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New Laser Source Technology

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Since the invention of the laser in the late 1950's the characteristics and capabilities of laser sources have undergone a dramatic evolution. This article will examine several recent developments in laser source technology which are viewed as technologically significant. Some of these innovations have been commercialized; others are yet to reach the marketplace. Their future will depend to a large extent on their ability to effectively compete with existing devices and to withstand the onslaught of future R & D efforts. To broaden the perspective in which the new sources are viewed, introductory material will be presented which overviews laser industry economics and laser R & D funding. Factors that influence the potential utility of new laser sources will also be discussed. Following description of four new types of sources a concluding section will summarize some potential applications of the new devices.

Summary. Over the past 5 to 8 years several new laser sources have been developed as a result of R & D efforts stimulated by a growing number of laser applications. Four families of new devices—semiconductor diode laser arrays, free electron lasers, rare gas halide excimer sources, and several new tunable solid-state lasers—show particular promise.

Laser R & D and the Laser Market

Early laser devices were, for the most part, the serendipitous offspring of basic research efforts funded at relatively low levels at large corporate laboratories or universities. Practical applications were rare, and the overall utility of lasers in the everyday world was often questioned. In the past 2½ decades, however, the market for laser-related systems that solve practical problems has grown to over $3 billion per year. Laser R & D efforts are now commonly motivated by the lure of potential applications in both the public and private sectors. It is instructive to review some of these applications with an eye toward establishing a practical definition of progress in laser R & D.

Laser applications generally fall into one of two categories: those relevant to large-scale defense and energy projects funded by the federal government and those addressed by the private sector in the commercial marketplace. For the latter category Table 1 gives rough breakdown by type of application of 1983 sales of laser sources and systems containing lasers. Sales of laser sources themselves, including those used in larger systems, totaled about $316 million.

Table 2 shows a breakdown of laser sales by laser type. Many of these lasers have been commercially available for years but are continually undergoing refinement by the manufacturers. Since a successful high-technology company normally must spend 5 to 10 percent of its gross sales on R & D, Table 1 suggests that $160 million to $320 million was spent by industrial organizations on development of advanced laser systems, with perhaps $16 million to $32 million used for research on laser sources.

Government spending for R & D on laser systems in 1983 totaled $800 million and was dominated by efforts on high-energy laser weapons ($375 million), inertial confinement fusion ($200 million), and laser isotope separation ($100 million (*1*). It is likely that at least 10 percent of the total, or $80 million, was spent for R & D on laser sources. A comparison of the estimates for commercial and federal laser R & D reveals the dominant role that the federal government still plays in the development of new laser technology. However, commercial and government objectives in this area are often remarkably similar, so that a substantial spin-off of technology from government programs to the private sector should be expected.

Lasers for Applications

Laser source 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 observations hold true:

1) An optimum wavelength exists.
2) A specific minimum power level is required.
3) Capital and operating costs of the laser must be minimized.
4) Size and weight constraints must be met.
5) The laser should be capable of operating for extended periods of time with little maintenance.
6) The laser output should have specific temporal and spatial characteristics.

The ideal laser that meets all of these requirements every time does not exist, of course, and systems designers must evaluate trade-offs between alternative sources when selecting a laser for a particular application. The economic value of new innovations is directly related to the observations above. 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, and it can

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Table 1. Sales of lasers and laser systems in 1983, distributed by application (*1*).

Application	Laser system sales ($ million)	Laser component sales ($ million)	Example
Nonimpact printing	805	19	High-speed printers
Optical communications	530	14	Fiber-optic communications
Color separation	505	9	Four-color printing
Tactical military	309	54	Range finding
Metrology, alignment	265	17	Leveling
Videodisk, audiodisk	222	7	Video, audio recording
Medical	196	41	Diagnosis, therapy
Materials processing	143	65	Cutting, welding
R & D	97	84	Laboratory instrumentation
Point-of-sale scanning	76	2	Supermarket check-out
Typesetting, platemaking	34	2	Newspapers
Entertainment, display	4	3	Light shows
Total	3176	317	

be said that progress has been made in laser source technology. The relative merits of a new laser source can be finally evaluated only after a great deal of development effort has been expended, since some device features such as reliability and maintenance requirements are a strong function of engineering development effort. However, it is desirable to evaluate the potential of a new device as early as possible in the costly R & D process.

