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HIGH POWER DIODE LASERS FOR SOLID-STATE LASER PUMPS

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Kurt J. Linden
Director, Commercial Products and Services
Optoelectronics Division
Spire Corporation
One Patriots Park
Bedford, MA 01730-2396

Patrick N. McDonnell
Vice President and General Manager
Optoelectronics Division
Spire Corporation
One Patriots Park
Bedford, MA 01730-2396

ABSTRACT

The development and commercial application of high power diode laser arrays for use as solid-state laser pumps is described. Such solid-state laser pumps are significantly more efficient and reliable than conventional flash-lamp pumps. This paper describes the design and fabrication of diode lasers emitting in the 780 - 900 nm spectral region, and discusses their performance and reliability. Typical measured performance parameters include electrical-to-optical power conversion efficiencies of 50%, narrow-band spectral emission of 2 to 3 nm FWHM, pulsed output power levels of 50 watts/bar with reliability values of over 2 billion shots to date (tests to be terminated after 10 billion shots), and reliable operation to pulse lengths of 1 ms. Pulse lengths up to 5 ms have been demonstrated at derated power levels, and CW performance at various power levels has been evaluated in a "bar-in-groove" laser package. These high-power 1-cm stacked-bar arrays are now being manufactured for OEM use. Individual diode laser bars, ready for package-mounting by OEM customers, are being sold as commodity items. Commercial and medical applications of these laser arrays include solid-state laser pumping for metal-working, cutting, industrial measurement and control, ranging, wind-shear/atmospheric turbulence detection, X-ray generation, materials surface cleaning, microsurgery, ophthalmology, dermatology, and dental procedures.

INTRODUCTION

Recent advances in semiconductor diode laser technology have led to significant improvements in device power and efficiency (1). These improvements have resulted from the use of extremely thin, optically active epitaxial layers known as quantum wells (2). Such quantum wells (QWs) are grown in our laboratory by metal organic chemical vapor deposition (MOCVD) (3,4). This technology, when properly applied, is capable of yielding epitaxial wafers with excellent compositional, doping, and thickness uniformity over 50 mm and 75 mm diameter GaAs wafers. Continual device improvements are being achieved through a progression of developments which have involved both epitaxial material growth and laser bar packaging techniques.

Recent advances in the use of strained QW epitaxial layers have led to diode lasers with the highest reported values of efficiency and long-term reliability (5). Reliability improvements in these strained layer structures are thought to result from the use of indium in the AlGaAs QW layers; indium which has the ability to stop the propagation of dislocation damage at the QW-barrier layer interfaces (6,7).

For diode laser array bar packaging technologies, two recent developments are relevant. A group at the Lawrence Livermore National Laboratory (LLNL) has designed a diode laser package having extremely low thermal-resistance, utilizing the microchannel cooling concept (8,9). This package is superior for high duty factor diode laser array operation, and has been shown capable of enabling standard 1-cm diode laser bars to emit over 20 watts of CW power with good reliability (10). For shorter duty factor operation (below 20%) and

pulse lengths of the order of 2 ms or less, a "bar-in-groove" package utilizing a metallized ceramic mounted on a copper heat sink has been shown to produce multi-bar diode laser arrays emitting over 1 kW of peak power for 300 μ sec pulses with excellent reliability (11). Larger duty factors (to CW) and longer pulse lengths can be used with high reliability, provided proper laser power derating is used. In this paper we describe recent high power diode laser array performance results for 1-cm wide laser bars mounted in the bar-in-groove package.

HIGH POWER LASER DESIGN AND FABRICATION

The basic epitaxial wafer structure used for the high power diode lasers described here consists of a GRaded INdex Separate Confinement Heterostructure (GRINSCH) which has previously been shown to give excellent performance (1). There are two techniques by which such epitaxial layers, with active QW regions as thin as 50Å, can be grown -- molecular beam epitaxy (MBE) and MOCVD. Whereas MBE involves ultra-high vacuum deposition equipment and has demonstrated good laser performance, the highest power diode lasers reported to date have been grown by MOCVD. It is the latter technique that was used to produce the high power lasers reported here. Spire has employed MOCVD over the past ten years and has pioneered much of the technology through the development and sale of such epitaxial reactors to the semiconductor community. This reactor development activity is continuing, and most of the epitaxial wafers reported here were grown in a Spire MOCVD-100S, single wafer, low pressure reactor. A block diagram of this reactor is shown in Figure 1. A larger version of this reactor, known as the MOCVD-400S, is presently under construction, and will grow up to 4-inch epitaxial GaAs wafers.

