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High Power, High Beam Quality Solid State Lasers for Materials Processing Applications

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Abstract

The Laser Science and Technology Department at Lawrence Livermore National Laboratory is developing solid state lasers with high average power and high beam quality. Specific systems include a laser to generate 10 to 14 Å x-rays for proximity print lithography, a 400 mJ, 500 Hz laser for 130 Å projection lithography and unique systems for speckle imaging, laser radars and medical treatments.

Introduction

The Laser Science and Technology Department of Laser Programs at Lawrence Livermore National Laboratory has a strong focus on developing solid state lasers with high average power and high beam quality. These lasers in general have characteristics which are beyond the capability of available commercial equipment and are intended to advance the state-of-the-art in a number of important applications. Specific activities in which the lasers are being employed include: proximity print x-ray lithography where a laser is used to generate x-rays in the 10 to 14 Å range for printing advanced integrated circuits; extreme ultraviolet (EUV) projection lithography where a laser is used to generate 130 Å radiation for even higher resolution printing of integrated circuits; cutting drilling and welding in the materials processing industry; and assorted applications that include the generation of x-rays for biological imaging, solid state lasers for 0.35 μm photolithography, photo-ablation for contouring shapes and profiles in a variety of materials, speckle imaging, laser radars, and specific medical treatments.

A common thread in the architecture of most of our laser systems is a master oscillator followed by a power amplifier in which non-linear stimulated Brillouin scattering (SBS) phase conjugation is used to obtain very high beam quality.[1] Depending on the output energy and average power requirements, the laser excitation media is Nd:glass or Nd:YAG. The lasers are pumped either with flash lamps in advanced design reflectors or by arrays of laser diodes.

The laser systems are in general developed to have unique properties not available yet in commercial devices. Examples include features such as: 30 J per pulse output in near-diffraction-limited beam quality and pulse lengths from 10 to 600 ns, and 400 mJ per pulse output at 200 Hz pulse repetition rate in near-diffraction-limited beam quality. We have used specific lasers to generate over 80% doubling efficiency from 1 μm to the green at energies of 25 J/pulse and average powers near 100 W. Additionally, when operated in a burst mode for a time period of 2 to 4 seconds (nominally equivalent to an IC field exposure), the laser produces up to 500 W of power at 1 μm; using the green laser output as pump, it produces up to 40 W average power of x-rays in the 10 to 14 Å spectral range. We have generated third harmonic 0.355 μm from the 1 μm wavelength for large area photolithography and have begun use of the diffraction-limited 400 mJ, 200 Hz output at 1 μm for pumping a plasma to generate 130 Å extreme ultraviolet light as well as its use as a high power beam for precision hole drilling in various substrates.

In this paper we discuss specifics of the laser architecture based on the master oscillator/multipass phase conjugated amplifier and how we have integrated the resulting lasers into a number of applications.

Phase Conjugated Master Oscillator/Power Amplifier

The basic design of the phase-conjugated master oscillator/power amplifier is shown in Figure 1. In this design, the output of a single-frequency master oscillator is tailored to the desired pulse length, beam quality and repetition rate and is then amplified to the desired energy in a regenerative amplifier. The exact number of passes required in the amplifier depends on the required output power and the specific gain to loss ratio of a beam transit through the amplifier. At the mid-point of the amplification, a phase conjugate mirror employing stimulated Brillouin scattering (SBS) reflects the beam back through its original path. The idea behind the conjugate mirror is that the phase error on the return path cancels the accumulated phase error on the input path and thus results in a near zero net phase error in the output beam at high power.

The master oscillator is typically operated in a self-seeded mode to produce single-frequency, diffraction-limited output. The single frequency is required for the phase conjugator to provide low threshold and high fidelity return. The oscillator's diffraction limited output provides the reference wave front for the phase-conjugated amplification. The oscillator output is preamplified, anamorphically expanded and then imaged into the regenerative amplifier ring.