As shown in Fig. 1, a laser source generally consists of an optical gain medium, a 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, often, a cooling system for waste heat removal. Advances in laser source technology can involve either identification of new gain media or improved engineering of other components with known gain media. Three parameters that can be investigated early in the R & D stage strongly influence device performance limits. These are (i) spectral characteristics, (ii) efficiency, and (iii) power scalability.

Investigations of the spectral characteristics of the laser medium identify the output wavelength of the device and the extent to which it can be varied. Since many applications require radiation at a specific wavelength or in a certain spectral band, wavelength is one of the primary parameters that influence the general utility of a laser source. Applications such as remote sensing and spectroscopic instrumentation require that the wavelength of the laser source be tunable, and in general wavelength tunability increases the number of applications for which the laser may be well suited. Wavelength tunability thus increases the versatility of a laser source and is a desirable feature in a new device.

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

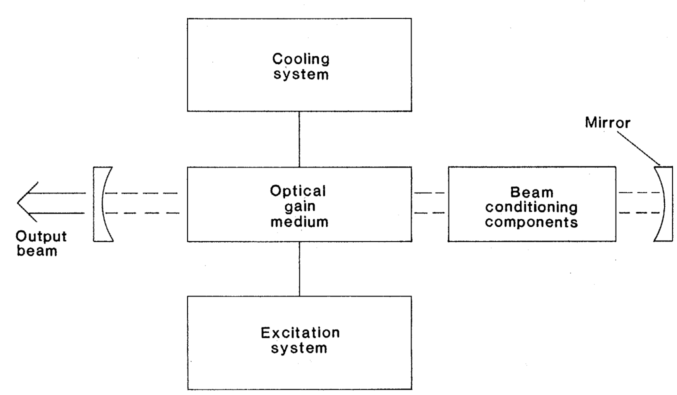
Power scalability—the feasibility of dimensionally scaling a laser to achieve high power levels—must be considered when evaluating new devices, since many applications involve effects that require high optical flux densities. With enough engineering effort almost any laser can be scaled to high power levels; however, some devices are much more easily scaled upward than others. Power scalability of several types of lasers has been considered in detail in connection with the laser fusion program. 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.

Although device innovations can have substantial practical and economic value without involving spectral characteristics, efficiency, or output power, these parameters rank among the most significant. They must be considered when evaluating the potential of new sources such as those described in the following sections.

Some New Laser Sources

Over the past 5 to 7 years there have been some impressive advances in laser source technology and ambitious new experiments that may lead to even more dramatic progress in the near future. Several new devices have resulted from the application of new engineering concepts to existing laser media and from the discovery of new media. Four of these—diode array lasers, free electron lasers, rare gas halide lasers, and new solid-state lasers—are discussed below.

Semiconductor diode arrays. In the red and infrared portions of the spec-



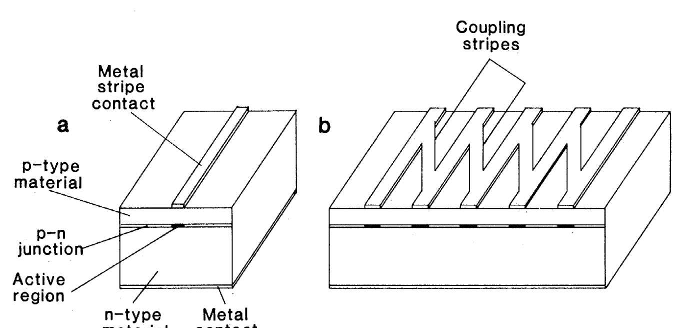


Fig. 1. Block diagram of a laser, showing major subsystems. Fig. 2. Simplified diagrams of (a) a semiconductor diode laser and (b) a diode laser array. In actual devices a multilayered (hetrojunction) configuration is normally used to confine carriers and photons in the junction region (*2*).

trum, semiconductor diode lasers with efficiencies in the 30 to 50 percent range are the most efficient of all coherent optical emitters. They have the potential for extremely long operating lifetimes that 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 source 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 (*2*).