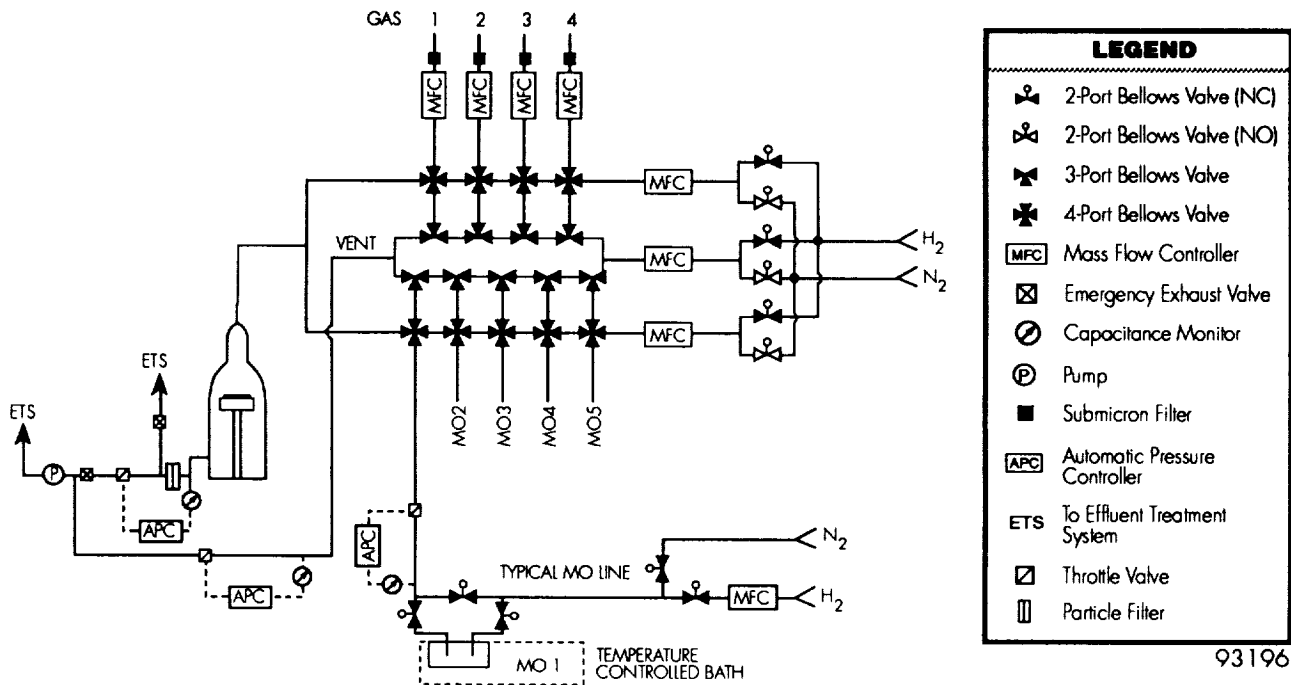


Figure 1 Block diagram of the Spire MOCVD-100S low pressure epitaxial reactor used for the growth of highly uniform epitaxial films.

The basic chemical reaction resulting in the deposition of the epitaxial films involves the pyrolysis of metal alkyls (trimethylgallium and trimethylaluminum) and a hydride (arsine) at temperatures of approximately 700°C in the presence of hydrogen and certain dopant gasses such as silane and dimethylzinc. Excellent film uniformity has been observed for wafers grown in this reactor.

The GRINSCH epitaxial structure, starting with an n-type GaAs substrate with low etch-pit density values, consists of an n-type GaAs buffer layer, an n-type $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ clad layer, the undoped GRINSCH layer with a single 80Å QW and a total thickness of 3000Å, a p-type AlGaAs clad layer of the same composition as the n-clad layer, and a p+ top contact layer for low electrical contact resistance. All layers are grown in one growth operation using a microprocessor driven controller.

Lateral mode control is achieved by gain-guiding in a coupled-mode configuration resulting from 5 μm active regions on 10 μm centers. For quasi-CW pulsed array bars the optical fill factor is over 90%; the entire bar emits, except for 40μm grooved regions between the active phase-locked emitting regions. A top (p-contact) view of a typical quasi-CW bar 1-cm wide with a 0.5 mm cavity length is shown in Figure 2.

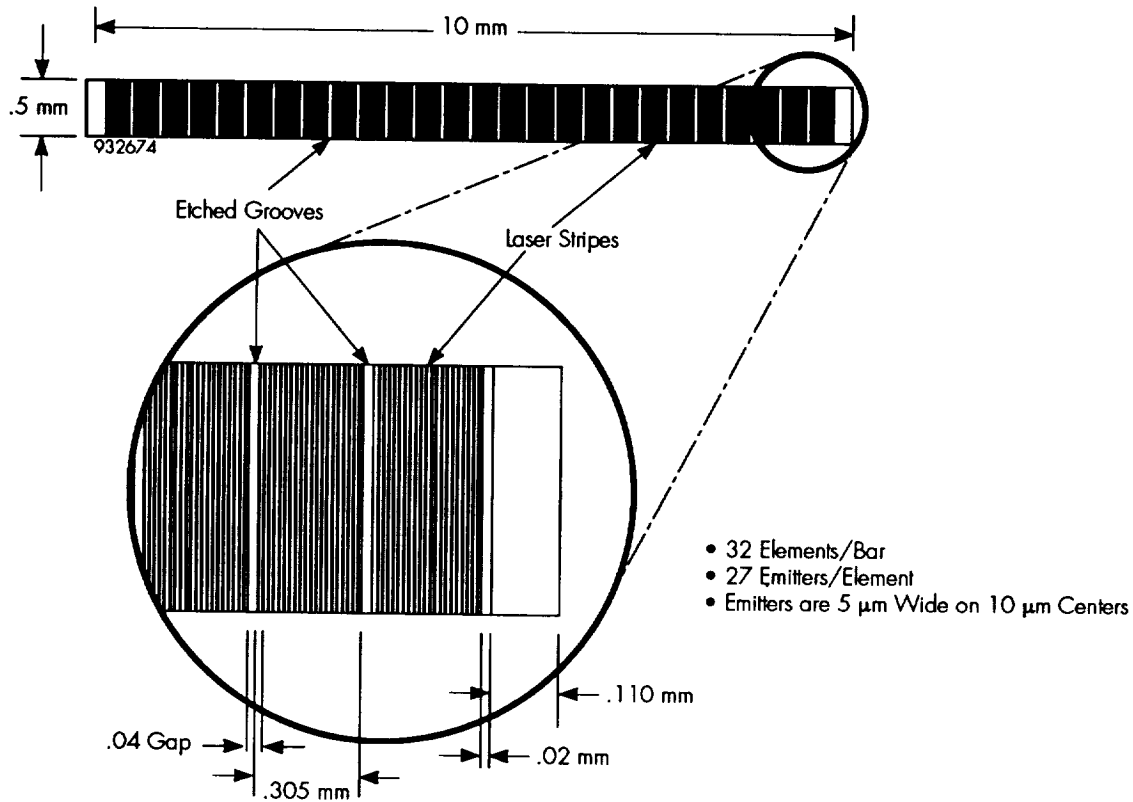


Figure 2 Schematic of the top of a 1-cm wide pulsed diode laser array bar with a 0.5 mm long cavity.

For CW bars, a lower fill factor configuration is used. Such a configuration facilitates more efficient heat removal in normal packages. To enable convenient coupling into optical fibers, the CW bar design consists of twelve sections of active regions, each of which consists of twenty, 5 μm wide active regions on 10 μm centers. The 200 μm wide active regions are on 800 μm centers, giving a 25% optical fill factor. A schematic of the CW array bar configuration is shown in Figure 3.

