Lasers approach take-off for industrial applications

Charles B. Stevens reviews how laser capabilities have become overripe for a broad revolution of industrial technology. Part I of two parts.

While the laser was first realized a little over a quarter-century ago, it is only in the last few years that this technology has reached the level required for widespread practical application to industry.

In fact, through a combination of continuing advances in demonstrated laser capabilities in the inertial confinement fusion energy R&D program and a series of major breakthroughs by the Strategic Defense Initiative program for developing defenses against nuclear-tipped missiles, laser capabilities have become even a little overripe for a broad-based revolution of industrial technology.

From the standpoint of the 21st century, the decade of the 1990s will be seen as the initiation of a second industrial revolution—if Americans have the courage and prescience to grasp this opportunity for economic revitalization and reindustrialization. Simply put, existing and emerging laser technology today promises to make it the "steam engine" of the 21st century.

Lasers transform more incoherent forms of energy into coherent beams of light. These coherent beams of light can be readily and efficiently transmitted and focused through a wide variety of media over great distances. The laser beams can be easily focused to power densities trillions of times greater than industry's current utilization.

Because of its coherence and ability to be focused, one and the same laser beam can be readily applied to an extremely wide range of applications. For example, applications range from the most delicate of medical operations, such as the removal of cataracts of the eyes and angeoplasty to remove blockages within the heart's arteries, through to optical-based communications and computer storage and processing of information, the forming and finishing of materials, and the generation of the super-high stellar densities, pressures and, temperatures needed to ignite thermonuclear fusion for energy production.

Lasers can also be tuned to precisely the right wavelength to get the job done. In many cases, this means that the laser energy can directly and efficiently be coupled to the atoms and molecules to be processed.

In very general terms, lasers will be the "transformer-electric motors" of the 21st century. With the development of electromagnetic induction, in the 19th century, industry realized the capacity to take various forms of mechanical and thermal energy and transform them into electrical currents. These electrical currents could then be efficiently transmitted over long distances and conditioned through the action of transformers to provide virtually any desired power density of electrical or mechanical power required for a particular industrial process.

Lasers take this process one step further. In this case, the electric currents can be transformed into coherent electromagnetic waves. These waves can then be efficiently transmitted, tuned, and focused to even greater power densities than those made available by electric transformers.

But beyond simple measures of efficiency and power density, lasers offer an entirely new universe of "quantum of action." Because of their coherence, lasers can be tuned to interact with specific atoms and molecules—even with specific electron orbitals within an atom or molecule. This means that lasers can accomplish a far greater variety of tasks, with a much higher degree of discrimination than simple electricity.

The perfect laser would have the following characteristics. It would operate at both extremely high efficiencies and average power levels at a minimum of capital and operating costs; it would be capable of reaching even the short ultraviolet end of the electromagnetic spectrum and be tunable over a wide range of electromagnetic wavelengths.

At present, such an ideal laser does not exist. But with the rapid development of the free electron laser, it is in the near future. In the meantime, existing laser technologies have been developed sufficiently to access a wide portion of these desired capabilities. In the following report, we will review the status of these laser technologies.

Current applications of lasers

Tables 1 and **2** review the projected numbers and costs for commercial lasers produced in the world in 1986 and 1987 outside the Communist bloc. Table 1 gives the number of lasers of a particular type for each of the two years and the major areas of industry the laser system was applied to, such as materials processing, therapeutic medicine, diagnostic medicine, scientific research and development, applications to the printing industry, optical memories (primarily for compact disc players), communications, universal price code scanners, alignment and control, test and measurement, and entertainment. Table 2 gives the total projected sales for each type of laser and application for 1986 and 1987.

Carbon-dioxide (CO_2) gas lasers currently dominate commercial industrial laser applications. In 1986, 1,300 CO_2 lasers were sold in this category. The largest and fastest growing segment of CO_2 laser applications is for 0.1-2 kilowatt systems. But this is primarily true for Japan—not the United States—where almost three-quarters of them were made and sold for small-job shops that perform contract machining for automobile and other manufacturers.

The number of high-power CO_2 lasers, in excess of 2 kilowatts, produced in the United States did increase in 1986. These lasers find their greatest uses in welding, followed by cutting and drilling.