The active region of a diode laser lies at the *p-n* junction, as shown in Fig. 2. 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 micrometer, 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 micrometer of stripe width (*3*). 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 micrometers 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 together limit the output power of diode lasers to levels substantially below those needed for a number of applications.

Researchers at the Xerox Corporation have developed a promising diode laser geometry, called the coupled multiple-stripe configuration, which is capable of much higher output power than more conventional devices (*4*). This arrangement, shown in Fig. 2b, utilizes an array of narrow-stripe diode lasers, which are coupled together so that the individual sources are mutually coherent. Some of the light generated by each stripe is 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. In experiments reported to date, as many as 40 stripes have been coupled to produce an average output power of 3.0 W at a wavelength of 832 nm (*5*). This new approach to power scaling of semiconductor diode lasers is expected to make them much more useful in a number of applications.

Table 2. Laser sales by laser type in 1983 (*1*).

Laser type	Wavelength (μm)	Sales ($ million)
Solid state	1.06	111
Ion	0.514, 0.488	60
Carbon dioxide	10.6	57
Diode	0.65 to 1.8	30
Dye	Visible (tunable)	21
Helium-neon	0.63	20
Rare gas halide	0.35, 0.25, 0.19	14
Helium-cadmium	0.442	4

Free electron lasers. A laser concept that is still in the relatively early stages of experimental investigation involves the use of a beam of high-energy electrons to produce the optical gain necessary for generating laser radiation. With this approach it appears that high efficiency, wavelength tunability, and high average power may be simultaneously achievable. Unlike most other types of lasers, which operate on transitions between bound states of atoms or molecules, the free-electron laser utilizes a relativistic beam of free electrons to produce optical gain. The concept is an outgrowth of both high-energy physics and microwave tube technology. Electron beam devices have been used for several decades to generate electromagnetic radiation in the microwave and millimeter wave portion of the spectrum. New concepts were required for use in the optical region.

There are several types of free electron lasers [optical wave–electron beam interactions have been reviewed by Gover and Yariv (*6*)]. The configuration most often used in the visible and near-infrared is shown in Fig. 3 (*7*). A relativistic electron beam is directed through a periodic magnetostatic field (wiggler field) which alternates in direction along the axis of beam propagation. The wiggler field forces the electrons in the beam to undergo transverse oscillations and to emit bremsstrahlung radiation peaked in the forward direction. In the laboratory frame this radiation is characterized by a wavelength $\lambda = \Lambda/2\gamma^2$, where Λ is the period of the wiggler field and γ is the

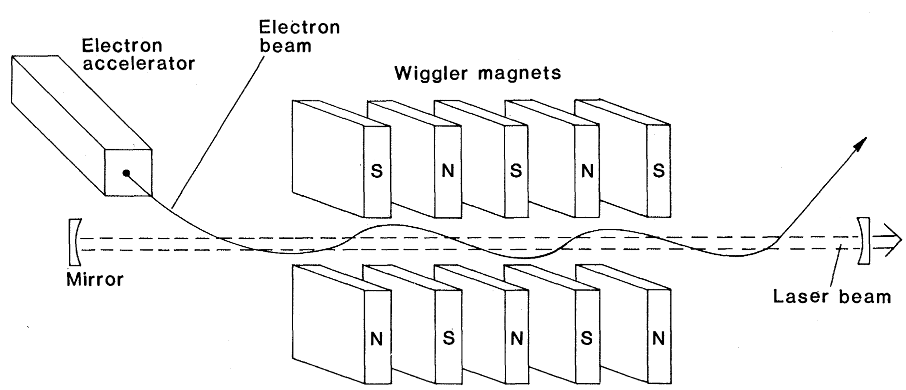


Fig. 3. Schematic diagram of a free-electron laser. Wiggler magnets create a magnetostatic field that induces undulation of the relativistic electron beam. Abbreviations: *N*, north; *S*, south.

ratio of the total energy of the electron to its rest energy (511 keV). If an optical wave of wavelength λ is propagating collinearly with the undulating electron beam, it can do work on the oscillating electrons and cause them to accelerate or decelerate. If the phase of the field is such that the electrons decelerate, the amplitude of the optical wave grows and optical gain is achieved. Using mirrors to form an optical cavity with its optical axis collinear with the beam axis allows a small portion of the spontaneously emitted bremsstrahlung radiation to be amplified to very high levels, and highly coherent optical emission is obtained. In lasers designed to operate at sufficiently long wavelengths (typically in the far-infrared) with high electron beam current densities, electron-electron interactions in the beam give rise to plasma oscillations that can enhance optical gain and the efficiency of extraction of optical energy. Consequently, the best results to date have been obtained at long wavelengths. For example, a free electron laser that can produce 75-MW pulses of 4-mm radiation at an efficiency of 6 percent has been demonstrated at the Naval Research Laboratory.