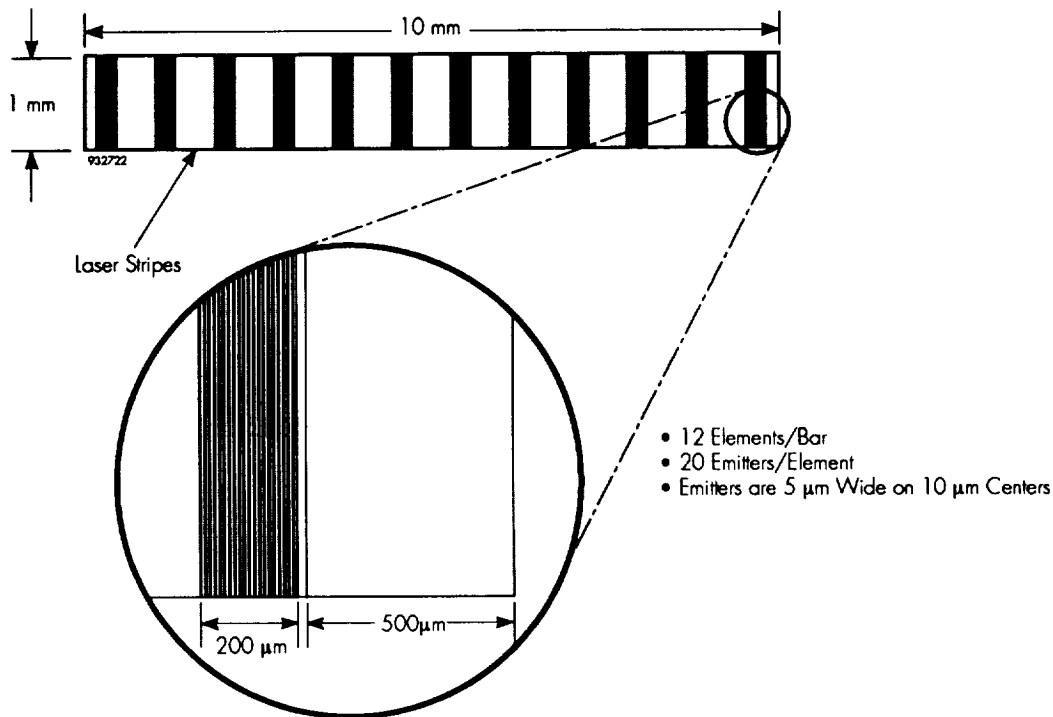


Figure 3 Schematic of the top of a 1-cm wide CW diode laser array bar with a 1 mm long cavity.

The 1-cm cavity length will increase the laser threshold current, but significant improvement in heat sink efficiency is expected.

The gain guiding discussed above is achieved by use of a deposited and patterned silicon nitride or silicon dioxide insulator layer into which the stripe openings are etched. Metallization of the 120 μm thick wafers is carried out on both the n-side and p-sides. In each case, a multi-layer metal system is deposited to ensure metallurgical stability when the laser bars are exposed to high temperatures. Spire's metallization configuration is compatible with the solder required for bar-in-groove mounting. Post-metallization sintering is used to ensure low contact resistance and metallurgical stability.

Individual diode laser array bars are produced by cleaving. Automated equipment provides reproducibility in laser cavity length. Mask codes allow for identification of individual laser bars with their location on each epitaxial wafer. Front and rear facet coatings are applied immediately after cleaving. Rear coatings consist of multilayer dielectric layers with reflectivities of nearly 100%, while the front coatings are half-wavelength with approximately 30% reflectivity. Front coating reflectivity will affect threshold current and output power. After coating, all bars are 100% inspected for cosmetics, particulates and metallization/coating appearance. Any bars which exhibit flaws or defects which could affect operation under high power conditions are rejected prior to assembly. The individual bars are stocked by emission wavelength in gelpak packages for sale to the semiconductor diode laser industry as off-the-shelf, inventory items. Facet colors allow users to distinguish between the front and the rear facets. Representative bars from each wafer are tested for P-I, V-I, efficiency-I, emission spectrum and reliability for 250,000 shots at full operating current. A map of the emission wavelengths measured on laser bars fabricated from a typical 50 mm epitaxial wafer is shown in Figure 4.

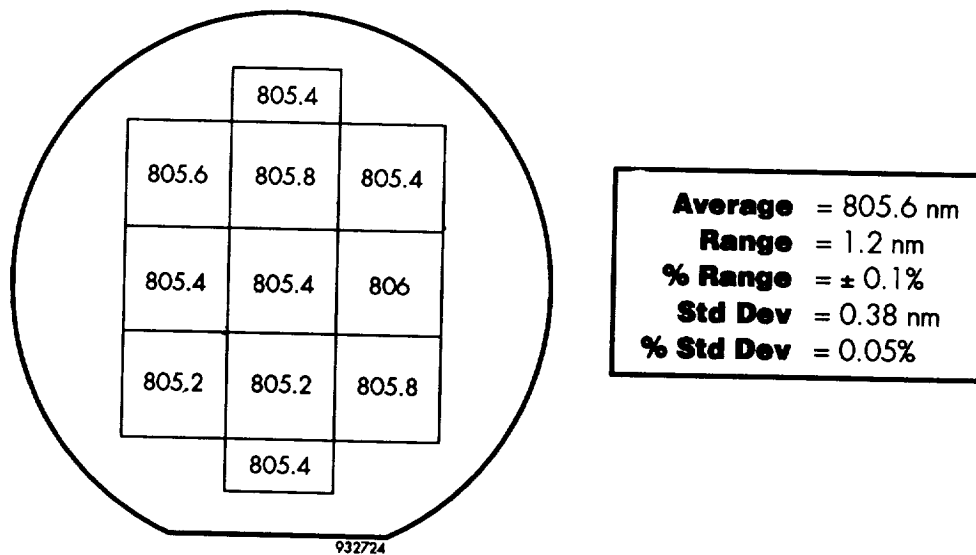


Figure 4 Laser emission wavelength map showing emission wavelength uniformity over a 50 mm diameter epitaxial QW wafer.

The laser bar emission wavelength uniformity has a range of 1.2 nm, with a standard deviation of 0.38 nm. This represents a $\pm 0.1\%$ emission wavelength uniformity, with a standard deviation of only 0.05%.

The overall diode laser array bar fabrication process is summarized in Figure 5.

