LASER DESKTOP MACHINING

Harnessing a massless beam of light energy for heavy manufacturing applications like cutting, drilling, welding, soldering, surface hardening, cladding, sintering metal powder for rapid part fabrication, and so on, is almost like science fiction becoming reality to engineers (1). There is no need to replace expensive cutting tools repeatedly. The reality was demonstrated in the 1960s with the invention of ruby, Nd–YAG, and CO_2 lasers delivering pulsed high peak power. By the early 1990s, engineers realized the potential of the desktop manufacturing revolution, with the advent of compact high-power diode lasers (DL) arrays (2–17).

Of all the lasers, DLs are the most efficient ones. Some of the commercial ones now reach 40% to 50% electrical to optical efficiency. They are very compact: a 1 W laser is the size of a grain of table salt, with emission intensity about 1 MW/cm^2 to 10 MW/cm^2. They operate at about 2 V, and their pulse rate and shape can be controlled to almost any desired value from direct current (dc) to multigigahertz. DLs have not only helped usher in the Knowledge Age through fiber-optic communication network, but they are also beginning to compete in the manufacturing applications when a larger number of them are combined to produce tens to thousands of watts of continuous-wave (CW) or pulsed power. DLs are comparatively the safest lasers on manufacturing desktops. Since DLs are mass producible like computer chips, they will also be the cheapest lasers to buy and maintain during the next decade and will replace the current inefficient, bulky and/or environmentally unsafe lasers wherever the DL wavelengths, from 0.4 μm to 5 μm, are acceptable. Current high-power diodes are mostly confined to a range of around 0.8 μm and 0.98 μm for historical reasons and also because of demand from communication markets. Since these wavelengths are shorter than those of CO_2 (10.6 μm) and Nd-YAG (1.06 μm), the light energy couples more efficiently on metal work pieces. In the future, as the laser manufacturing market opens up, high-power diodes will become available over a

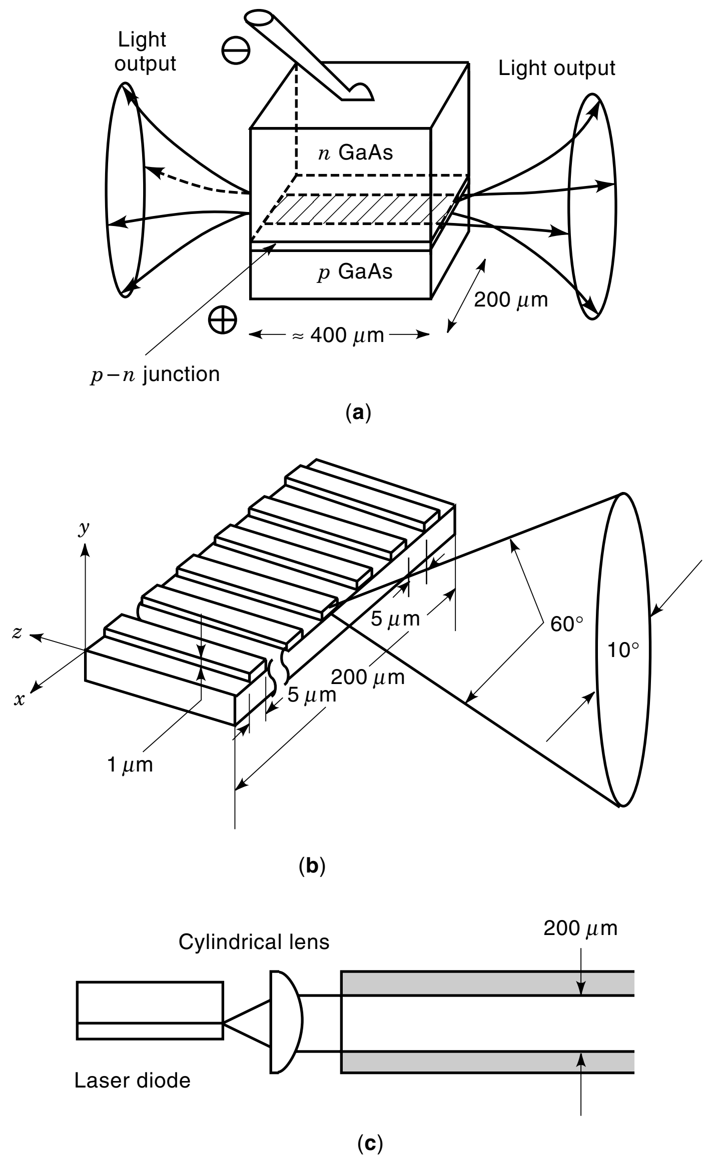


Figure 1. Semiconductor diode lasers and their coupling to glass fiber. (a) An enlarged view of a single microscopic diode depicting the thin active layer that limits the maximum power and produces highly divergent and asymmetric beam. (b) An example of a bar of a monolithic incoherent array of diode lasers. (c) The cross-sectional view of coupling of such a bar of laser array to a multimode optical fiber using a cylindrical lens.

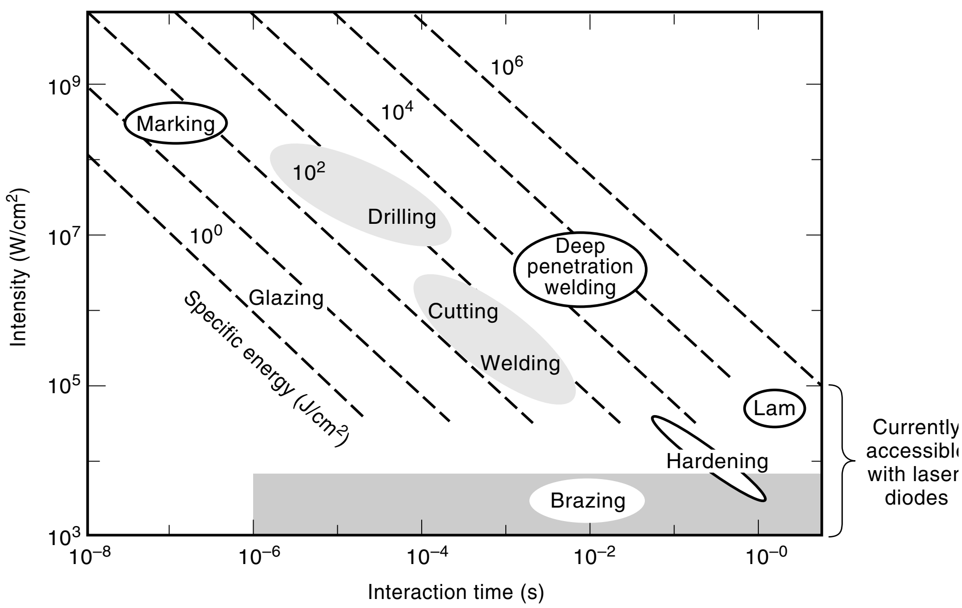


Figure 2. Intensities and interaction times required for various laser material processes. (Courtesy of Lawrence Livermore National Laboratory and Fraunhofer Resource Center at Ann Arbor; see also Ref. 10.)

much wider range of wavelengths from deep blue (0.35 μm) to near-infrared (5 μm).

HIGH-POWER DIODE LASERS

Diode lasers (Fabry–Perot type) are produced by cleaving epitaxially grown *p–n* junction semiconductor materials GaAlAs (0.8 μm), GaAsSb (0.98 μm), InGaAsP (1.55 μm), and so on, and then electrically pumping across the *p–n* junction orthogonal to the microscopic waveguide cavity (5) (500 μm to 1000 μm long) [see Fig. 1(a)]. Single-mode waveguide facets are about 1 μm $\times$ 3 μm, through which a 10° $\times$ 60° divergent beam is emitted.