In 1986, 890 solid-state lasers were sold for industrial applications; 200 of these were valued at $25,000 each; 300 of these solid-state lasers were for metalworking; and 390, valued at an average of $20,000 each, were for the electronics industry.

Production of ion and excimer lasers for industrial applications is at an early stage. Total sales in 1986 were about $1 million for each kind.

Half of the industrial ion lasers are ultraviolet water-cooled models that the electronics industry uses to fabricate integrated circuits.

Laser production and sales for scientific research and development have continued to grow at about a 12-15% rate each year. As the tables show, a wide range of lasers is used in R&D.

Therapeutic medicine laser production increased 18%. These lasers are used in a variety of surgical procedures, ranging from neurosurgery to podiatry. The primary lasers used in this area are the Nd:YAG (neodymium-doped yttrium iron garnet) and CO_2. Ophthalmology made the greatest use of lasers, roughly 1,100 ion lasers and 850 pulsed Nd:YAG lasers. The Nd:YAG application to ophthalmology is recent, and the rapid growth of Nd:YAG lasers in this area of therapeutic medicine is due to the decrease in system costs. It is projected that half the world's 14,000 ophthalmologists will begin using lasers once the cost per system falls below $40,000.

Most of the 1,000 ion lasers used in therapeutic medicine are used for surgery, as are 1,200 CO_2 lasers. Carbon-dioxide lasers are chiefly used in obstetrics and gynecology, but other types of medical applications are in neurosurgery, podiatry, and dermatology. In the fastest-growing application, endoscopy—with a threefold increase since 1983—only the continuous-wave Nd:YAG is so far being applied. In Europe, helium-neon (He-Ne) and the diode laser have been applied to bio-stimulation and wound-healing therapies.

In diagnostic medicine, He-Cd (helium-cadmium), He-Ne, ion, and dye lasers are the chief systems being applied. The He-Ne laser is utilized for patient alignment in large computer tomography scanners and other diagnostic x-ray devices. Ion lasers are being used for cell sorting and counting. And while argon lasers have been used in this way for some time, it is only now, with the introduction of air-cooled systems, that they are being applied clinically and no longer are limited to medical research. Screening for AIDS virus is a major potential application of this technology. Among the new applications recently being developed are the use of ion lasers in research for reading DNA sequences. A single strand of DNA is "read" through a complex process involving laser-induced fluorescence.

As with the development of the transistor, in today's service sector-oriented economy, new technologies first proliferate through simple consumer applications such as the transistor radio and recording devices. In the case of optical memories, this has occurred through development of laser printers and compact disc players. While many types of lasers are used for printers, the most explosive has been growth in the diode laser, which is also applied to compact disc players.

Overall, it must be recognized that while the above aggregate figures look large, they represent world production, while the actual per capita figures are quite small. The laser industry is still in its infancy.

General requirements for laser applications

Laser requirements vary widely among specific applications. Practical systems require a large range of wavelengths, output powers, spatial and temporal beam characteristics, and other features. In almost every application, however, the following is required:

1) an optimal wavelength;
2) minimum power level;
3) minimized capital and operating costs of the laser;
4) size and weight constraints must be met;
5) operation for extended periods of time with little maintenance;
6) the laser output should have specific temporal and

TABLE 1
Worldwide commercial laser production 1986-87
(By unit)

	CO_2		Solid-State		Ion		Diode	
	1986	1987	1986	1987	1986	1987	1986	1987
Materials processing	1,300	1,400	890	1,000	90	135		
Therapeutic medicine	1,200	1,450	1,020	1,200	2,100	2,500	1,045	1,254
Diagnostic medicine					650	1,100		
R&D	436	480	804	930	800	950	9679	11,614
Printing					5,500	5,000	432,000	1,400,000
Platemaking					140	140		
Color separation					5,000	5,200		
Optical memories					130	250	9,100,000	14,500,000
Communications							45,000	45,000
Barcode scanners							6,000	10,000
Alignment & control							13,000	15,000
Test & Measurement	25	27	27	30	200	250	4,700	5,405
Entertainment					250	320		
Total commercial	**2,961**	**3,357**	**2,741**	**3,160**	**14,860**	**15,845**	**9,611,424**	**15,988,273**

spatial characteristics.