At shorter optical wavelengths, electron beams of higher energy and higher quality are required, optical gain is inherently lower, and device construction is much more difficult. The first free electron laser, which was demonstrated by J. M. J. Madey and co-workers at Stanford University, used a low-current, 43-MeV electron beam to produce a coherent output at 3400 nm with about 0.2 percent efficiency (*8*). Since then a number of experiments have been carried out with an emphasis on producing light of shorter wavelengths and achieving higher efficiency. Recently, 1600-nm light was generated with 1.2 percent efficiency as the result of a TRW-Stanford collaboration, and a free electron laser operating at visible wavelengths was demonstrated as the result of a 3-year collaboration between Stanford researchers and a French group at Orsay LURE. In the latter experiments a 160-MeV electron storage ring was used as the beam source to generate coherent radiation at 650 nm, the shortest wavelength reported to date (*9*). A number of investigations are in progress around the world to explore free electron laser operation at wavelengths extending from the millimeter range to the far-ultraviolet.

In principle, free electron lasers could efficiently generate coherent light over a wide range of power levels at almost any wavelength between the far-infrared and far-ultraviolet. Theoretical estimates of the maximum conversion efficiency (ratio of laser power to electrical input power) range as high as 20 percent for free electron lasers using linear accelerators, optimally designed wiggler structures, and techniques for recovering unconverted beam energy. Since high-power accelerator technology is already available, average output powers in the range 10 to 100 kW are potentially achievable, and output wavelength can be adjusted by changing the wiggler period or the beam energy. It seems likely that free electron lasers will be best suited to applications that put a premium on efficient generation of large amounts of optical power with less emphasis on physical size, since compact yet very high energy electron accelerators will be difficult to construct. Although the initial results are encouraging, a great deal of research remains to be done before the utility of these devices can be accurately assessed.

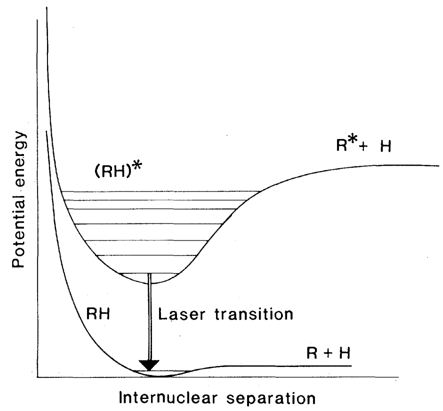


Fig. 4. Potential energy diagram for the interaction of a rare gas atom in its ground (*R*) and metastable excited (*R**) states with a halogen atom. The RH molecules formed through photon emission of the (*RH*)* excimer quickly dissociate because of the very low binding energy of the RH complex.

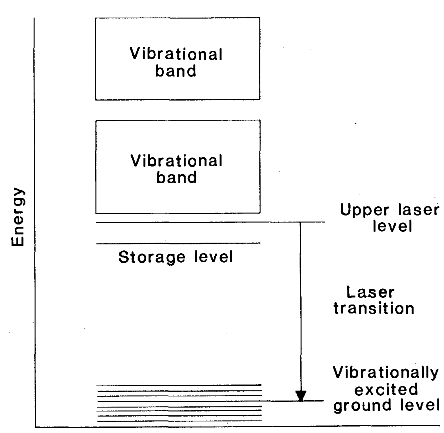


Fig. 5. Energy level diagram for the alexandrite laser. Laser operation is based on vibronic transitions of the chromium ion, in which both a photon and phonons are generated.