A monolithic array (6–9) of such lasers can easily emit 1 W to 20 W as shown in Fig. 1(b). The light is generally incoherent from element to element, but a cylindrical lens can collect it into a glass fiber of approximately 200 μm core diameter (as an example), matching the width of one monolithic diode array [Fig. 1(c)]. Such a system, with 80% coupling efficiency, can easily provide an output working intensity exceeding 50 kW/cm^2.

Let us focus briefly on the intensity (or power density) requirements for various laser materials processing functions (10,11) as shown in Fig. 2. The figure does not explicitly identify processes like metal powder sintering for rapid prototyping, soldering, cellulose cutting, vapor phase deposition, and so on, that require power density in the low kilowatt domain with total power from 10 W to 100 W only. Figure 2 does show that most of the traditional laser material processing functions can (eventually) be carried out by DLs since their intrinsic emission intensity is about 10^7 W/cm^2 albeit at low individual device power of about 1 W or less. Thus, heavy manufacturing requires collecting laser light from a large number of devices into a small spot to achieve high total power at high intensity. Technically, this is called high brightness requirement; and the associated engineering difficulty, along with the limited market acceptance, has kept the cost of the current commercial system relatively high. A diode coupled fiber bundle as shown in Fig. 1(c) is capable of providing CW power exceeding 100 W or more. Such devices are commercially available from several international suppliers. Figure 3 shows a different geometry to achieve intensity reaching 50 kW/cm^2 to 100 kW/cm^2. This is achieved by folding the beams from a bar of incoherent laser array into a closely packed vertical stack to achieve higher brightness.

Much higher total power in the kilowatt domain is commercially available with a geometry called "rack-n-stack." In this geometry a two-dimensional dense stack of incoherent diode bars are stacked on very special thin cooling plates. The average intensity at the surface of the stack can reach as high as 2 kW/cm^2. By separately collimating each horizontal bar by miniature cylindrical lenses (monolithic or discrete), followed by a large focusing lens, one can obtain an intensity

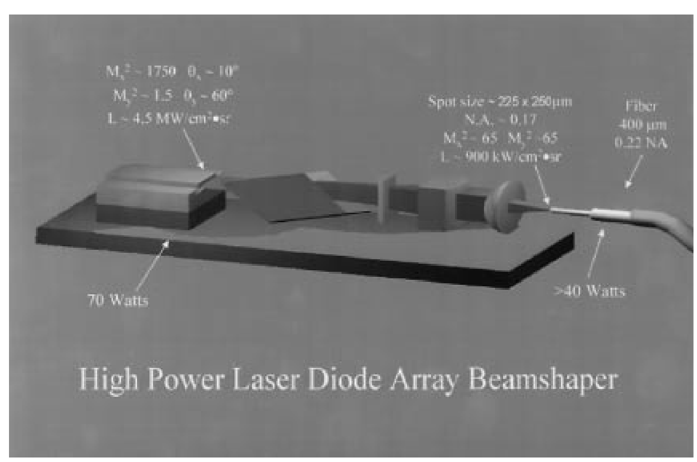


Figure 3. High brightness diode laser spot from an incoherent bar after vertically stacking horizontal source array by a pair of tilted and translated mirrors. (Courtesy of Opto Power Corporation.)

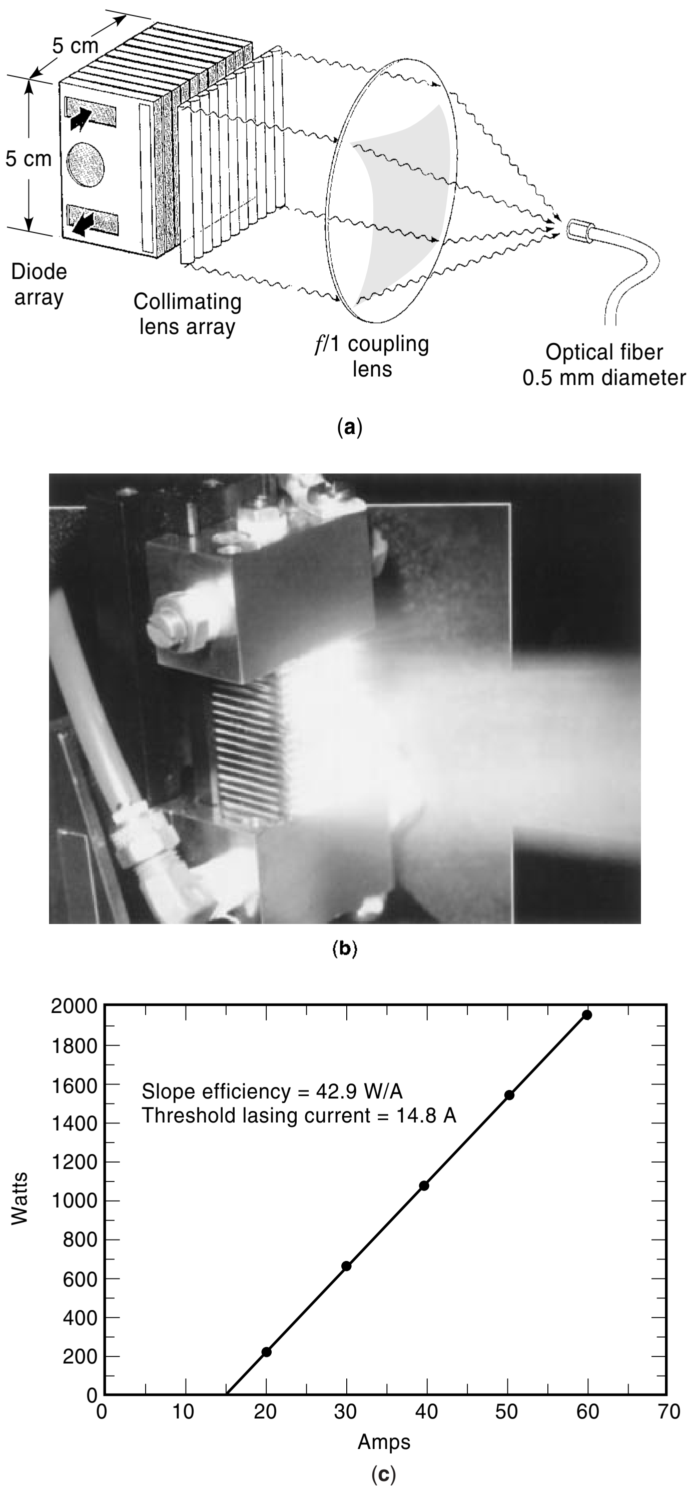


Figure 4. High-power "rack-n-stack" diode array. (a) A compact rack-n-stack array can provide kilowatt range power with high intensity by using microcylindrical lens array and a big spherical lens. (b) Diode laser light emitting from such a rack-n-stack structure. (c) Optical output power versus drive current for the stack. Fifty modules with 1.5 cm InGaAs bars. (Courtesy of Lawrence Livermore National Laboratory and Fraunhofer Institute.)