At present the ideal laser that meets all these characteristics for every application does not exist. (Though we should make note that the rapidly developing free electron laser does have promising potentials to meet the requirements of such a universal laser machine.) Systems designers must evaluate trade-offs between alternative sources when selecting a laser for a particular application. If a new source allows attainment of new operating wavelengths, higher output powers, lower cost, smaller size, better beam characteristics, or improved combinations of these factors it is likely to find use in practical applications.

Figure 1 diagrams the major components of a laser system. These consist of an optical gain medium, a pumping system for exciting this medium, an optical system for repetitively directing the beam through the gain medium and controlling its spatial and temporal characteristics, and a cooling system for the removal of waste heat—energy which is not

TABLE 2
Worldwide commercial laser production 1986-87
(In $ millions)

	CO_2		Solid-State		Ion		Diode	
	1986	1987	1986	1987	1986	1987	1986	1987
Materials processing	82	88	37	40	1.3	1.9		
Therapeutic medicine	18	21	21.4	25.2	26.5	31.2	.3	.4
Diagnostic medicine					8.10	11.1		
R&D	9.9	11.2	25.4	28	20.20	23.5	4.8	5.8
Printing					7.50	7	2.6	8.4
Platemaking			.5	.5	.60	.6		
Color separation					13.50	14		
Optical memories					1.90	3.6	72.8	87
Communications							36	27
Barcode scanners							.05	.06
Alignment & control							.55	.6
Test & measurement	.3	.4	.3	.3	3.90	4.7	3.9	4.4
Entertainment					2.10	2.7		
Total commercial	**110.2**	**120.6**	**84.6**	**94**	**85.6**	**100.3**	**121**	**133.6**

He-Ne		Dye		Excimer		He-Cd		Totals	
1986	**1987**	**1986**	**1987**	**1986**	**1987**	**1986**	**1987**	**1986**	**1987**
				36	77			2,316	2,612
8,000	7,000	45	60						13,464
9,500	11,000	20	35			50	70	10,200	12,205
14,000	15,000	660	740	440	495	400	450	27,219	30,659
37,000	45,000					950	800	475,450	1,450,800
								140	140
400						80	85	5,480	5,705
						220	260	9,100,350	14,500,510
90	90							45,090	45,090
110,000	125,000							116,000	135,000
16,000	17,000							29,000	32,000
30,000	34,000	85	85			250	280	35,287	40,077
2,500	2,600	25	25	2,775	2,945				
227,490	**257,110**	**835**	**945**	**476**	**572**	**1,950**	**1,945**	**9,862,737**	**16,271,207**

converted into the output laser beam.

Advances in laser technology can involve either identification of new gain media or improved engineering of other components with known gain media. Three essential parameters for any new laser are 1) spectral characteristics—that is, the laser wavelength and its coherence; 2) system efficiency—the percentage of pump energy that is converted to laser beam output; 3) power scalability.

Research into the spectral characteristics of a laser identify the output wavelength of the device and the extent to which it can be varied. Most applications require light at a specific wavelength and sometimes within a specific spectral band. Wavelength is one of the primary parameters that determine the utility of a particular laser. Many applications, such as remote sensing and spectroscopy, require that the wavelength of the laser be tunable, and in general, wavelength tunability increases the number of applications a laser may be used for.

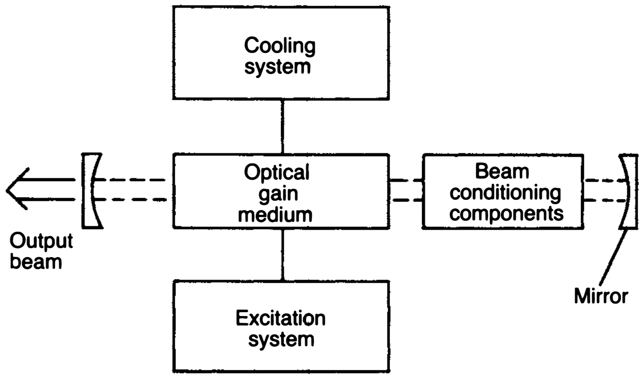
He-Ne		Dye		Excimer		He-Cd		Totals	
1986	**1987**	**1986**	**1987**	**1986**	**1987**	**1986**	**1987**	**1986**	**1987**
				1	1			121.3	131.7
1.4	1.2	1.1	2					68.7	80.95
2.4	2.7	.5	.3			.25	.35	11.25	14.45
5.4	6	27	31	18.3	20.2	2.3	2.6	113.3	128.3
14	17					1.6	1.3	25.7	33.7
								1.1	1.1
.09	.095					.2	.2	13.79	14.295
						.7	.8	75.4	91.4
.05	.05							36.05	27.05
9.4	10.5							9.45	10.56
1.8	1.9							2.35	2.5
8.1	9	2.3	2.3			1	1.1	19.8	22.2
1.2	1.2	.3	.3					3.6	4.2
43.84	**49.645**	**31.2**	**35.9**	**19.3**	**22**	**6.05**	**6.35**	**501.79**	**562.4**