The ring amplifier is configured with a polarizer and a 90° polarization rotator which act as a passive polarization switch. The input beam transits the ring once, double passing the amplifier, rotates in polarization and then passes the ring a second time. After the second ring pass, the polarization has rotated to deflect the beam to the phase conjugate mirror. With sufficient gain in the amplifier, the phase conjugate mirror is brought above threshold and generates a return beam which retraces the path of the input pulse. It thus results in a high power output beam with essentially all phase error removed. Due to its threshold activation, the phase conjugate mirror plays a second role as a multistage gain isolator since high input power is required to produce a reflection. The output beam having been rotated 90° in polarization is separated from the input by means of the polarization rotation within the ring and the polarizer. Thus this non-linear component inexpensively replaces Pockels cells and fast power supplies and provides the required stage to stage gain isolation.

This laser configuration is used with both glass and crystal based Nd laser systems. Per pulse output energies from the various systems range from 400 mJ to 30 J per pulse and pulse durations from 5 to 600 ns. Glass systems have been run at repetition rates up to 6 Hz and the crystal systems up to 2.3 kHz. In all cases the output beam are near diffraction limited with extremely stable pointing stability. Figure 2 shows an example of the far field beam profile of the laser operated with and without the phase conjugator. The dramatic improvement provided by phase conjugation is clear.

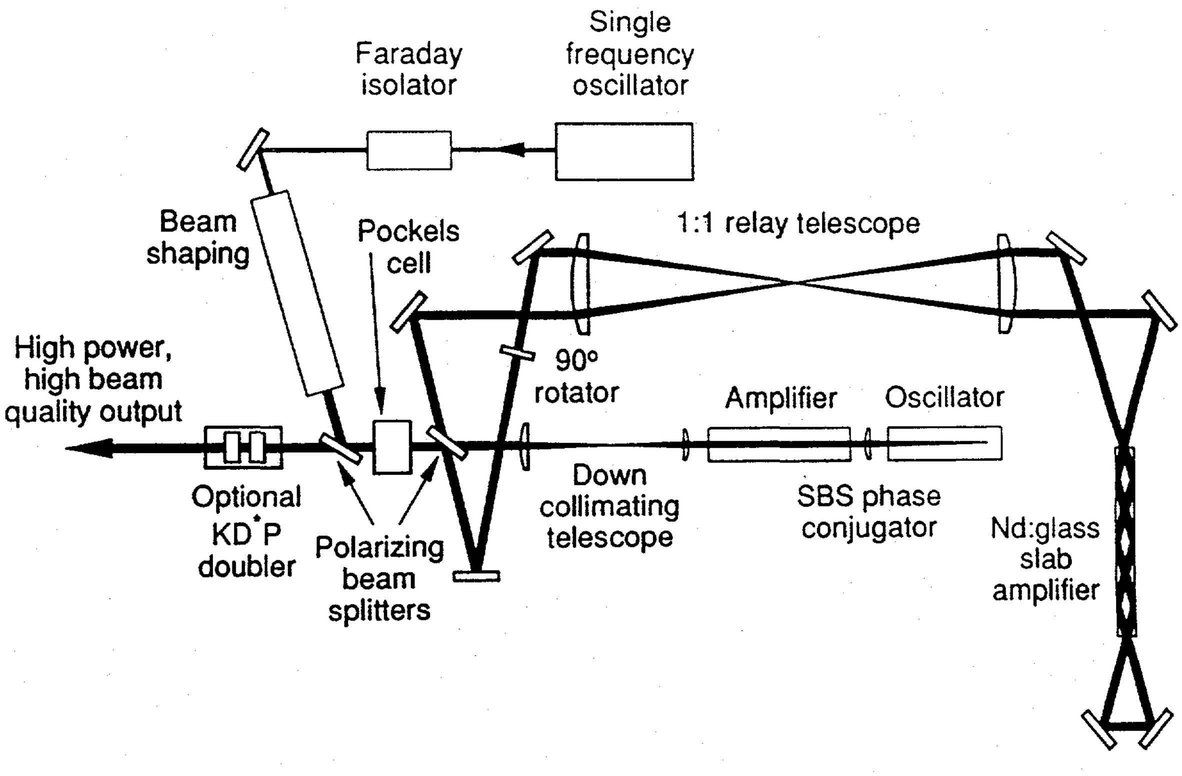


Figure 1. A schematic of the multipass amplifier geometry incorporating an SBS phase conjugate mirror. A passive 90° rotator in the regenerative amplifier ring causes the injected pulse to make two ring passes (4 slab passes) before it is directed into the phase conjugator. The SBS wavefront reversed return then retraces the input path for an additional two ring passes, for a total of 8 gain passes, before it exits and is isolated from the input pathway by a Pockels cell. Other similar geometries require fewer or more passes.