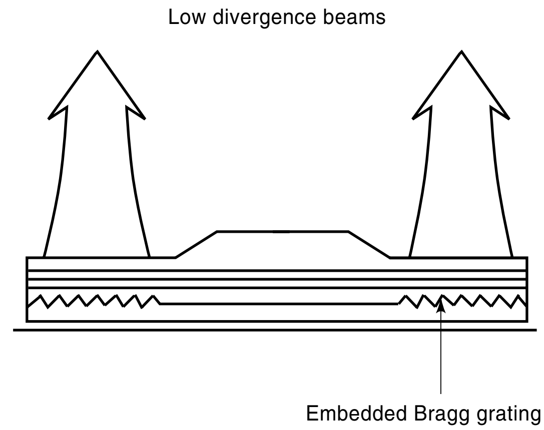


Figure 5. Schematic diagram of a next-generation high-power DL using broad area embedded gratings. Second-order distributed Bragg reflector is part of the laser resonator and output coupler through the surface.

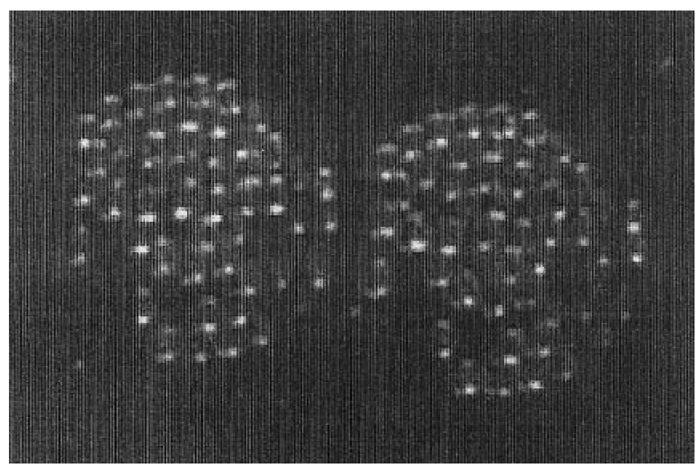


Figure 6. Diode laser marking by a two-dimensional array of lasers on a plastic plate.

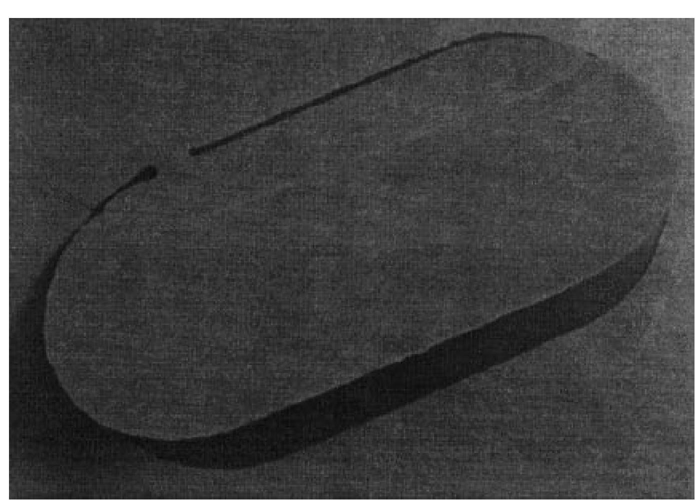
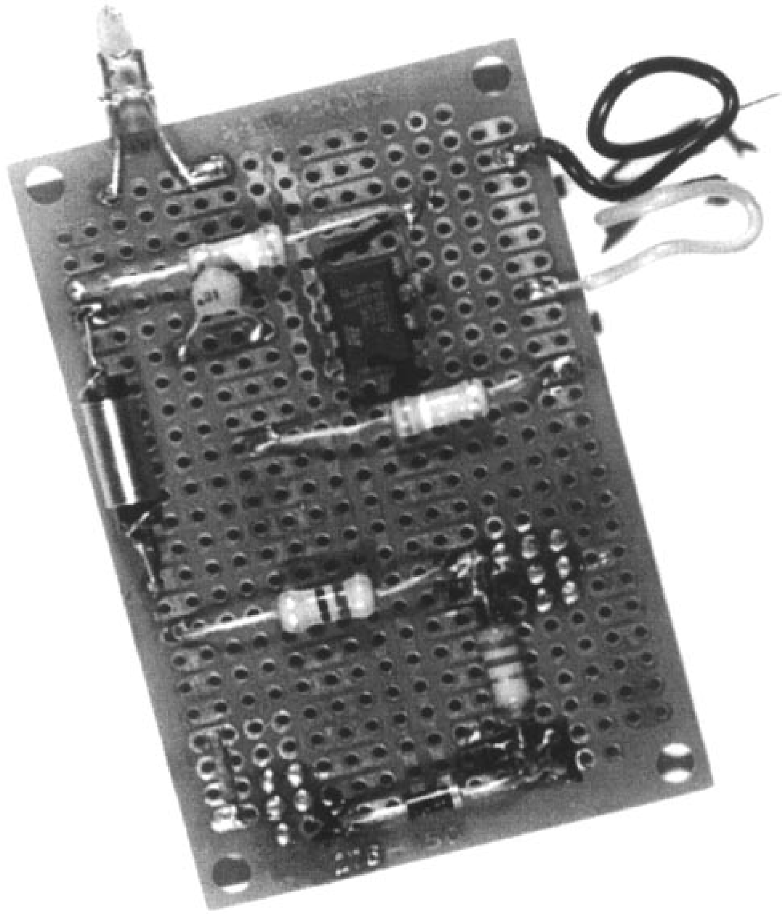
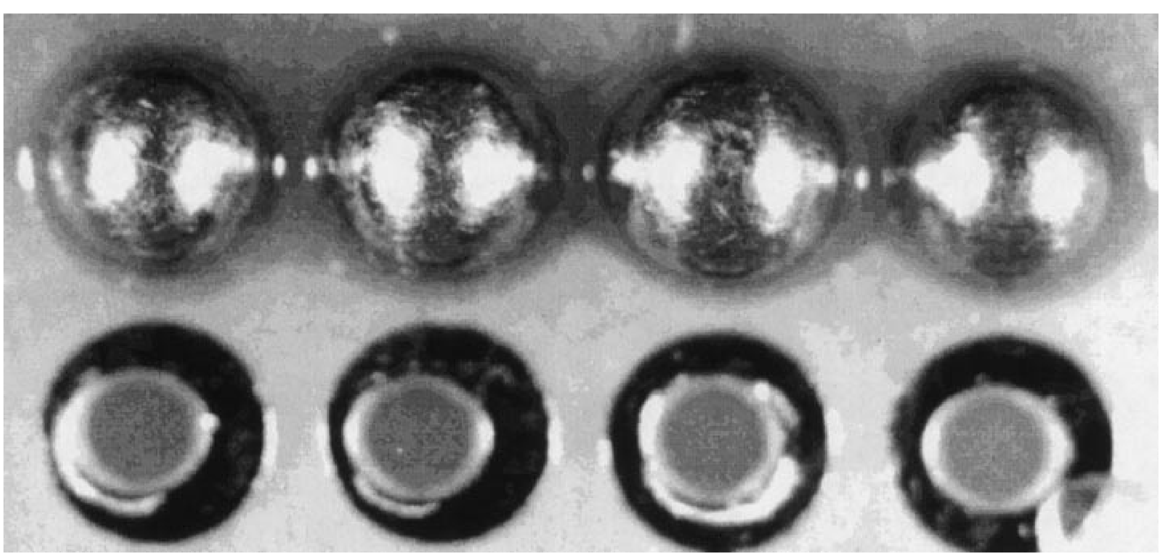


Figure 7. Diode laser cutting of cellulose (paper) material by a scanning laser beam.