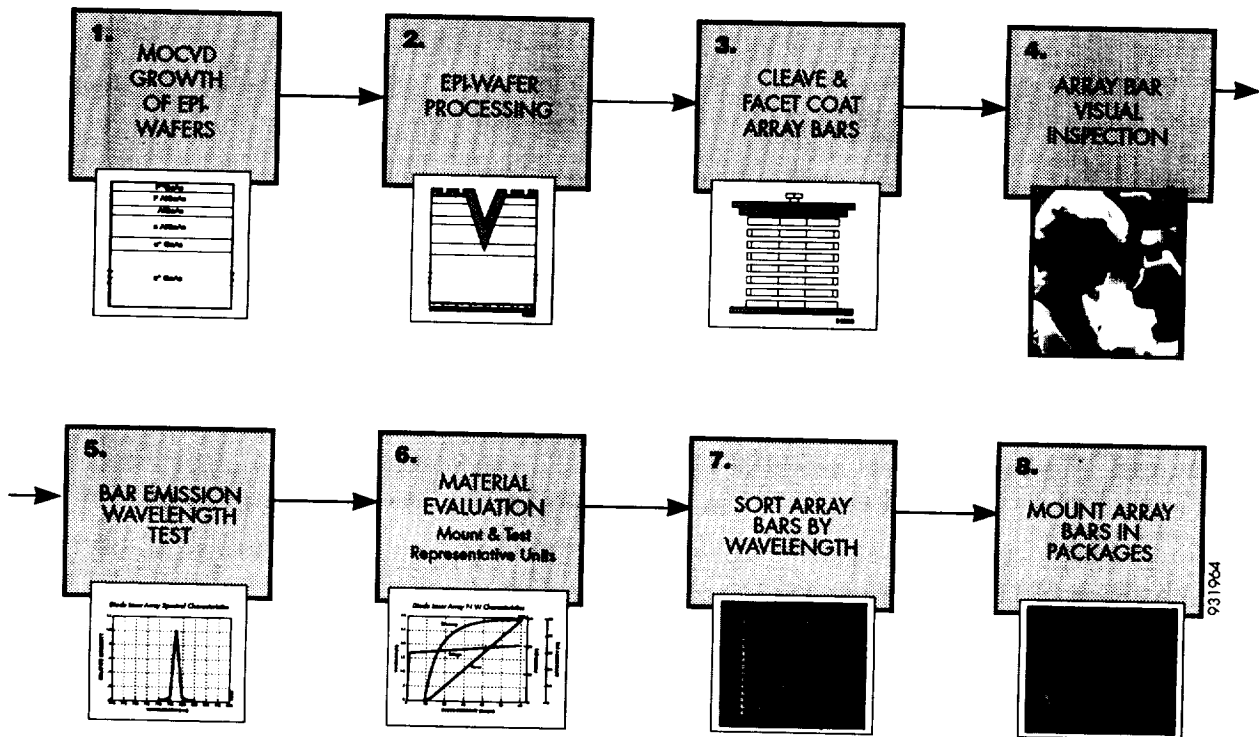


Figure 5 Diode laser array bar manufacturing sequence illustrating the various processing and evaluation steps.

A multiplicity of diode laser array packages are available, depending on the required output power and duty cycle. A photograph of a typical 6-bar diode laser array, with bars mounted in the "Z-format" package by Laser Diode Arrays, Inc. (LDAI), is shown in Figure 6.

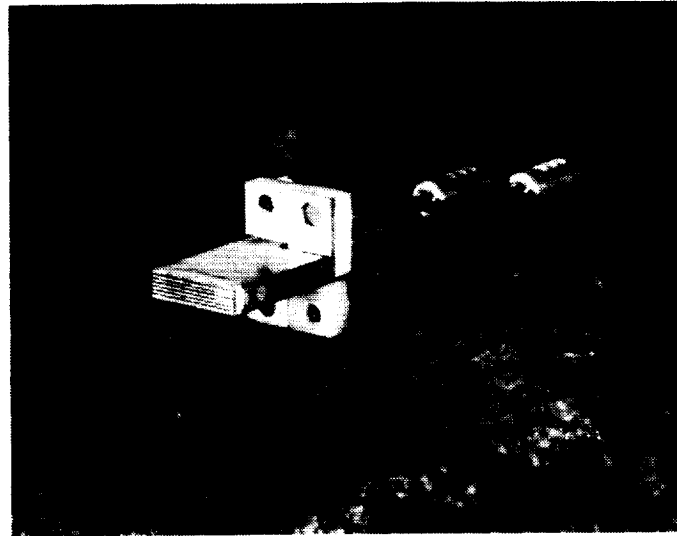


Figure 6 Photograph of the Z-format diode laser array package with 6 emitting bars. Such an array is rated at 300 W, quasi-CW emission (50 W/bar).

Packages of this type with up to 40 bars can be readily fabricated. Some of the critical performance parameters of these lasers and laser arrays are summarized in the next section.

LASER PERFORMANCE DATA

In this section we will present some of the important performance parameters of multibar diode laser arrays for quasi-CW operating conditions. With typical threshold current values of 8 A, these devices exhibit electrical-to-optical conversion efficiency values of from 45 to 50%. Figure 7 shows the P-I, V-I and efficiency-I characteristics of a typical 6-bar array of the type shown in Figure 6.

Each array is burned-in for at least 250,000 shots prior to delivery. No changes in performance are observed during this burn-in period. The array of Figure 7 was burned-in with 1 ms pulse lengths at a 10 Hz repetition rate. With bars on 0.5 mm centers, the array exhibited a power density of 1240 watts/cm². Arrays of this type have been operated at 100 million shots with a measured reduction in output power of approximately 2%.

A typical emission spectrum for this type of 6-bar array is illustrated in Figure 8.

The three curves shown in this figure represent emission spectra for 100, 250 and 500 μ sec long pulses. As can be seen, there is not much change in emission spectrum with pulse length under these conditions. The operating current of this array is 50 A at room temperature. The FWHM of the emission spectrum is approximately 2.5 nm. Typical far-field patterns (full width, half maximum, FWHM) are 38 degrees (fast axis, perpendicular to the junction plane) by 10 degrees (slow axis, along the junction plane). The polarization (E-vector) is along the junction direction.