Efficiency—the ratio of average laser output power to the average input pumping power—strongly influences the ulimate size, weight, capital cost, and operating cost of a laser. The size, weight, and capital cost of a laser are largely determined by its pumping and cooling systems. For a given average output power, the pumping power delivered to the gain medium and heat removed from the medium must be minimized if the overall size, weight, and cost of the laser are to be minimized. Consequently, an efficient laser is likely to be smaller, lighter, and less expensive than an inefficient one.

Power scalability—the feasibility of scaling a laser to achieve higher power levels—is a crucial parameter that determines the range of applications of a particular laser. Most applications require some minimal optical power flux density. With enough engineering effort, almost any laser can be scaled to high power levels. However, some devices are much more easily scaled upward than others. Optical damage processes, parasitic oscillations, energy storage times, excitation homogeneity, cooling limitations, and a host of other factors influence the ease with which high power levels can be obtained from a device.

FIGURE 1

Block diagram of a laser, showing major subsystems



The core is a optical gain medium, such as neodymium-doped glass. This is pumped by an excitation system, such as flashlamps as in the neodymium glass laser. The optical gain medium usually must be simultaneously cooled. Various optical beam conditioning systems are used to maintain the quality of the laser beam output. Mirrors are used to reflect the laser beam many times through the optical gain medium in order to extract as much energy as possible before the beam is output.

Semiconductor diode array lasers

In the red and infrared portions of the spectrum, semiconductor diode lasers, with efficiencies in the 30-50% range, are the most efficient of all coherent optical emitters. They have the potential for extremely long operating lifetimes, which is associated with solid-state electronic devices, and are intrinsically compact. A great drawback, however, has been their relatively low output power. A good semiconductor diode laser of conventional design is typically capable of an average output of only a few tens of milliwatts. This limit is imposed by optical damage and heat dissipation problems.

The active region of a diode laser lies at the p-n junction (see **Figure 2a**). Electrons and holes are injected into the junction region when forward current is passed through the diode. Their recombination gives rise to optical gain, and facets created by cleaving the semiconductor crystal act as mirrors for the laser structure. The junction region typically consists of several thin layers that differ in composition or doping and act to confine both the injected carriers and the emitted radiation.

The thickness of the active region, typically a few tenths of a micron, is limited by heat dissipation constraints and by the kinetics of the injected electrons and holes. Its width is determined by the current distribution through the plane of the junction and can be controlled by using photolithographic techniques to define a stripelike conducting channel leading from the exposed metal contact electrode to the junction region. Thus, the optically active region is defined by the thickness of the junction region, the width of the conducting stripe, and the distance between the two reflecting facets.

When the width of the active region is of the order of an optical wavelength, the laser tends to operate in a single, low-order transverse mode, and transverse intensity variations in the optical output beam are minimized. Power output from a narrow-stripe device is roughly proportional to drive current, but is limited by optical damage to the reflecting facets at average power levels of a few tens of milliwatts per micron of stripe width. As the width of the stripe is increased, however, the spatial quality of the output beam decreases, and in junctions more than a few tens of microns in width, the output of the device can be in the form of almost independent beamlets which are not completely coherent with each other. These effects limit the output power of individual diode lasers to levels substantially below those needed for a number of applications.

In recent years, researchers have developed new diode laser geometries. One of these is shown in **Figure 2b** and utilizes an array of narrow-stripe diode lasers, which are coupled together so that the individual sources are mutually coherent. The output beam from this device exhibits lower divergence than would be obtained from a single stripe, but contains the optical emission of all of the stripes. The array thus emits as a single high-power diode laser with good beam quality. These new geometries for diode lasers are expected to make higher power outputs practical.