(a)



(b)

Figure 8. Diode laser soldering of electronic components in (a) and melting of solder in (b).

exceeding 10^5 W/cm^2. Figure 4(a) gives the schematic diagram of such a rack system, and Fig. 4(b) is a photo of such a system showing an unfocused laser beam. Figure 4(c) shows the optical output power curve against the dc pump current.

Figure 5 shows the geometry of the next generation DL that emits the light vertically through the wafer surface by virtue of second-order Bragg gratings. The emission cross section can be very wide—for example, 15 μm $\times$ 200 μm instead of 1 μm $\times$ 3 μm as in edge-emitting Fabry–Perot laser stripe. This broader coherent source size provides a much higher brightness source due to lower divergence and is capable of giving an intensity of 1 MW/cm^2 or higher at a focused spot. A two-dimensional array of such lasers will eventually replace most of the current lasers for laser material pro-

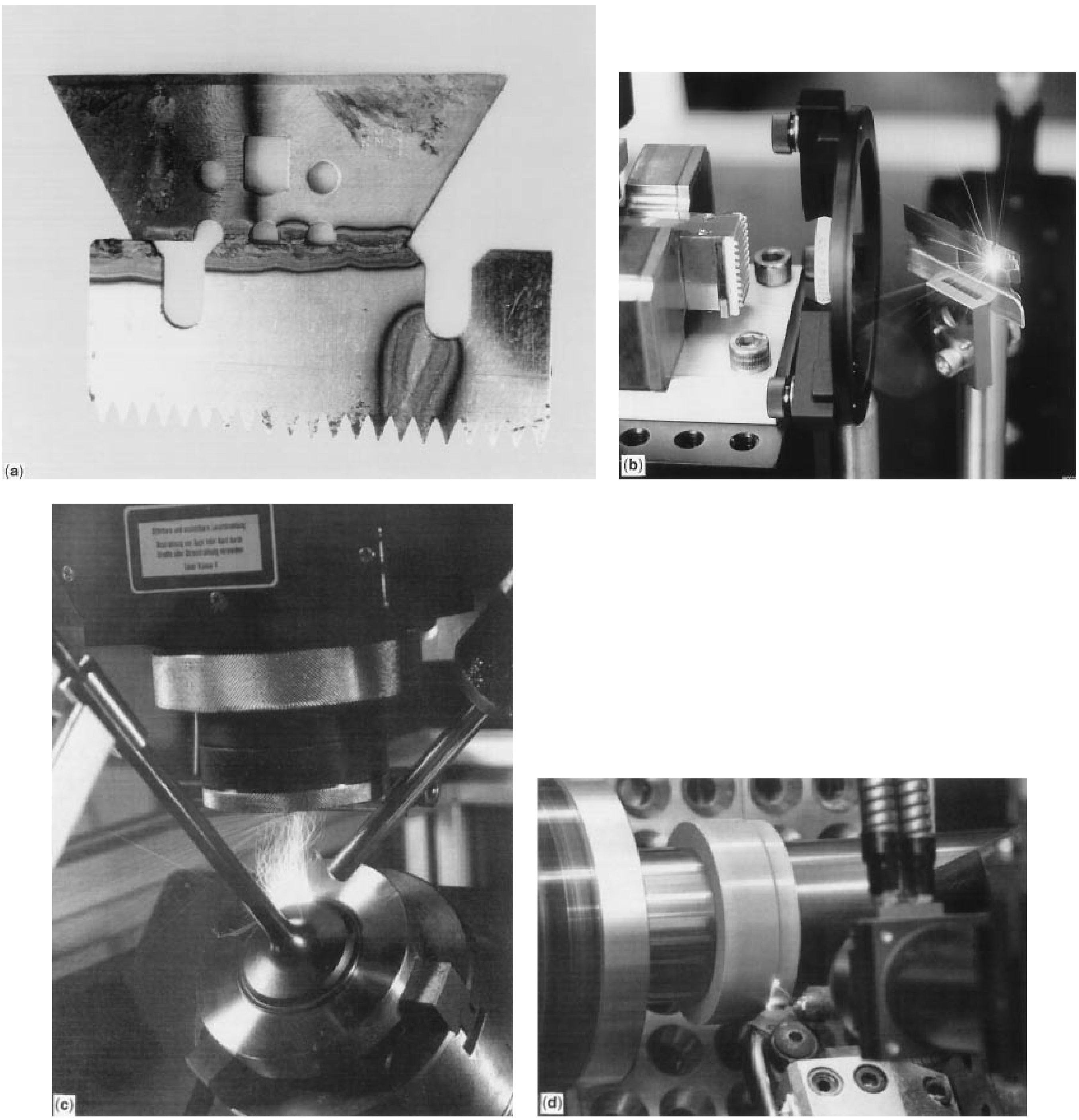
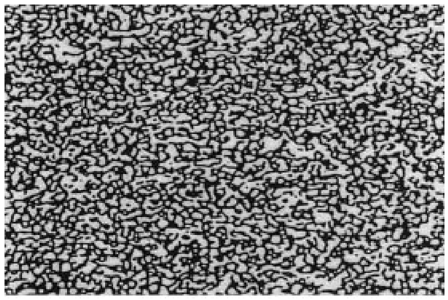


Figure 9. Diode laser welding, cutting, and cladding. (a) Welding of a razor blade to a steel saw blade. (b) Cutting a razor blade. (c) Cladding a valve by stellite powder. (d) Laser-assisted (heated) machining of SiN cylinder. [Courtesy of (a) Zediker of Nuvonyx, (b) SDL Inc., (c) Fraunhofer IWS, (d) Fraunhofer Institute of Production Technology.]


(a)

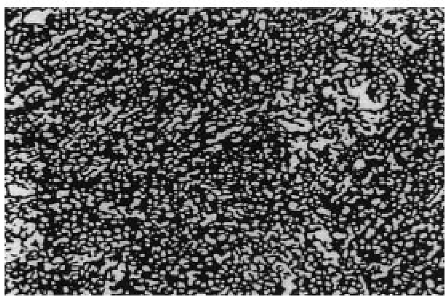

(b)

Figure 10. Diode laser surface hardening of a steel tape. (a) Micrograph of pearlite phase before laser hardening. (b) Micrograph of the martensite phase after hardening by diode laser.

cessing. Commercialization of such lasers is expected in the near future.

EXAMPLES OF DIRECT DIODE MATERIAL PROCESSING

Marking/Engraving

Laser marking is an important growing market to replace environmentally risky approach of using inkjet (12). A hand-

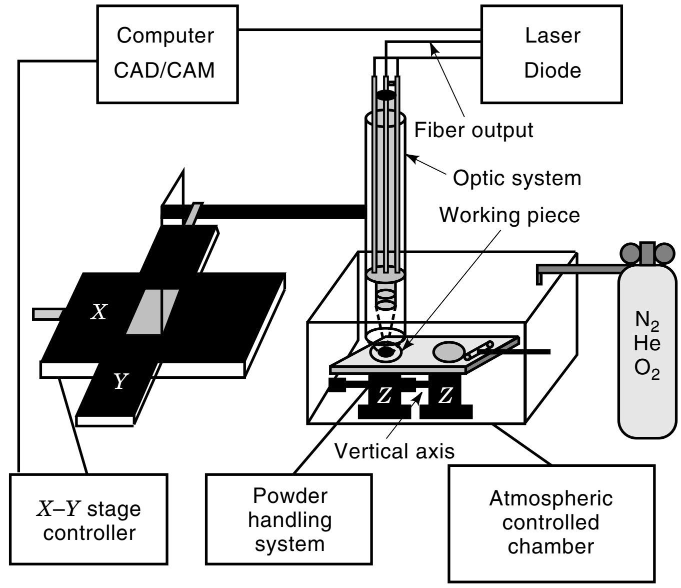


Figure 12. Schematic diagram of a computerized sintering system designed for producing SFF directly from metal powder by sintering thin layers of powder, sequentially one over another.

held, independently addressable, high-peak power diode array can carry out a number of the commercial jobs. Figure 6 shows an elementary demonstration of marking (engraving) plastic (Acrylonitrite butadiene styrene) with a fiber-coupled laser array. The laser wavelength was 810 nm; power density was ~100 W/cm^2.