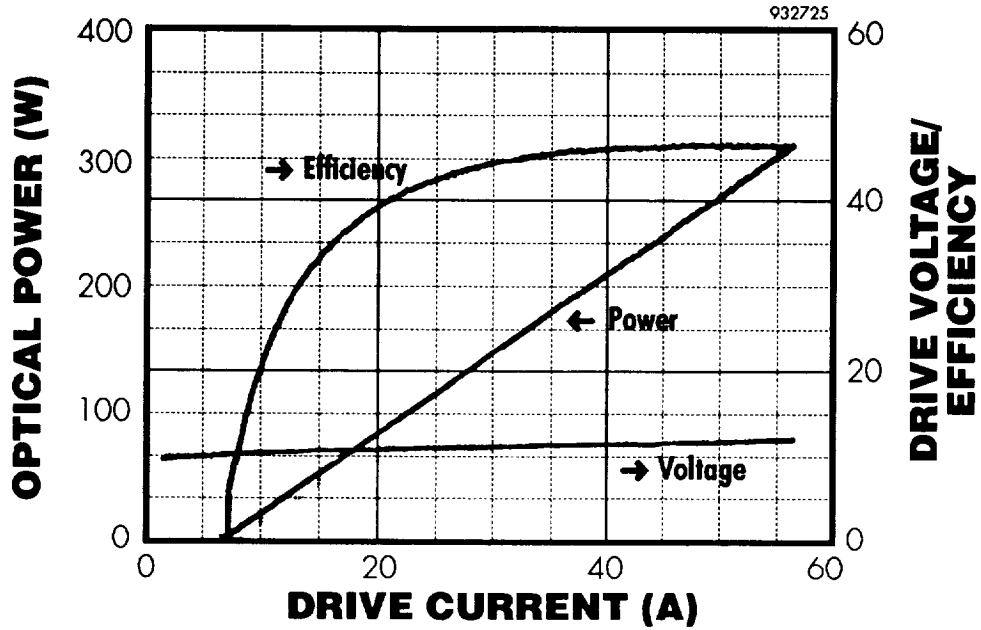


Figure 7 P-I, V-I and efficiency-I characteristics of a typical 6-bar diode laser array of the type shown in Figure 6.

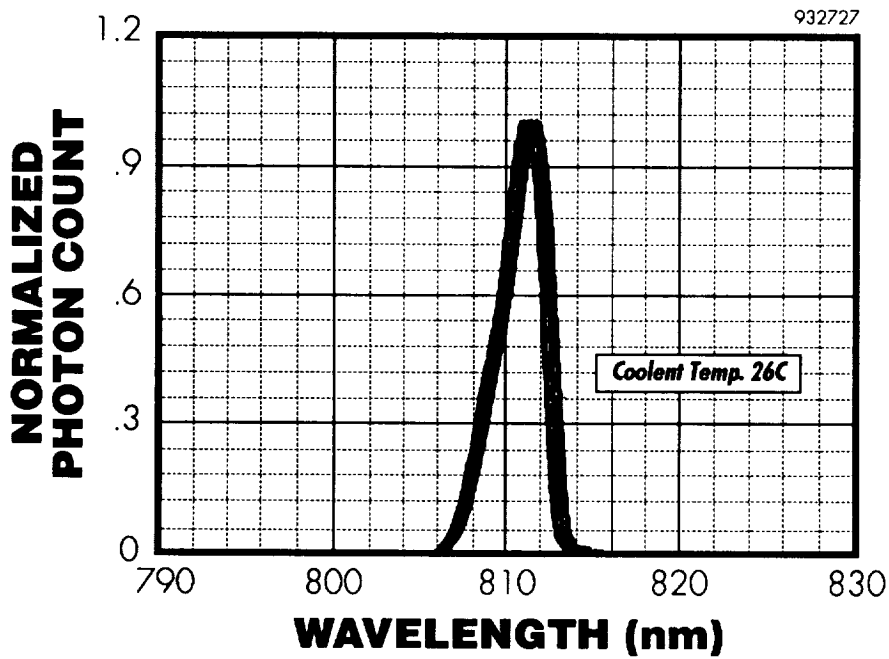


Figure 8 Emission spectrum of a typical 6-bar, 810 nm, bar-in-groove, quasi-CW diode laser array under various pulse-width conditions.

The performance of typical 6-bar diode arrays in the bar-in-groove package has been measured under conditions of heavy thermal stress by the NASA Langley Research Center. Figure 9 shows the measured variation in FWHM of the emission spectrum at a variety of very long pulses (up to 3.5 milliseconds).

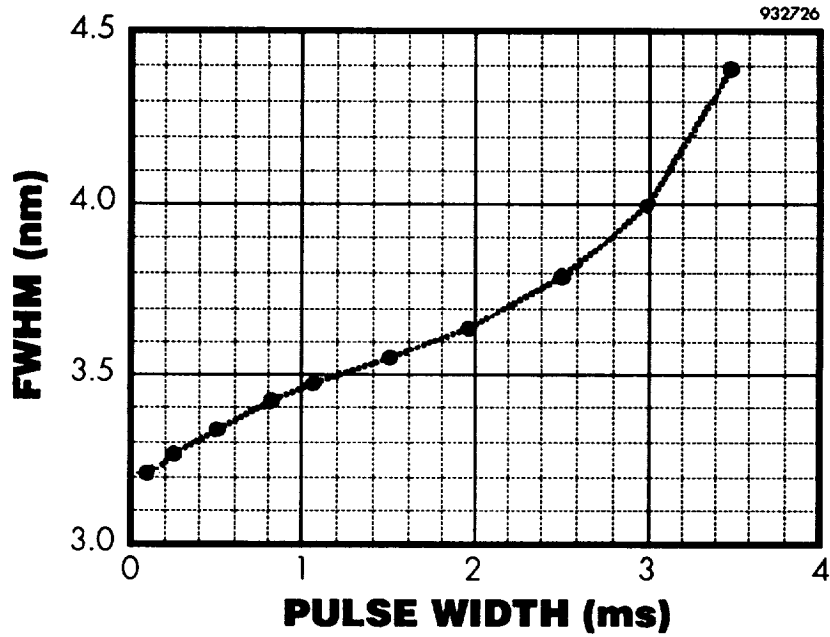


Figure 9 Measured FWHM of the emission spectrum of a typical 6-bar, quasi-CW diode laser array mounted in the LDAI bar-in-groove package.

