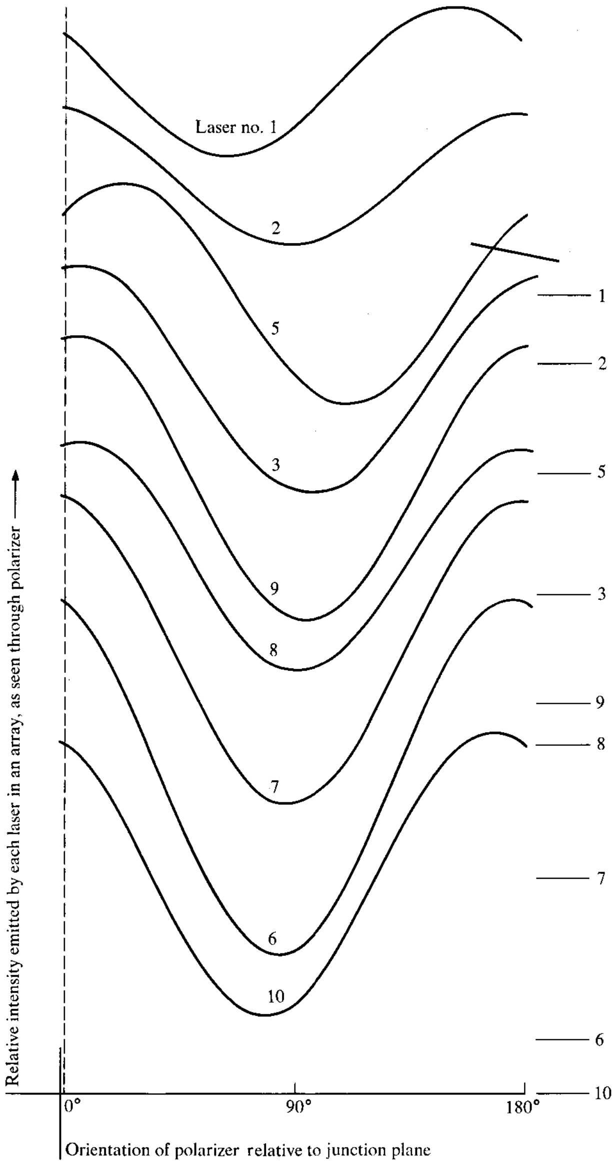

Figure 3 Relative intensity and orientation of polarization for nine of twenty lasers in Array No. LA0143. The baseline for each curve is indicated at the right of the figure. The junction plane is located along the origin.

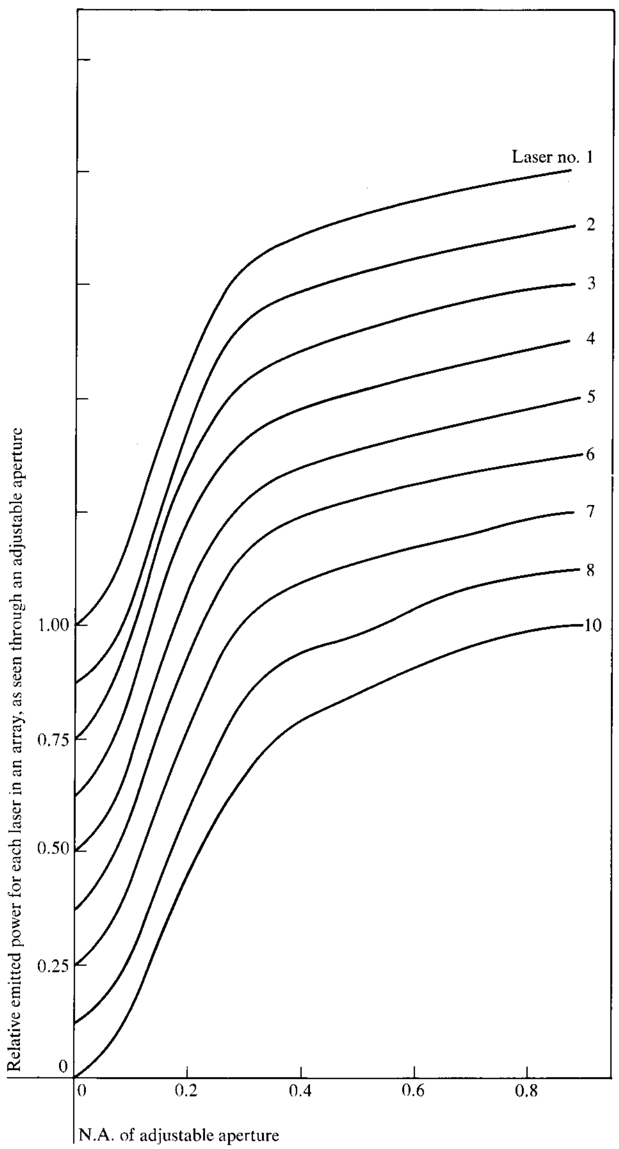

Figure 4 Relative power emitted by nine of ten lasers in Array No. CD184-4 into a given solid angle, indicated by its numerical aperture. The baseline of each curve is shifted an equal amount, each curve beginning at zero at the left. The ordinate is labelled for curve 10.