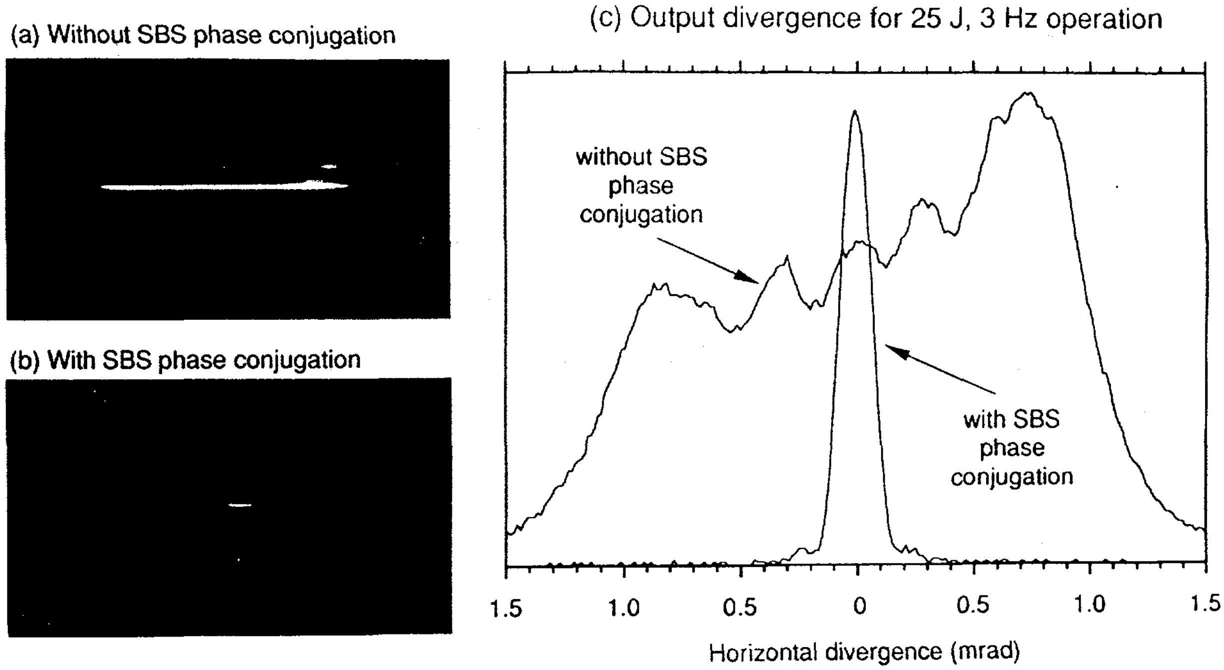


Figure 2. A comparison of the far field profiles measured at the focus of a 120 cm lens for 3 Hz, 75 W operation (a) without and (b) with SBS phase conjugation. Plot (c) overlays horizontal cross-sections of both cases.

Applications of the Laser Technology

1. Proximity Print X-Ray Lithography

Proximity print x-ray lithography is at the forefront of efforts to develop a commercial lithography system capable of producing circuit features of 0.25 μm and smaller. A schematic drawing of the concept is shown in Figure 3 where a 25 J/pulse, 10 ns pulse length laser output is focused to a ~ 50 μm spot (~ 10^{14} W/cm2) on a metal or dense gas target. The resulting plasma generates x-rays in the 10 to 14 Å range. Conversion efficiencies are in excess of 10%. At 20 to 40 cm distance from this point source, the x-rays pass through a mask which is placed ~ 40 μm above a resist coated silicon wafer. The mask contains a replica of the circuit features to be printed allowing x-rays to pass through transparent areas and activate the exposed resist. The process is repeated on approximately 38 such fields on a typical 20 cm wafer followed by a development, etching and washing process to create the circuit features. For the rapid printing required in a commercial process, this technique has required advances in scanner capability to rapidly move and precisely align to each succeeding field as well as the development of a source capable of providing approximately 100 mJ of useful x-ray output per second. This requirement translates into a laser average power of 500 W to 1 kW for a full production machine providing 40 wafer levels per hour of throughput.