The increase in FWHM is a result of the frequency chirping that occurs during the long on-pulses, and is caused by thermal heating of the array bars. We estimate the thermal time constant (ratio of heat capacity to thermal conductivity per unit area) of this type of package to be in the 40 to 60 ms range for 1-cm bars with a 0.5 mm cavity length. It is thus important to keep the time-separation between pulses well above this range if pulse lengths of greater than 2 or 3 ms are used.

A graph of the center wavelength of the emission peak as a function of pulse width for this type of array is shown in Figure 10. With a pulse repetition rate of 10 Hz, the duty cycle is 1 % for a 1 ms pulse and increases to 5% for a 5 ms width. Increasing pulse width increases heating of the bars, thereby shifting the emission wavelength towards long wavelengths. The emission wavelengths shown in this graph represent the average observed over the pulse lengths indicated. During the actual pulses, chirping occurs, as represented by the increasing FWHM values of Figure 9. With a known wavelength shift of approximately 0.25 nm/degree C, we estimate an average junction temperature increase of 4 degrees for every ms increase in pulse length. The actual junction temperature at the end of each of these long pulses can be considerably larger than this.

The near-field emission pattern of diode laser arrays mounted in the bar-in-groove configuration can be observed with either a CCD camera (home video camera) or with ordinary color film using a 35 mm camera. Figure 11 shows a head-on view of a 15-bar diode laser array. Part (a) shows the cut grooves with bars inserted, while part (b) is a 35 mm photograph taken of the array operating just above threshold. As can be seen, every portion of each 1-cm bar is lit up, with no dead spots.

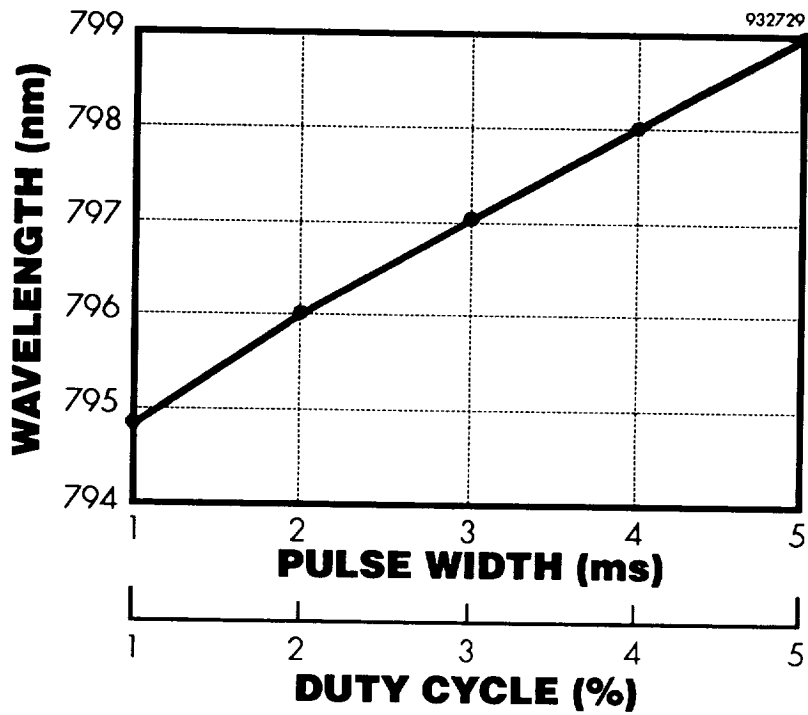


Figure 10 Emission wavelength vs. pulse width (10 Hz drive frequency) for a 6-bar diode laser array.

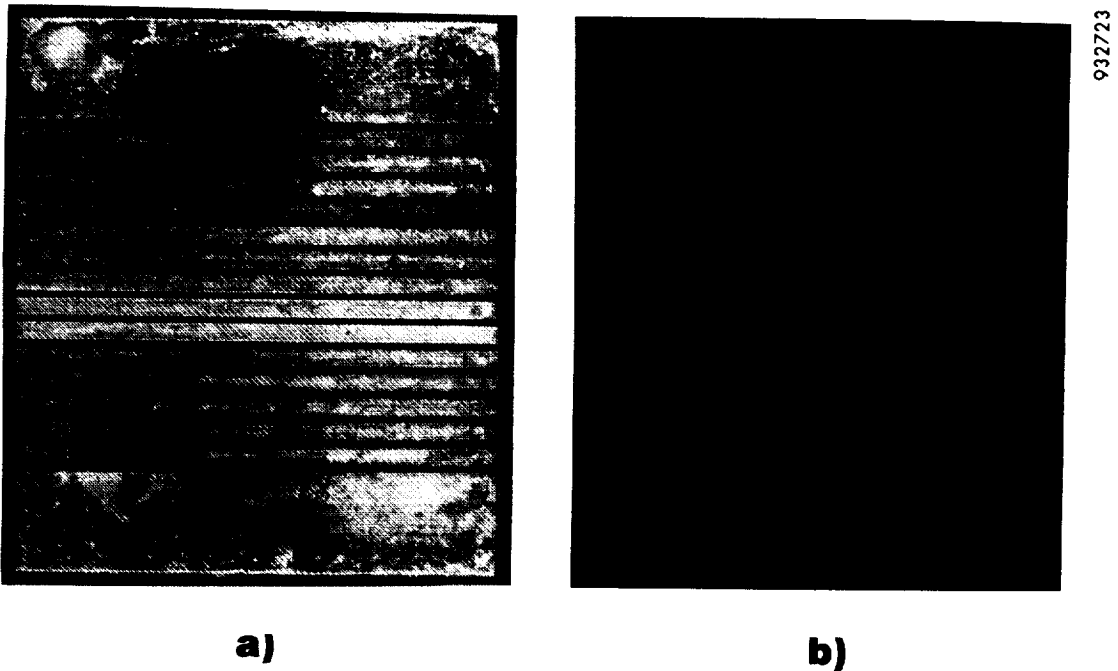


Figure 11 Head-on photographs of a 15-bar diode laser array consisting of 15 one-cm bars mounted in narrow grooves cut into a metallized, thermally-conducting ceramic plate. Part (a) shows the grooves with the laser bars inserted, while part (b) shows the light emitting regions just above threshold, as seen on a 35 mm film.