Tunable solid-state lasers

Tunable solid-state lasers are now emerging from the laboratory into industry. Recent developments promise to revolutionize a wide range of scientific domains, remote sensing capabilities, laser medical applications, micromaterial, and microelectronic engineering.

Among the first lasers demonstrated in the early 1960s were those utilizing transition metal ions doped into crystalline hosts, for example the neodymium-doped yttrium iron garnet (Nd:YAG) and the chromium-doped sapphire (ruby) glass lasers. These lasers have found broad application. The characteristics of crystalline laser media of this type are influenced by both the dopant ion and the host crystal. Laser operation involves optically induced transitions between excited states of the ion, with energies that are perturbed by interaction with the crystal host fields. Thermal properties of the medium, which often are the essential constraint on average output power and pulse repetition rate, are primarily those of the host crystal.

Both Nd:YAG and ruby lasers operate at a single fixed wavelength. Wavelength tunability is possible with certain ion-host combinations. With the recent development of new crystalline media, tunable solid-state lasers for practical applications have begun to be realized. These new crystalline media operate in the deep red or near-infrared and are similar to the well-developed Nd:YAG and chromium-doped sapphire (ruby) lasers, in that they are optically pumped by use of a flashlamp or another laser.

They differ in that they are wavelength-tunable, because of the vibronic nature of the laser transition. Vibronic transitions involve simultaneous emission of an optical photon and excitation of a vibrational mode of the crystal—or what is called a phonon. Ions are optically excited by pump radiation to a broad continuum of high-lying states and rapidly decay to the closely spaced laser and storage levels. The laser transition terminates on one of the many vibrationally excited ground states. The high density of vibrational ground states in vibronic laser systems allows partitioning of the total emitted energy between photons and phonons, and results in optical gain over a broad continuum of wavelengths.

Most vibronic lasers are relatively efficient converters of absorbed pump light to tunable laser output, but overall efficiency (the ratio of optical laser output to electrical power input) is tightly constrained by the efficiency of generating suitable pump radiation. In addition, most of these devices, with the notable exception of the alexandrite laser ($Cr:BeAl_2O_4$), must be cryogenically cooled for optimum operation.

A second class of tunable solid-state lasers which has been extensively researched over recent years is based on the optical properties of color centers in alkali halide crystals. **Table 3** reviews the operating wavelengths and excitation and cooling requirements of several color-center lasers and some of the vibronic sources.

Color centers are specific types of point defects in the crystal lattice which trap electrons and result in optical absorption and emission in the normally transparent crystal. Color-center lasers utilize a doped alkali crystal, which is usually cryogenically cooled and optically pumped by a second laser operating at a wavelength within the absorption range of the color center. Absorption of a pump photon transfers the trapped electron from the ground state to an excited electronic state. Excitation of the electron changes the force distribution on surrounding ions, which distorts the lattice to a new equilibrium configuration. Emission of a laser photon returns the electron to its ground state and is followed by a restoration of the lattice to its original configuration. There is a sizable wavelength shift between the maxima of the absorption and emission bands associated with these pro-

FIGURE 2

Simplified diagram of (a) a semiconductor diode laser, and (b) a diode laser array