Under support of the Advanced Research Projects Agency, National Lithography Program, we have developed a laboratory scale laser source operating at 150 W and producing x-rays with greater than 10% conversion efficiency. We are now in the process of building a field prototype in a two-step upgrade which will take the laser source first to 300 W and then to 600 W average power. This will be sufficient output for high throughput production demonstrations. We expect this build to be completed within the next 12 to 18 months and the equipment integrated with a stepper for high throughput testing. Following successful testing, LLNL intends to find and transfer the technology to an industrial firm for commercial manufacturing.

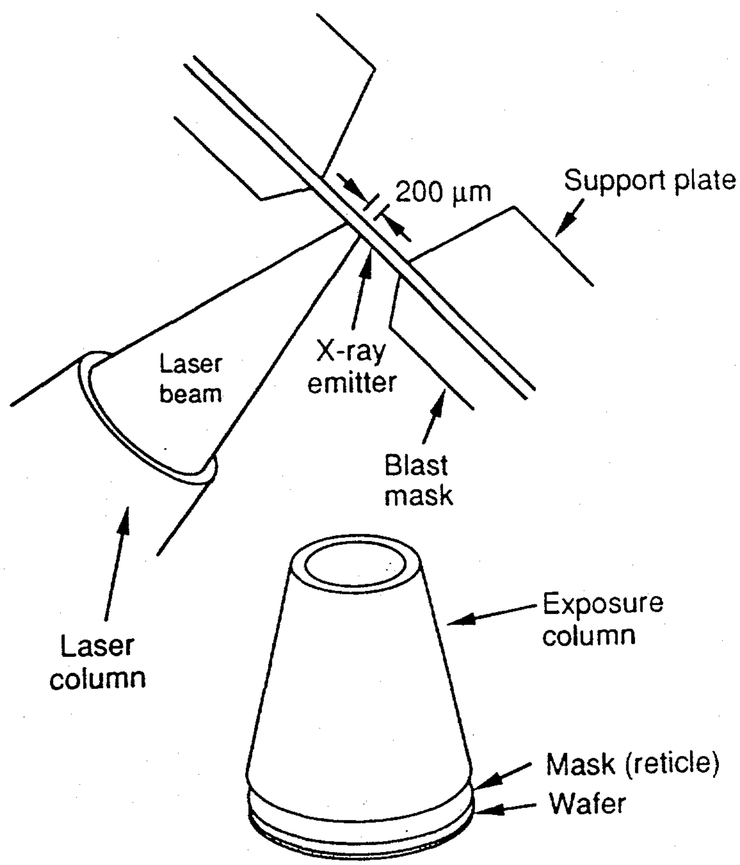


Figure 3. A schematic diagram of a proximity print x-ray lithography setup. A high energy laser is focused onto a target generating x-rays which pass through an exposure column and print circuit mask onto a resist coated silicon wafer. Approximately 10 to 50 mJ/cm^2 of x-ray flux is required.

2. Extreme Ultraviolet Projection Lithography

Projection lithography using extreme ultraviolet light offers the potential for ultra-fine resolution lithography down below 0.2 μm.[2] In the concept, schematically shown in

Figure 4, EUV light near the 130 Å region with a bandwidth of approximately 3 Å is generated from a point plasma source. This wavelength choice results from the existence of high performance narrow band multilayer optics at 130 Å, a wavelength just longer than the silicon L-edge. The x-ray source is proposed as a laser produced plasma generated by the interaction of laser light of intensity greater than 10^{11} W/cm^2 with a high-Z target material. As shown in the figure, EUV light from the target is efficiently collected by a pair of multilayer-coated condenser mirrors. The condenser mirrors project the narrow-band radiation onto a mask or master-reticle which works in reflection. The mask is a thin metallization pattern over a multilayer coating which, in turn, is supported by a flat, highly polished, precision, four-mirror imaging system. While there are a number of different designs for the imaging optical system, it generally can be characterized as follows: it is a ring-field imaging system providing for step and scan exposure of the wafer; an f# of f/6 or smaller will provide resolution of < 0.1 µm at the wafer: it will project a virtually distortion-free image over the ring-field (distortion of < 0.01 µm at the wafer) and it will be a demagnifying system with a reduction factor of approximately five-fold in dimension.