Cutting Cellulose

This is another growing market because leather, cotton material, and paper need to be cut precisely and optimally with computer intelligence for many different product markets. Figure 7 shows an example of cutting a paper by a computer-

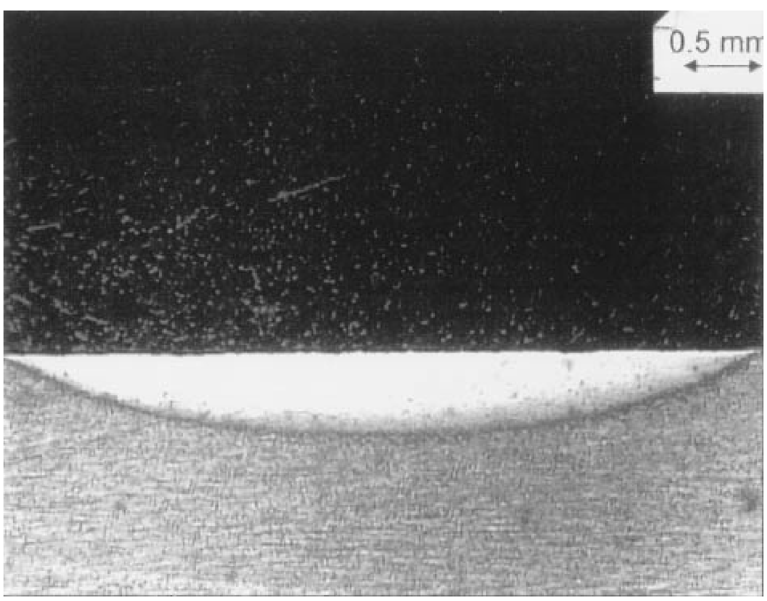
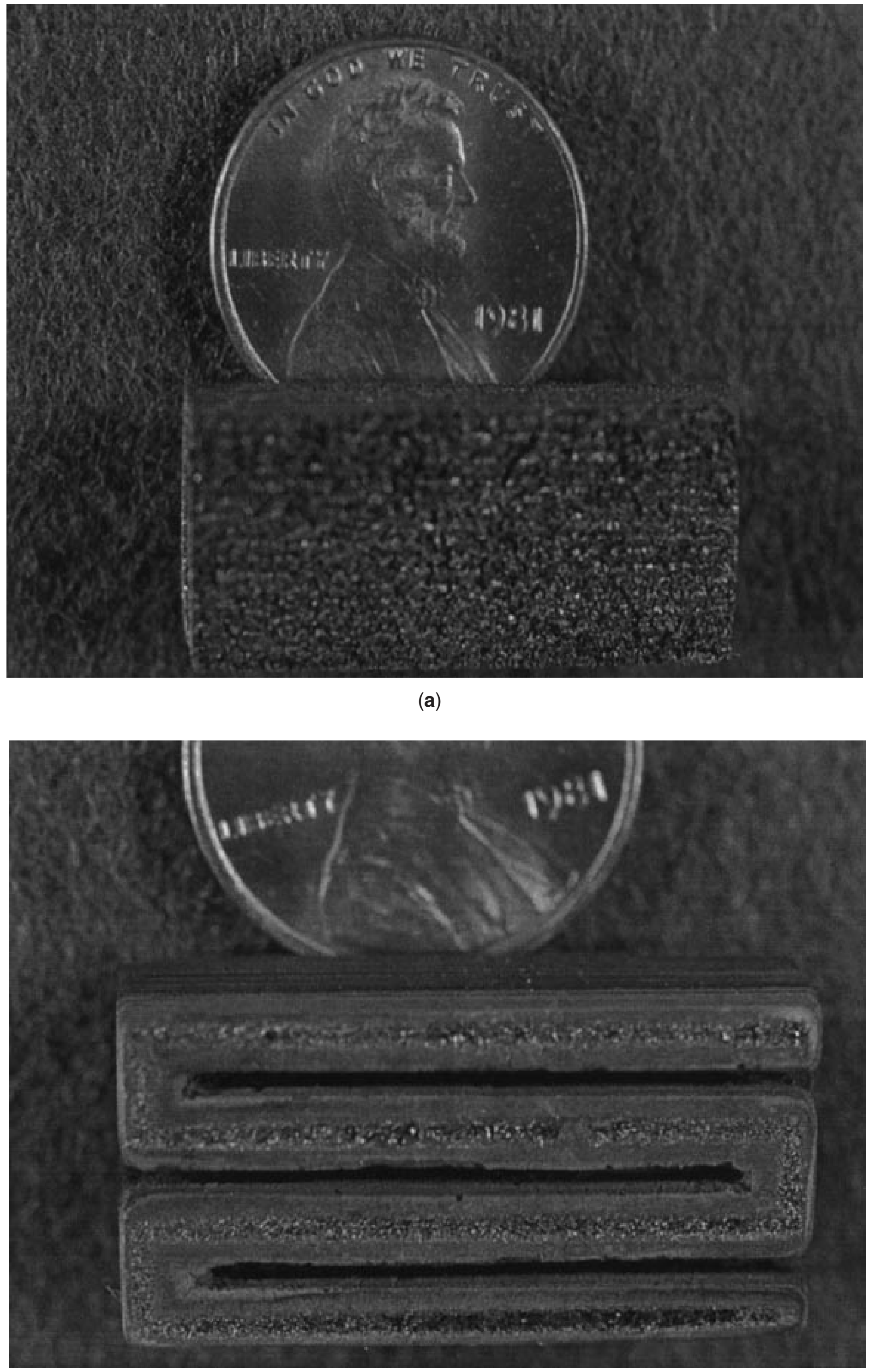


Figure 11. Micrograph of the cross section of a steel plate hardened by a diode laser. (Courtesy of Lawrence Livermore National Laboratory.)



(a)

(b)

Figure 13. Two 36-layer sintered parts fabricated from 150 μm and 44 μm Fe powders, shown in (a) and (b), respectively, demonstrating curl-free sintering by diode lasers.

controlled diode laser head (fiber-coupled). The material was 70 lb stock black paper. The laser was a CW 980 nm diode at 6 W power level with a cutting beam spot size of 0.8 mm moving at a rate of 2.5 mm/s. This technique is also useful for laminated object manufacturing (LAM) where a stack of appropriately cut sheets are cemented to create a three-dimensional object.

Soldering

Since small electronic components and circuit-board soldering do not require heavy melting energy, it is possible to combine low-duty cycle, high-peak pulsed power with low dc-biased laser power to carry out fluxless soldering to achieve an environmentally cleaner manufacturing process. Figure 8 shows soldering examples; the circuit-board soldering was done with a CW 980 nm diode at 25 W (0.6 mm spot). When soldering is carried out below 1 s exposure, there is no damage in the masking layer (11). The solder globule test [Fig. 8(b)] was done with the laser at 7 W requiring less than 2 s exposure.