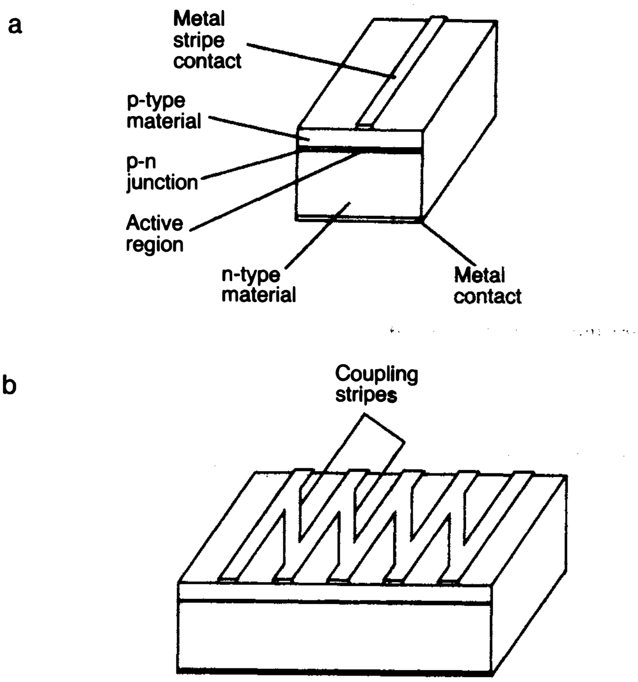


Diagram (a) shows a semiconductor diode laser in which the optical gain medium lies at the p-n junction. Electrons and holes are injected into the junction region when forward current is passed through the diode. Their recombination gives rise to optical gain, and facets created by cleaving the semiconductor crystal act as mirrors for the laser structure. Diagram (b) shows a coupled multiple-stripe configuration, which is capable of much higher output powers than more conventional devices. This arrangement utilizes an array of narrow-stripe diode lasers, which are coupled into adjacent stripes by interconnecting gain regions and by slight overlap of the optical beams generated by adjoining stripes. The stripes, which would otherwise oscillate independently, oscillate in phase as a result of this coupling, and coherent emission is obtained from the entire array. The output beam from this device exhibits lower divergence than would be obtained from a single stripe but contains the optical emission of all of the stripes. The array thus emits as a single high-power diode laser with good beam quality.

cesses, so that absorption by the crystal at the laser wavelength is small.

Color-center lasers typically convert 5-30% of the pump laser radiation to tunable output emission. Overall efficiency depends strongly on the efficiency of the pump source and is often rather low. Cryogenic cooling requirements and the instability of many color centers during operation and storage complicate work with color-center devices.

However, recent developments have identified new types of color centers that have good thermal and optical stability and allow extended spectral coverage. And while tunable lasers made with solid materials were first demonstrated in 1963, only with development of new methods laser pumping and the recent discovery of the alexandrite and titanium sapphire lasers, have tunable solid-state lasers attained sufficient efficiency and reliability to find practical applications. Leading experts point to three specific areas as responsible for this transformation in solid-state tunable laser technology:

1) The development of slab and disk geometry for the lasing medium. Sometimes the lasing atoms are embedded in host crystals such as neodymium, and Cr:GSGG. These geometrical configurations and host materials permit the lasing medium to be efficiently and rapidly cooled, and thus maintain the optimal operating temperature for high-repetition-rate firing and combined with minimal maintenance and misfire damage.

2) Diode-laser pumping in which more efficient, lower-power, single-wavelength lasers are used to pump the solid-state tunable laser medium. Diode-laser pumping has led to the realization of compact, efficient, and frequency-stable neodymium-doped lasers, which operate with low power inputs. The use of diode-arrays will permit the development of efficient, high-power systems.

TABLE 3

Examples of tunable solid-state lasers based on transition metal ions and color centers in crystalline hosts

Dopant	Host crystal	Operating wavelength (nm)	Pump source	Cryogenic cooling
Cr3+	Alexandrite	701 to 818	Lamp	No
Cr3−	Emerald	751 to 759	Lamp	No
Ni2+	MgF2	1630 to 1750	Laser	Yes
Co2+	MgF2	1500 to 2300	Laser	Yes
Ti3+	Al2O3	715 to 770	Laser	Yes
Li+	KCl	2200 to 3000	Laser	Yes
Li+	RbCl	2700 to 3300	Laser	Yes
Na+	KCl	2200 to 2800	Laser	Yes
Na+	RbCl	2400 to 2900	Laser	Yes
	RbCl	1700 to 2000	Laser	Yes
	RbCl	1600 to 1900	Laser	Yes

3) The development of new pumping schemes for the cobalt magnesium difluoride, or Co:MgF_2 laser, and the recent discovery of the alexandrite and titanium sapphire lasers.

Solid-state lasers have numerous advantages over lasers operating with gaseous and liquid media, such as the CO_2 and tunable liquid-dye lasers. For example, solid-state lasers have essentially unlimited shelf and operational lifetimes. Furthermore, there is no need for flow systems, which greatly increase required maintenance. (Most gaseous and liquid lasers require such media flow systems.) Therefore, solid-state lasers are uniquely fitted for applications necessitating either long service lives and/or long shelf-lives and high levels of system reliability. In fact, this long-life potential for solid-state lasers has made them the prime candidates for space-based communication and sensing systems.

Solid-state lasers can also operate at a much wider range of wavelengths than those available to tunable dye lasers. At present, continuous-wave dye lasers operate only up to a wavelength of 1,000 nanometers. The longer-wavelength infrared dye lasers are rapidly degraded in operation due to thermal decomposition.