The performance characteristics of a 32-bar array fabricated from four sections of 8-elements each, stacked side by side to provide an emitting region of 4-cm by approximately 0.5 cm are shown in Figure 12. This array emitted over 1.2 KW of peak power with 250 μ s pulses at a 10 Hz repetition rate. The FWHM of the emission wavelength of the entire array was measured at 4 nm for 100 μ s pulses, and increased to only 4.5 nm for 500 μ s pulses. The array is presently in use in a commercial laser system, and has shown outstanding performance reliability.

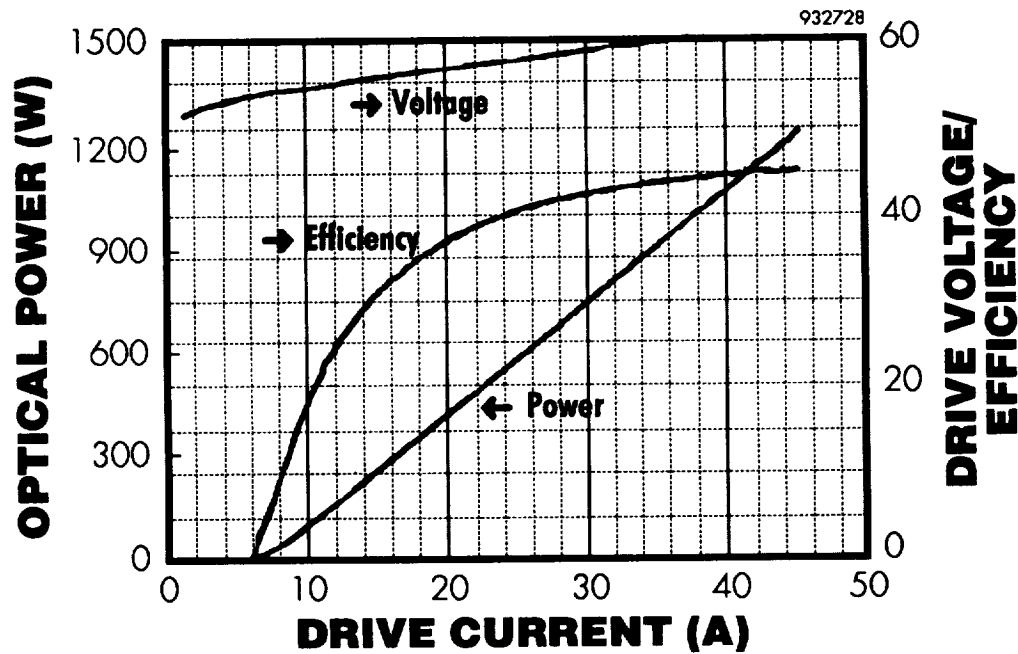


Figure 12 P-I, V-I and efficiency-I characteristics of a 32-bar diode laser array emitting over 1.2 KW of peak power with 250 μ s pulses at 10 Hz.

LASER RELIABILITY

Long-term reliability is one of the most important issues to be addressed if wide-spread use of high power diode laser arrays is to be achieved. Such reliability is effected by the quality of the GaAs substrate wafers used, the structure and quality of the epitaxial layers, the metallization technique used for both the n- and the p-side of the epitaxial wafers, the facet coatings, and the handling of the epitaxial wafers and finished bars. Experience has shown that with proper manufacturing and handling techniques, excellent reliability can be achieved. Spire laser array bars have been evaluated in a variety of packages, and under various operating conditions. The longest pulsed-performance data available to date has been obtained by Jenoptik GmbH in Wiesbaden, Germany, where a 10 billion shot test is in progress. To date, almost 2 billion shots have been carried out on a collection of 6 1-cm bars. The data are shown in Figure 13.

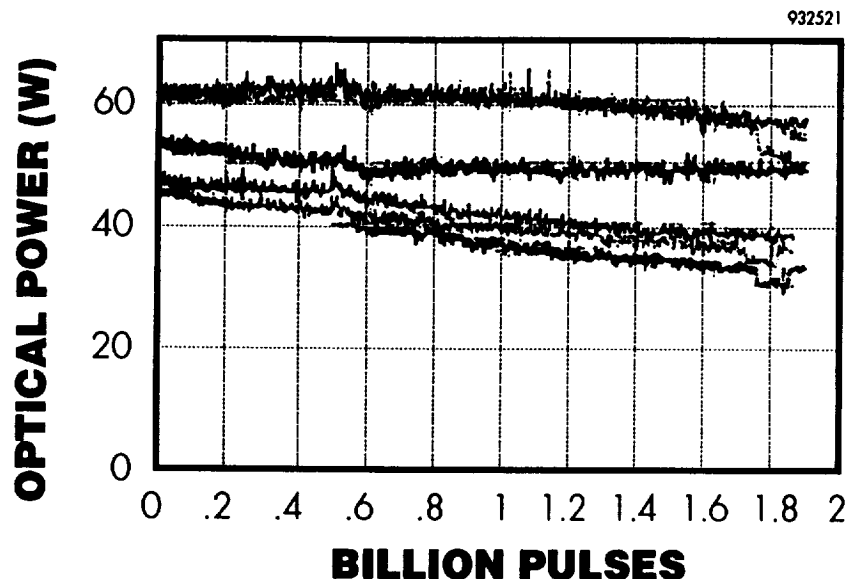


Figure 13 Long-term reliability data for Spire high power diode laser bars (obtained by Jenoptik GmbH). The bar tests are currently at over 2 billion shots, and are scheduled for termination at 10 billion shots.

The tests are being conducted at room temperature, with 300 μ s pulses, 60 A current, and 135 Hz repetition rate (4% duty factor). These data are for a random sampling of laser bars, but all bars had passed a critical visual and electrical inspection prior to mounting.

Additional reliability data have been obtained at other laboratories. Lawrence Livermore National Laboratory has mounted two bars (reduced in length to 0.9 mm by cleaving the ends off) in one of their microchannel coolers (8). In spite of the excessive mis-handling (chopped off ends) of these bars, they have operated at 22 W per bar (44 W, CW, for the two bars) for 70 hours with no degradation (10). Additional reliability tests of Spire materials are presently in progress at this laboratory.