Welding, Cutting, Cladding, and Machining

Welding, cutting, cladding, and so on, of metal parts and tools are heavy-duty laser manufacturing jobs. Figure 9(a) shows an example of welding steel blades using a CW 40 W (at 0.8 μm) rack-n-stack Fabry–Perot diode laser array first collimated by a cylindrical lens array, followed by a common focusing lens. Intensity at the focus exceeds 100 kW/cm^2. Figure 9(b) is a demonstration of cutting a steel blade using rack-n-stack α-DFB laser arrays (13). Figure 9(c) shows the ongoing stellite cladding process with a 1.4 kW diode laser system. The spot size was 4 $\times$ 2 mm, and the processing speed was 400 mm/min. Figure 9(d) is a demonstration of laser-assisted machining of a silicon nitride ceramic that is normally not machinable. The laser power was 1.2 kW, and surface roughness of 1 μm was achieved.

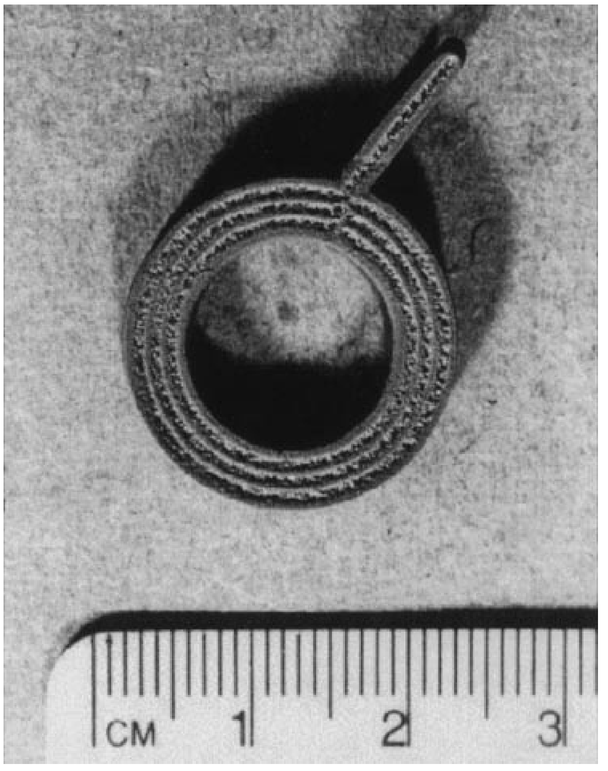
Surface (Transformation) Hardening

One of our earliest experiments was surface hardening of a stainless steel ribbon because CO_2 (10.6 μm) laser was not economically suitable due to its high reflectance. We carried out the hardening of a 500-series stainless steel ribbon (6 mm wide, 0.1 mm thick) with a 980 nm diode laser at a power level of 15 W on a 0.8 mm spot with 3 s exposure time. Figure 10(a) shows the pearlite phase (hardness 30 on the RC scale) before heating. Figure 10(b) shows the martensite phase after heat treatment (hardness 80 on the RC scale). An example of the hardening of a steel plate (11) by a factor of four, using laser diodes, is shown in Fig. 11.

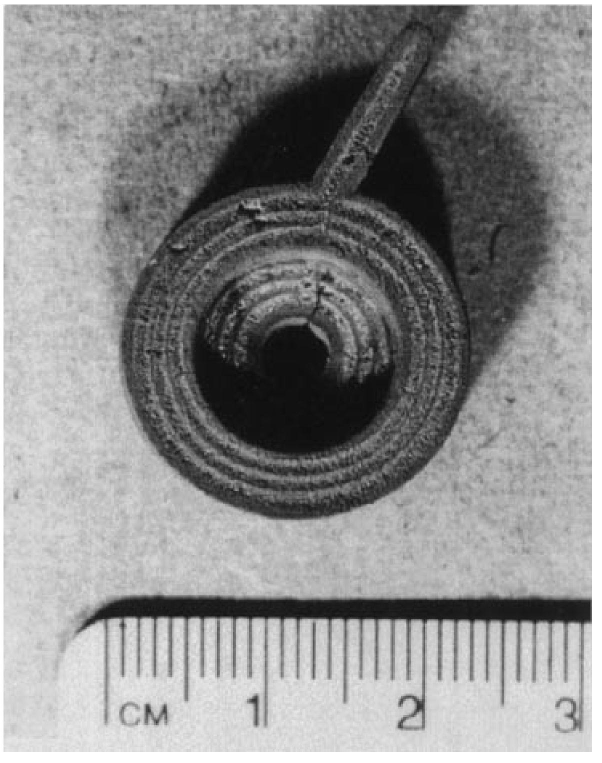
Solid Free Form from Metal Powder (Sintering)

This section establishes the advancement of diode laser technology in solid free-form fabrication (SFF) directly from metal powders by sintering with diode laser beam without any postprocessing. This is a rapidly growing field with almost a dozen different variations in approaches (1,14,15). Commercial systems using CO_2 and YAG lasers are already in the market. We show a series of results that demonstrate that diode lasers are better suited for the process because of the convenience of computer control, compactness, and efficient coupling of 0.8 μm laser energy. The schematic diagram of the experimental arrangement is shown in Fig. 12. When the commercial processes are fully matured, direct diode sintering can unleash the marketing dream of supplying customized parts deliverable overnight at almost the "mass production cost."

Noncurling. Curling of metal powder sintered parts with CO_2 and YAG lasers are quite common. We found that multimode fiber (600 μm core), when it delivers a diffuse diode laser beam, easily gives curl-free layer growth when precaution is taken to make the initial layers curl-free using thermalizing substrates. The results are shown in Fig. 13. The laser wavelength was 810 nm delivering CW 15 W laser into a 0.7 mm spot with a scan speed of 1 mm/s.

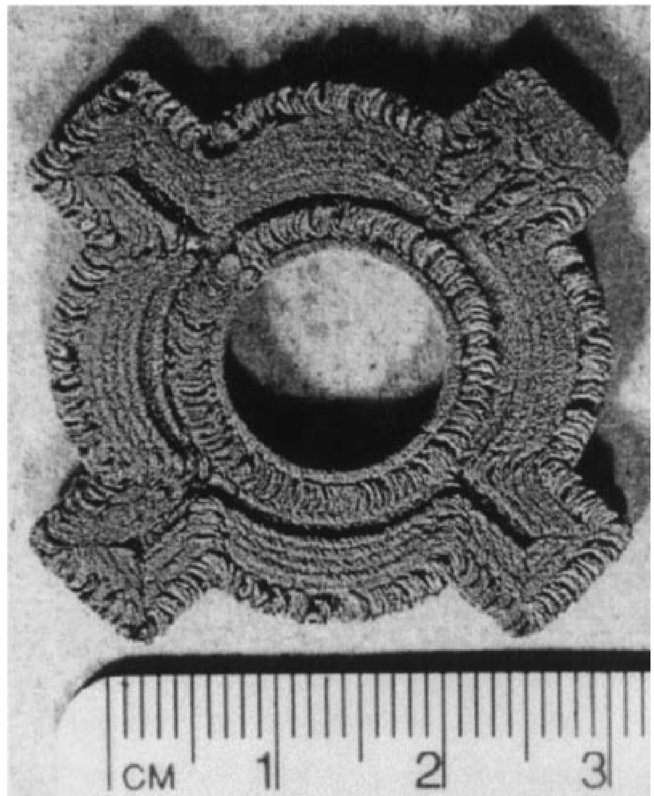


(a)