Rare gas halide lasers. Before 1976 there were few really good laser sources of ultraviolet radiation. Argon ion lasers, frequency-tripled or -quadrupled Nd:YAG lasers, and nitrogen lasers—all capable of a few watts of average power at selected wavelengths between 250 and 350 nm and overall efficiencies of a few tenths of a percent—were commercially available. All of these devices had size and cost problems associated with low efficiency, and high average power in the ultraviolet was difficult to achieve. In 1975 Setser and co-workers at Kansas State University showed that rare gas atoms in metastable excited states could react with halogen-bearing molecules to form diatomic rare gas halides in a bound excited (excimer) state (*10*). Decay of these excimer molecules to a weakly bound or unbound ground state was accompanied by emission of an ultraviolet photon. Typical potential energy curves for the rare gas–halogen interaction are shown in Fig. 4. Later research showed that rare gas halide excimers can also be formed through rare gas–halogen ionic reactions and that they can be produced with relatively high efficiency when a suitable gas mixture is subjected to electron impact excitation (*11*).

As a laser candidate the rare gas halides are particularly interesting since the very short lifetime of the ground state almost ensures population inversion and hence optical gain whenever the excited molecule is formed. This was recognized by a number of research groups, and by late 1975 lasers based on the bound-free transitions of the XeBr, XeF, XeCl, and KrF excimers had been demonstrated (*12, 13*). These lasers used electron beam irradiation of rare gas–halogen mixtures to produce coherent output at 282, 351, 308, and 249 nm. Subsequently, similar lasers using transitions in ArF (193 nm) and KrCl (222 nm) were demonstrated, and it was shown that they could also be excited by creating a self-sustained electrical discharge in the laser gas mixture. KrCl and XeBr typically exhibit lower power and efficiency than the other excimers and have received much less emphasis in development work.

For optimum operation, the composition of the excimer laser gas mixture is normally a few tenths of a percent halogen donor (NF_3, HCl, F_2, and so on), a few percent active rare gas species (Xe, Kr, or Ar), and a large percentage of a second rare gas used as a buffer. Total operating pressures usually lie in the range of 1 to 5 atmospheres. Self-sustained discharge excitation of the laser is desirable for most applications because of the greater simplicity and component reliability associated with that approach, but it is difficult to produce uniform discharges of long duration in gas mixtures of this type. Onset of discharge inhomogeneities typically limits laser pulse durations to a few tens of nanoseconds in discharge-excited devices, although pulses of 1 μsec have been produced with electron beam excitation. Dissociation of the halogen donor imposes an upper limit of about 1 μsec on the duration of pulses from any rare gas halide device.

Most excimer lasers excited by self-sustained discharge have overall efficiencies in the range 1 to 3 percent, although the ratio of laser pulse energy to energy deposited into the laser medium can be as high as 7 to 9 percent in KrF systems excited by electron beams (*11*). Average power levels in excess of 100 W are available from devices now on the market, and experimental systems capable of an average output as high as 1 kW have been explored. Rare gas halide lasers capable of pulse energies in the kilojoule range are also being investigated at some national laboratories (*14, 15*).

Maintenance-free operation of excimer devices has been difficult to achieve because of the use of reactive gas mixtures in the discharge, intense ultraviolet radiation on the optics, and the need for fast, repetitive, high-power excitation of the medium. In early systems, rapid gas degradation due to wall and electrode reactions terminated laser operation after a few thousand pulses, and replacement of the gas mixture was required for continued operation. After a few million pulses, switching components in the excitation system began to fail and windows and mirrors began to show optical damage. A great deal of development work has resulted in XeCl lasers that are much less susceptible to these problems and can be operated for tens of millions of pulses without appreciable attention. Rare gas fluoride lasers typically have a somewhat shorter maintenance period, however, because of the more reactive nature of the fill gases and products of the discharge.

Table 2 shows that sales of rare gas halide excimer lasers exceeded $14 million in 1983. Excimer laser technology has been rapidly introduced into the marketplace because of the demand for efficient, high-power, ultraviolet sources. Therefore continuing evolution of excimer laser technology should be expected.