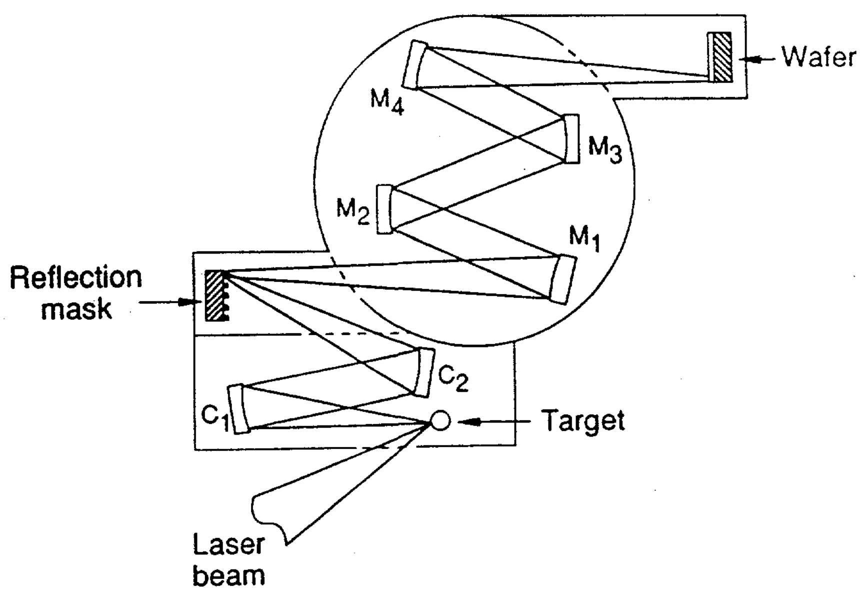


Figure 4. Schematic representation of a 5 X reduction, ring field EUV projection lithography system. Setup employs four imaging mirrors, a reflective mask, two condenser mirrors and is driven by a solid state laser to generate plasma produced EUV.

A significant amount of work remains to be done to field a commercial quality system. This includes the fabrication of precision aspherical mirrors and the mechanisms to align and rigidly hold them, the production of a high quality imaging resist, and an alignment and registration system capable of supporting the very fine printed features. It also involves the development of a compact, high efficiency, high average power laser source to generate the laser plasma.

We are currently working on the development of a diode-pumped solid state laser as the source driver for the EUV lithography system. The laser for this system has been designed to a set of specifications appropriate for generating EUV radiation at 130 Å. The specifications of the laser are 340 mJ/pulse, 5 to 7.5 ns pulse length, and a 1.3 kHz repetition rate.

In order to build a laser meeting these specifications, we have used a appropriately scaled version of the master oscillator/multipass amplifier technology discussed above. The oscillator for this device is a self-seeded Q-switched Nd:YAG rod pumped by an array of laser diodes. The power amplifier is also Nd:YAG in the form of a slab pumped by two large arrays of laser diodes. The slab has a gain of 4 per pass (1.4 nepers). As in the previously described design, high beam quality and high extraction efficiency will be maintained in this device through the use of an SBS phase conjugator placed at the mid-transit point in the amplifier. The amplifier is configured to use passive polarization and 8 amplifier passes for efficient extraction.

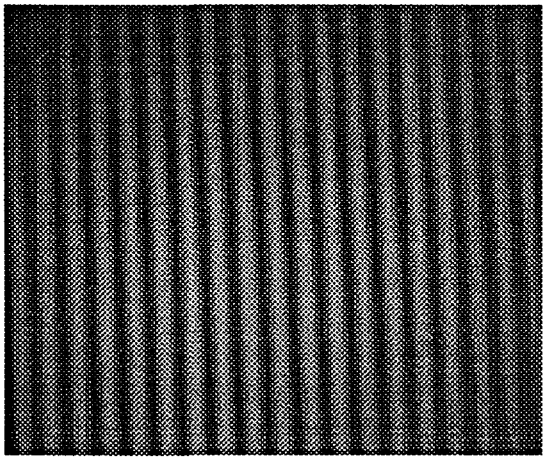
The high repetition rate of the laser diode pumps is achieved through the use of an aggressive heat removal method using silicon microchannel coolers.[3] These coolers can maintain acceptable diode operating temperatures while rejecting heat at rates up to 1 kW/cm^2 Each cooler consists of a silicon package on which two 0.9 mm long diode bars are mounted. These are then stacked at a density of 10 packages per cm with a single water inlet and outlet. Each package requires a cooling flow of 1 cm^3/s with a pressure of 60 psi. In this configuration each 1.8 cm wide diode package is capable of 100 W peak power output. No reduction in this peak power is observed at a duty cycle of up to 25% resulting in an average power of 25 W/package and a diode array average pumping irradiance of 140 W/cm^2.