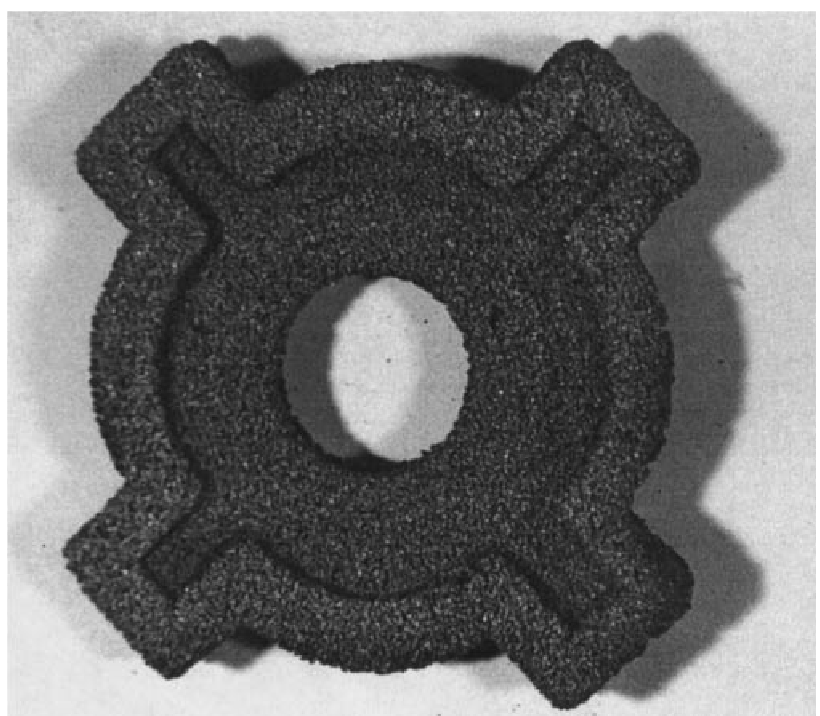


(b)

Figure 14. Wavelength effect in sintering when same power is used. (a) Part sintered by 810 nm diode shows partial melting due to higher absorption of laser light. (b) Part sintered by 980 nm diode shows bonding due to sintering only.

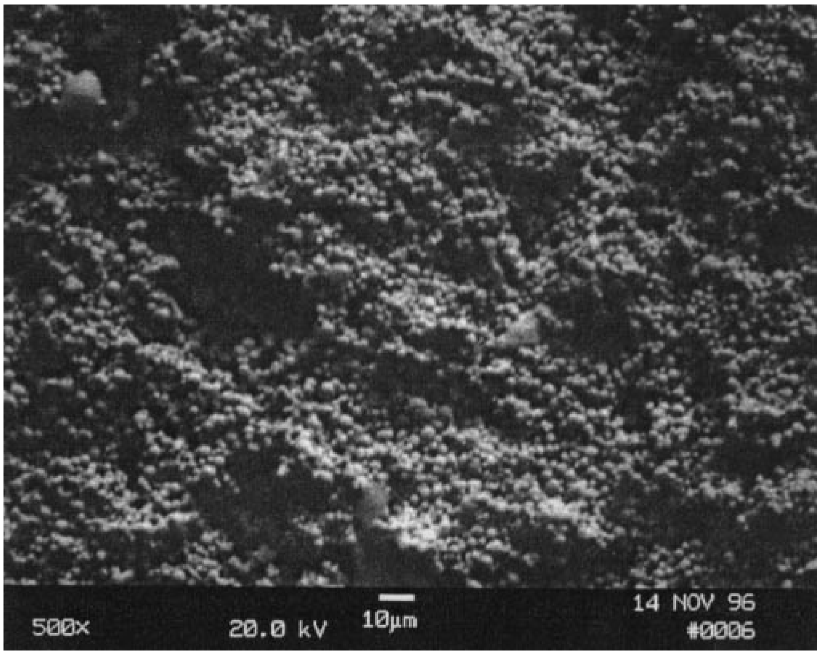


(a)

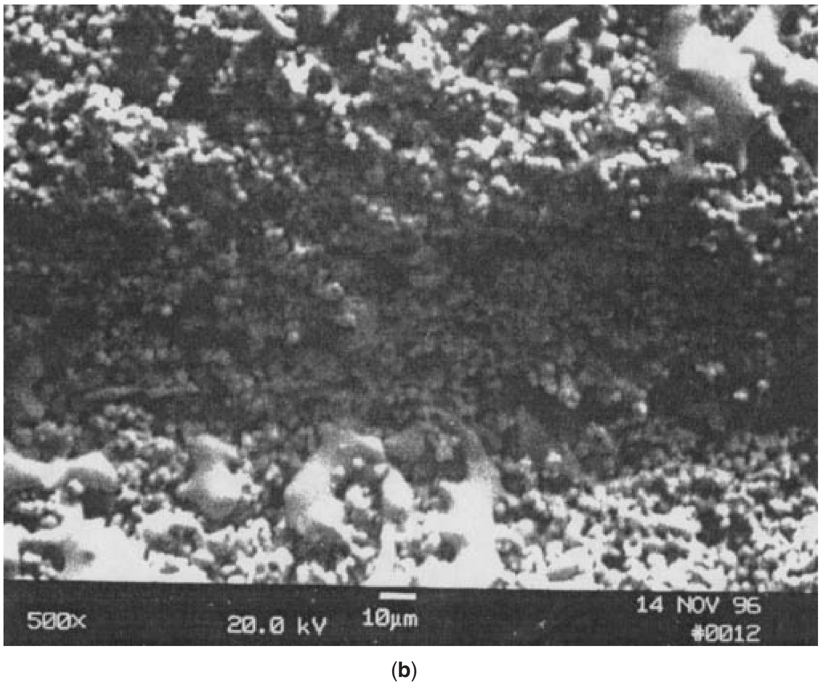


(b)

Figure 15. Impact of particle size on diode laser sintered part density. (a) Part made of 44 μm Fe-bronze has 80% density with structure showing partial melting. (b) Part made of 150 μm Fe-bronze has a density of 50% only.



(a)



(b)

Figure 16. Diode laser sintered part density under N_2 and Ar atmosphere. (a) Micrograph of a part with 80% density sintered in N_2 atmosphere due to iron nitride. (b) Micrograph of a part with 70% density sintered in Ar atmosphere.

Wavelength Effect. Absorptivity of metal powder increases with shorter laser wavelengths. This is verified by using two different wavelengths at 810 nm and 980 nm. The two pictures in Fig. 14 compare the differences in sintering effects. The same 44 μm Fe powder was used in both cases under an inert Ar atmosphere using the same total power of 15 W in a focused spot of 750 μm at a scan speed of 1 mm/s. The test showed that, while 980 nm just sinters the powder, 810 nm sintered and also partially melted some particles due to higher absorption.

Part Density with Particle Size. The density and the hardness of sintered parts are of critical importance if this method is to become a commercially acceptable process for rapid prototyping. Figure 15 shows the intuitively obvious assumption that finer particles make denser and harder parts. Two parts were made using identical computer-controlled processes from Fe-bronze powders of 44 μm and 150 μm particle sizes. The part density made of 44 μm powder is 80% [Fig. 15(b)] with partial melting, while that made out of 150 μm powder is only 50% [Fig. 15(b)] and sintered only. Laser power was

15 CW (at 980 nm) focused to a spot size of 0.8 mm and scan rate of 1 mm/s. Crystollographic analysis of the microstructure showed that the miscibility of particles, of different metals, in the sintered part is significantly better for 44 μm powder than for 150 μm powder.