In the case of solid-state systems, commercially available color-center lasers operate at wavelengths from 1,400-1,700 nm and from 2,300-3,500 nm. Laboratory-based systems have been demonstrated for ranges from 800-4,000 nm. Co:MgF_2 and other transition-metal-doped lasers have demonstrated tuning ranges from 1,510-2,450 nm in laboratory experiments.

Many tunable-laser applications, such as ultrahigh-resolution spectroscopy and holography, require extremely high frequency stability. Frequency jitter caused by the flowing dye stream in continuous-wave dye lasers, therefore, puts major limitations on the application of these systems. Considerable effort has been put into realization of feedback loop systems to reduce this stream-induced jitter in frequency.

Solid-state lasers can also be subject to frequency-output instabilities. Changes in the refractive-index are generated by fluctuations in the ambient media temperature and/or pump-power variations in deposition in the solid-state laser media. The self-induced focusing instability is among the more notorious examples of this problem in solid-state lasers. (This is the case where the transiting laser beam itself induces a change in the index of refraction of the laser media, causing the beam to focus to higher power densities. This higher power density, in turn, increases the beam-induced change in the index of refraction and leads to further self-focusing of the beam. When the self-focusing beam exceeds the damage-threshold power level, catastrophic failure of the laser disk results.)

But as it turns out, these instabilities are much smaller in magnitude than those seen in dye lasers. And the instabilities have much lower characteristic frequencies for solid-state lasers. Therefore, feedback loops to control jitter in the output are much easier to achieve. In general, the frequency stability of solid-state lasers is expected to be far greater.

Laser technologies

The current operational range of tunable solid-state lasers is best represented by three specific systems: 1) the titanium sapphire laser has a continuous-wave (CW) output from 700-1,000 nm and a pulsed output from 660-1,200 nm; 2) alexandrite: contininuous wave and pulsed from about 700-820 nm; 3) $Co{:}MgF_2$: continuous wave from 1,550-2,100 nm and pulsed from 1,500-2,450.

The alexandrite ($Cr{:}BeAl_2O_4$) laser, currently the most developed system, was first developed at the Allied-Signal Corporation in Mt. Bethel, New Jersey, by J.C. Walling in 1979. This laser can be simply pumped with flashlamps and operates at room temperatures and higher. Average pulsed power outputs of 100 watts have been demonstrated together with CW outputs utilizing arc-lamp and laser pumping. High peak powers have also been demonstrated, which permit the alexandrite laser to be used to drive various nonlinear processes, such as stimulated Raman scattering.

Recently, Los Alamos National Laboratory has chosen the alexandrite system for its project on laser isotope separation. The specifications are a pulsed output at 790 nm, with a 250 Hertz repetition rate of an operational lifetime of 120 hours before requiring replacement of any laser components. Allied-Signal has already delivered two such lasers.

Alexandrite lasers are currently being experimentally investigated by NASA as the prime candidate for DIAL atmospheric sensing satellite. A space-based system could detect water vapor concentrations at 724 nm and oxygen concentrations at 760 nm.

The titanium sapphire ($Ti{:}Al_2O_3$) laser was first discovered at the MIT Lincoln Laboratories in 1982. The short upper-state lifetime of the titanium sapphire laser means that the use of laser pumping rather than flashlamp pumping is favored for this system. Continuous wave outputs of 1.6 watts have been achieved utilizing argon-ion lasers for pumping. Several-hundred-millijoule pulsed outputs have also been attained. The use of frequency-doubled neodymium lasers to pump titanium sapphire systems is currently being envisioned as a candidate for the NASA DIAL atmospheric sensing satellite. If the Nd pumping laser is pumped with diode lasers, the overall system would be able to operate as an all-solid-state laser package, giving the system a high reliability and long life.

The $Co{:}MgF_2$ laser was demonstrated by L.F. Johnson at Bell Labs in Murray Hill, New Jersey in 1964. Because of its requirements for cryogenic cooling with flowing liquid nitrogen, this system was not considered suitable for practical applications until recently. Research at the MIT Lincoln Labs has demonstrated that laser pumping of the $Co{:}MgF_2$ significantly reduces the cryogenic cooling requirements. CW outputs of 4.3 watts have been achieved with a 1300 nm neodymium laser pump.

To be continued