3. Coherent Laser Radar

The high power laser systems developed by means of the phase-conjugated master oscillator/multipass power amplifier display two properties often critically important to laser radar applications; they have long coherence lengths with the absence of frequency chirp and the output beam quality is nearly diffraction-limited. The long coherence length results from the single frequency nature of the master oscillator and the preservation of this narrow bandwidth in the stimulated scattering process of phase conjugation. Coherence lengths near the transform limit are generally expected. Figure 5 shows an example in which full contrast fringes are generated in a 15 J per pulse output of a 600 ns long pulse. The second important attribute for radar applications is the near-diffraction-limited beam quality. As discussed above the low power master oscillator can rather easily be operated in a diffraction-limited TEM_{00} mode and the phase conjugation process restores this high quality wavefront to the amplified beam. High beam quality ensures maximum energy on target and hence maximum radar return signals.

4. Laser Machining

The high power and high beam quality make this laser system ideally suited for laser machining applications. Various configurations of this laser architecture result in a range of laser parameters important for different applications. One configuration utilizing Nd:glass slabs can produce per pulse energies up to 30 J with pulse lengths adjustable from 10 ns to 1 μs and repetition rates up to 10 Hz, all with near-diffraction-limited focus control. In another configuration employing Nd:YAG crystal slabs the 400 mJ per pulse can be generated at rates up to and exceeding 3 kHz, again with diffraction-limited beam quality.



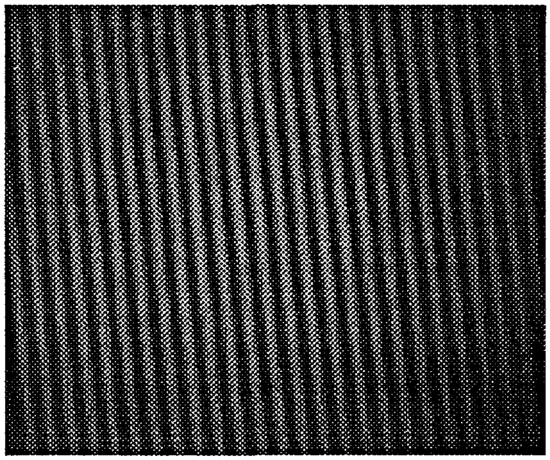


Figure 5. High fringe visibility is observed for (left) equal fiber pathlengths and (right) a fiber pathlength of 20 m. A fiber index of ~ 1.5 translates into a pathlength difference of 30 m equivalent. The sampled light was the 15 J/pulse, 600 ns pulse length output of the Nd:glass laser system.

Summary

The technology of advanced solid state lasers employing a master oscillator/phase conjugated power amplifier architecture is being developed which can be useful in a broad range of industrial applications. We believe that the high level of performance from these lasers can be maintained in field situations.

Acknowledgments

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References

1. L. A. Hackel, J. L. Miller, and C. B. Dane, "Phase Conjugation in a High Power Regenerative Laser Amplifier System," *Int. J. Nonlin. Opt. Phys.* **2**, 171-185 (1993).

2. A. M. Hawryluk and L. G. Seppala, "Soft X-Ray Projection Lithography Using an X-Ray Reduction Camera," *J. Vac. Sci. Tech.* **B6**, 2162-2166 (1988). Also, W. T. Silfvast and O. R. Wood II, "Tenth Micron Lithography with a 10 Hz 37.2 nm Sodium Laser," *Microelectron. Eng.* **8**, 3-11 (1988).

3. D. Mundinger, R. Beach, W. Benett, R. Solarz, W. Krupke, R. Staver, and D. Tuckerman, "Demonstration of High Performance Silicon Microchannel Heat Exchangers for Laser Diode Array Cooling," *Appl. Phys Lett.* **53**, 1030-1032 (1988).