FUTURE AREAS OF DEVELOPMENT

Recent developments have indicated that the operation of high power diode laser arrays can be extended both into the visible spectral region and further into the infrared. High power visible diode lasers emitting in the red (633 nm) region of the spectrum have been reported (12). The GaInP/GaInAlP/GaAs visible materials have been extensively studied in Japan and are becoming widely available from companies such as NEC, Sony, Toshiba, Sumitomo Electric, Matsushita Electric and Hitachi, mostly in low power versions, for printing and bar-code readers. High power diode lasers of this material system are currently under study at a number of laboratories, and Spire also is involved in their development. Such short wavelength lasers have potential applications in pumping the tunable solid-state lasers, LiSAF, LiCAF, and Alexandrite, whose optical absorption regions tend to be quite broad. They also have medical applications for ophthalmology and photodynamic therapy (PDT).

In the longer wavelength infrared, the recent announcement of 2-5 μ m diode lasers fabricated from GaInAsSb/AlGaAsSb represents a major advance in the state of the art (13,14). Prior to this announcement, the only diode lasers operating in this spectral region were those fabricated from lead-chalcogenide materials, and

such lasers require cryogenic cooling. Recently, near IR lasers emitting in the 2 μm region have been fabricated from the InGaAsP material system (15). This system is somewhat simpler to handle by MOCVD than the Sb-based compounds (which were grown by MBE at the MIT Lincoln Laboratory), and Spire is presently involved with their development as well. Such high power lasers can be used for pumping Ho:YAG solid state lasers at 1.9 μm , with significantly less quantum heating than that encountered in conventional 792 nm pumping of the Ho,Tm:YAG and YLF solid-state laser systems.

SUMMARY AND CONCLUSIONS

We have described recent progress resulting from a development effort supported, in part, by the NASA Langley Research Center through two Phase I and two Phase II SBIR programs aimed at developing a technology for producing low-cost, high power diode laser arrays emitting in the 800 nm spectral region for solid-state laser pumping. Such high power diode lasers are used as efficient and reliable optical pumps for the Nd:YAG, Nd:YLF and Ho,Tm:YAG solid-state laser systems. The technical achievements of these programs, together with continued IR&D support and a strong corporate commitment, have positioned Spire as a leading supplier of commercial epitaxial laser wafers, high power laser array bars, and high power diode laser arrays. Spire now offers such products, some as off-the-shelf items, to the semiconductor laser industry and to the optoelectronic OEM community. These products are being sold domestically and overseas. Spire's standard products include epitaxial wafers of the GRINSCH-SQW or multi-QW design, 50 W diode laser array bars in standard 1-cm wide configurations, metallized and ready for mounting, as well as multi-bar diode laser arrays with 45 - 50% efficiency and reliability values exceeding 2 billion shots. Such bars have been operated at up to 100 W of pulsed output power, and with pulse lengths of 5 milliseconds. Reliability evaluation trials of 300 μs pulsed devices will be terminated at 10 billion shots. With good high-duty factor heat sinks, Spire's standard pulsed laser designs have been operated under continuous, CW conditions. Lower fill-factor CW laser designs are presently nearing the final phase of development and will be introduced shortly. The company is actively involved with expanding the wavelengths of operation of such arrays, both towards the visible and the infrared regions, thereby opening more areas of application.

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FLEXIBLE MANUFACTURING FOR PHOTONICS DEVICE ASSEMBLY

Shin-ye Lu
Thrust Area Leader, Engineering Research Division, Engineering Department
Michael D. Pocha
Group Leader, Engineering Research Division, Engineering Department
Oliver. T. Strand
Physicist, L-Division, Nuclear Test Experimental Sciences Department
K. David Young
Project Engineer, Engineering Research Division, Engineering Department
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

The assembly of photonics devices such as laser diodes, optical modulators, and opto-electronics multi-chip modules (OEMCM), usually requires the placement of micron size devices such as laser diodes, and sub-micron precision attachment between optical fibers and diodes or waveguide modulators (usually referred to as pigtailed). This is a very labor intensive process. Studies done by the opto-electronics (OE) industry have shown that 95% of the cost of a pigtailed photonic device is due to the use of manual alignment and bonding techniques, which is the current practice in industry. At Lawrence Livermore National Laboratory, we are working to reduce the cost of packaging OE devices through the use of automation. Our efforts are concentrated on several areas that are directly related to an automated process. This paper will focus on our progress in two of those areas, in particular, an automated fiber pigtailed machine and silicon micro-bench technology compatible with an automated process.

INTRODUCTION

At present, the cost of opto-electronic devices is dominated by the effort required to package those devices into an integrated system. Components such as laser diodes and modulators, designed for high-performance applications, are single-mode devices; they must be connected together using optical fibers or other type of waveguide with sub-micron alignment accuracies. Presently, the OE packaging is usually performed by highly skilled technicians looking through microscopes and manually adjusting sub-micron stages. For single mode fibers, six degrees of freedom for positioning are sometimes required. Once the alignment is correct, the components must be held in place using epoxy, solder, or other attachment techniques, and realigned before the gluing process is settled. This labor-intensive process results in only a few packages being produced per day by each technician. The packaging costs are by far the highest fraction of the total cost of an assembled OE package. The consequences of this low-volume labor-intensive process of packaging OE devices are readily apparent. The costs are too high to allow the advantages of fiber optics to penetrate such markets as on-chip interconnects, interboard connections in computers, and local area networks.

At LLNL, we believe that the packaging process must be automated to significantly reduce the costs of OE devices. The electronics industry has successfully reduced the costs of its products through the massive use of automation, including alignment, parts handling and feeding, and in-situ quality control. A simple model (Figure 1), which takes into account the initial cost of the automated machinery, the labor costs of an operator, and the material costs of the devices, shows that substantial cost savings may also be realized in the opto-electronics industry at even modest production rates. Unfortunately, the sub-micron precisions, and six-axis alignment required for OE packaging greatly exceeds the requirements of the electronics industry. The automated systems developed to assemble integrated circuits cannot be applied to the problem of packaging opto-electronic circuits.

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