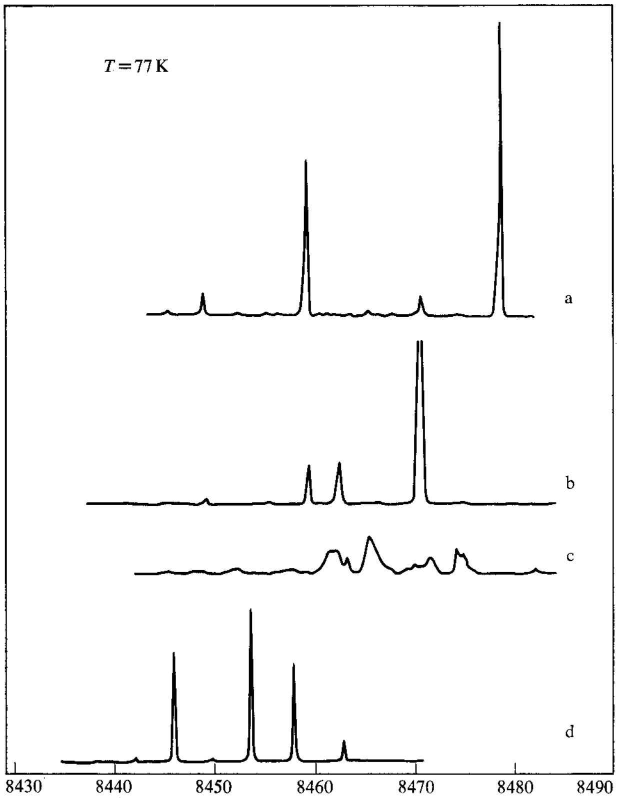

Figure 5 Effects of degradation on mode spectum of a GaAs diode laser. (a) Mode spectrum of Array LA 0057 slightly above threshold, taken at 77 K before degradation. (b) Same spectrum shortly after the laser was subjected to a dc current of 3A, leading to a reversible degradation (spectrum taken before annealing). (c) Same spectrum after severe degradation. (d) Same as (c) after overnight annealing at room temperature.

to a single array. Such variations imply a nonuniformity of strain[7] which is present in the crystal or which is induced by nonuniform mounting techniques. This is also borne out by the fact that many arrays show a random polarization among all the lasers[8]. Bandwidths as narrow as 25 Å and as wide as 100 Å have been observed for moderate power levels. The spectral properties, while not of immediate concern in a BAM application, are indicative of the need for better control of the fabrication process to achieve greater uniformity of the arrays.

• *Degradation*

Long-term degradation studies of these arrays[3] have shown that they are remarkably stable when used at an input current level of 500 mA. As discussed below this should be adequate to achieve a writing rate of about 10 MHz. By deliberately degrading some of the lasers (i.e., by operating them at 2 to 3 A for periods up to one hour), we were able to make some tenative conclusions about the degradation process. Figure 5 shows the effect on the spectral output of a laser which was subjected to such treatment. The initial effect is to shift the spectral components, usually toward shorter wavelengths [Fig. 5(b)]. This is reversible if the loss in efficiency is also reversible, but the recovery period may be several hours. With the application of higher current densities the spectral linewidths are increased [Fig. 5(c)] and the shift to shorter wavelengths is not reversible. However, the line spectra do become narrower with overnight annealing at room temperature, as shown in Fig. 5(d).

These effects can be explained by assuming that a strain develops as a result of strong thermal or electric field gradients in the crystal. At lower power levels the strain can be annealed and this usually occurs during thermal recycling of the laser. At higher levels only partial annealing is possible, leaving the crystal with a permanent strain, which not only shifts the luminescence band but also causes the modes to broaden by reducing the Q of the resonator. There is some evidence that a rapidly reversible strain is introduced at an even lower power level than has been discussed here[6].

Discussion

The principal properties of most significance for array usefulness in a BAM are tabulated for a number of arrays in Table 1. The most significant variations occur in the values of average polarization loss. Other properties fluctuate somewhat from one array to another but, on the whole, these differences can be tolerated.

Calculations indicate[8] that threshold writing on EuO at a bit rate of 10 MHz can be achieved for 50 nsec pulses with an energy density of 0.04 nJ/μm^2. For the laser arrays listed in the table, an energy pulse of 0.07 nJ/μm^2 at the storage plane can be achieved with an input current of 500 mA applied for 50 nsec. Thus, in spite of the 75 percent loss of emitted power density, all these arrays should be capable of being used in a real BAM system. In fact, each of these arrays has been used to generate and read bits, some at a frequency of 10 MHz.

The two areas that need attention in these arrays are the polarization nonuniformity and the large beam spread. Both could show substantial improvement with the use of dislocation-free material. According to Hatz[9], such material leads to homogenous near-field patterns, which result in diffraction-limited Gaussian patterns parallel to the junction plane. This could increase the flux collected by the optics by at least a factor of two. Furthermore, nonfilamentary lasers have a lower threshold for modes polarized perpendicular to the junction plane than for those polarized parallel to the junction plane[9]. This property should significantly reduce the polarization variation now found in arrays. Another approach which can be taken is to deliberately introduce an anisotropy into the crystal or the cavity which favors only one polarization.

In summary, GaAs laser arrays have proven successful sources of energy for reading and writing information onto an EuO storage plane and, with some modification, such arrays will provide the kind of performance that approaches that of an idealized multi-element transducer for a beam addressable memory.

Acknowledgments

We thank J. Marinace and G. Sprokel for providing the arrays used in these studies, W. Schillinger for informative discussions on readout limitations, and G. Fan for helpful comments on the manuscript.

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Received December 24, 1970

The authors are located at the IBM Research Laboratory in San Jose, California 95114.