Part Density with N_2 and Ar Atmosphere. An appropriate gas inside the sintering chamber can be utilized to control the part density. This was verified by fabricating sintered parts under N_2 atmosphere for Fe powder in contrast to the inert Ar gas. Sintered parts grown under otherwise identical conditions showed 80% density for N_2 gas, due to nitride formation, in contrast to 70% for inert Ar gas. The micrographs are shown in Fig. 16(a) and Fig. 16(b), respectively. Low-melting Pb powder is another possibility of obtaining higher density and strength for laser prototype parts. We verified the anticipated result; but because of environmental risks, we would not recommend it for manufacturing.

SOLID FREE FORM FROM GAS PHASE (CHEMICAL VAPOR DEPOSITION)

Laser-assisted chemical vapor deposition is another well-established field (16). Figure 17 shows an almost 0.5 mm tall SiC rod grown in a chamber containing tetramethylsilane (TMS at 25 torr) by focusing an 8 W diode beam (at 810 nm) into a 0.6 mm spot on an Si wafer. This particular SiC rod took 30 min to grow. The base of the rod is about 700 μm.

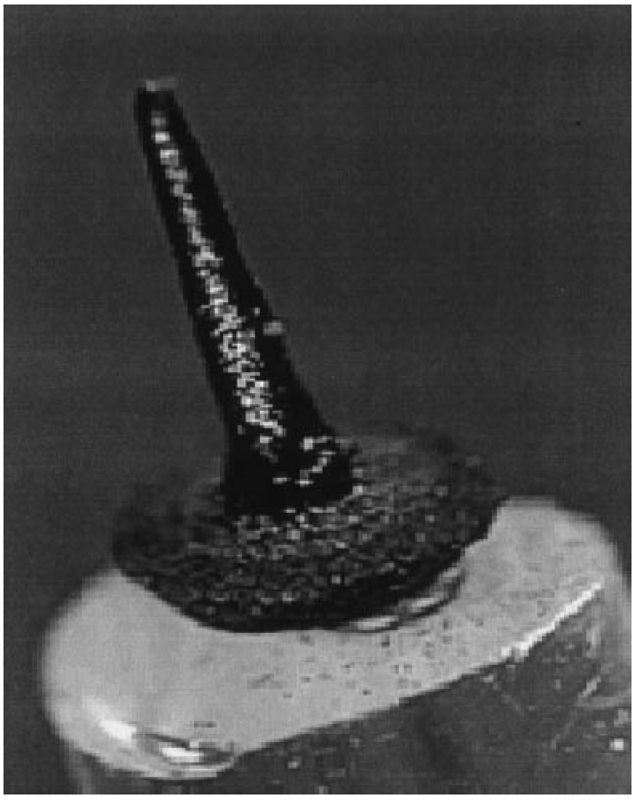


Figure 17. Micrograph of a 700 μm tall solid rod of SiC grown from gas phase using a focused diode laser beam inside a sealed chamber containing tetramethylsilane.

Because of compactness and wavelength diversity, complex three-dimensional optoelectronic and other devices can be fabricated on a single substrate by changing the gas composition inside a small chamber. Spatially distributed individual laser beams with different optical frequencies and beam energies can simultaneously or sequentially develop complex multilayer optoelectronic devices comprising dielectric, metallic, and semiconductor materials.

ACKNOWLEDGMENTS

The author would like to acknowledge Weiq-un Chen and Tariq Manzur for carrying out most of the experiments demonstrated in our institution. Acknowledgments for experimental results from outside institutions have been explicitly mentioned in the figure captions. Dong-Ik Lee and Doug Bradway have put the manuscript together. Support from Connecticut Innovations, Inc. of Connecticut is gratefully acknowledged. The SiC growth experiment was carried out under DARPA support received by Harris Marcus of the Institute of Material Science, University of Connecticut.

BIBLIOGRAPHY

Reference 1 is a lucid and comprehensive book on the subject and is quite inspiring to read. Reference 5 is a comprehensive book on the physics of laser diodes, but from the viewpoint of a communication physicist. References 6–9 give the current state of technology on high-power diode lasers. Reference 17 is a recent book on design and fabrication of high-power diode lasers.

1. M. Steen, *Laser Material Processing,* 2nd ed., New York: Springer, 1998.
2. M. Zediker, Direct-diode laser competes with Nd-YAG and carbon dioxide, *Ind. Laser Rev.,* **August**: 17, 1993.
3. C. Roychoudhuri and W. Chen, New applications of high power diode lasers, *Proc. MOC, GRIN Conf.,* Japanese Soc. Appl. Phys., 1993, paper F1.
4. W. Chen, C. Roychoudhuri, and C. Banas, Design approaches for laser diode material processing systems, *Opt. Eng.,* **33** (11): 3662, 1994.
5. G. P. Agrawal, *Semiconductor Lasers: Past, Present and Future,* New York: American Institute of Physics, 1995.
6. J. W. Tomm, A. Jaeger, and A. Barwolff, Aging properties of high power laser diode arrays analyzed by Fourier transform photocurrent measurement, *Appl. Phys. Lett.,* **71** (16): 2233, 1997.
7. N. G. Landry, J. W. Rupert, and A. Mittas, Multiple-stripe and broad-area diode lasers operating at high power: Aging and thermal degradation influences on performance, *Opt. Eng.,* **32** (1): 157, 1993.
8. J. G. Endriz, M. Vakill, and G. S. Browder, High power diode laser arrays, *IEEE J. Q. Electron.,* **28** (4): 95, 1992.
9. M. J. Landry, J. W. Rupert, and A. Mittas, Coupling of high power laser diode optical power, *Appl. Opt.,* **30** (18): 2514, 1991.
10. C. Banas and R. Webb, Macro-materials processing, *Proc. IEEE,* **70**: 556, 1982.
11. S. Pflueger et al., Using high power laser diodes in material processing: An alternative for fabricating applications, *The Fabricator,* **October**: 52, 1995.
12. T. Manzur et al., Potential role of high power laser diodes in manufacturing, *Proc. SPIE,* **2703**: 1996, 490.
13. A. Schoenfelder et al., 2D high brightness laser diode arrays, *Conf. Proc., IEEE Lasers Electroopt. Soc.,* **2**: 480, 1997.

14. J. Dong, T. Manzur, and C. Roychoudhuri, Rapid prototyping using fiber coupled high power laser diodes, in J. Dong (ed.), *Rapid Response Manufacturing,* New York: Chapman & Hall, 1998.
15. C. Roychoudhuri et al., Diode lasers point to desktop manufacturing, *Laser Focus World,* **September**: 1996.
16. J. Mazumder and A. Kar, *Theory and Application of Laser Chemical Vapor Deposition,* New York: Plenum, 1995.
17. N. Carlson, *Monolithic Diode Laser Arrays,* New York: Springer Verlag, 1994.

CHANDRASEKHAR ROYCHOUDHURI
University of Connecticut

LASER PRINTERS. See ELECTROPHOTOGRAPHY.

LASER PULSE COMPRESSION. See PULSE COMPRESSION.

LASERS. See LASER BEAM MACHINING.

LASERS, CHEMICAL. See CHEMICAL LASERS.

LASERS, DISTRIBUTED FEEDBACK. See DISTRIBUTED FEEDBACK LASERS.

LASERS, DYE. See DYE LASERS.

LASERS, EXCIMER. See EXCIMER LASERS.

LASERS, FREE ELECTRON. See FREE ELECTRON LASERS.

LASER SPECKLE. See ELECTRONIC SPECKLE PATTERN INTERFEROMETRY.

LASERS, SUBMILLIMETER WAVE. See SUBMILLIMETER WAVE LASERS.