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
Cr^{3+}	Alexandrite	701 to 818	Lamp	No
Cr^{3+}	Emerald	751 to 759	Lamp	No
Ni^{2+}	MgF_2	1630 to 1750	Laser	Yes
Co^{2+}	MgF_2	1500 to 2300	Laser	Yes
Ti^{3+}	Al_2O_3	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
	KBr	1700 to 2000	Laser	Yes
	KCl	1600 to 1900	Laser	Yes

Tunable solid-state lasers. Two of the earliest laser media—neodymium-doped yttrium iron garnet (Nd:YAG) and chromium-doped sapphire (ruby)—utilize transition metal ions doped into crystalline hosts. These sources, particularly Nd:YAG, have shown very broad utility. 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 fields. Thermal properties of the medium, which often constrain average output power or pulse repetition rate, are predominantly those of the host.

Both Nd:YAG and ruby lasers operate at a single, fixed wavelength. Wavelength tunability is possible with certain ion-host combinations. Some work on tunable solid-state lasers was initiated in the early 1960's, but there was little activity in this area until the mid-1970's, when an ambitious development program was initiated at Allied Corporation on $Cr:BeAl_2O_4$ (alexandrite) (*16*) and at the Massachusetts Institute of Technology Lincoln Laboratory on nickel, cobalt, and titanium ions in hosts such as MgF_2 and Al_2O_3 (*17*). These new crystalline media operate in the deep red or near-infrared and are similar to the well-developed Nd:YAG and ruby devices in that they must be optically excited by use of a flash lamp 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 (emission of a phonon). Figure 5 shows an energy level diagram for the alexandrite laser. 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-level states. The high density of vibrational ground states in vibronic laser systems allows partitioning of the total emitted energy between photon 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 (ratio of optical power out to electrical power in) is tightly constrained by the efficiency of generating suitable pump radiation. In addition, many of these devices must be cryogenically cooled for optimum operation. One device that does not require cooling is the alexandrite laser, which is marketed commercially by Allied. Flash lamp–pumped alexandrite lasers that are tunable over the range 700 to 820 nm with pulse energies in the range of joules and average output powers in excess of 100 W have been reported. Overall efficiency of alexandrite devices is typically 1 to 2 percent.

A second class of tunable solid-state lasers which has been extensively investigated over the past few years is based on the optical properties of color centers in alkali halide crystals (*18*). Table 3 summarizes the operating wavelengths and excitation and cooling requirements of several color-center lasers and some of the vibronic sources. As illustrated in Fig. 6, 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 band 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 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 processes, so that absorption by the crystal at the laser wavelength is small.

There are several types of color centers corresponding to various kinds of point defects. Although four different color-center types have been used in laser sources, some are relatively unstable and tend to bleach when stored at room temperature or subjected to intense optical excitation. However, the F_A (II) and F_B (II) centers in KCl and RbCl doped with lithium or sodium have been found to be thermally and optically stable and are now used in commercial devices. When pumped by a second laser at wavelengths in the range 500 to 700 nm, these media can produce tunable laser radiation over the wavelength band 2200 to 3300 nm. A number of other devices have been demonstrated which together cover the spectral region between 800 and 3650 nm, but these devices are not commercially available.

Color-center lasers typically convert 5 to 30 percent 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, they remain important sources of tunable radiation in a useful portion of the spectrum. Current research efforts in this area are directed toward identification of new types of color centers that have good thermal and optical stability and allow extended spectral coverage (*19*).

New Applications of New Source Technology

The new sources discussed in the preceding sections are expected to find a large array of applications; some of these are listed in Table 1, but others are less well developed. Several areas where new source technology may have an impact are reviewed below.

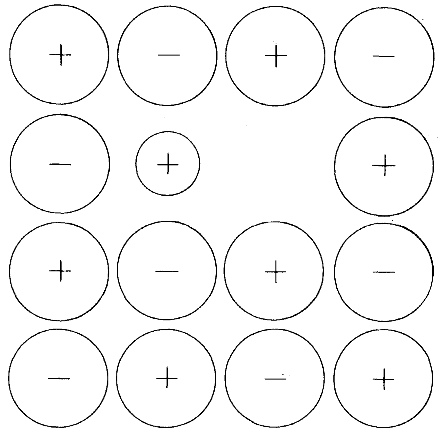


Fig. 6. Ionic configuration of an F_A(II) color center in an alkali halide crystal. A single electron is trapped at the point defect caused by the small impurity ion and an adjoining vacancy (*18*).

Robotics. The marriage of lasers and robots is a natural one, and it appears likely that the factory of the future will contain a variety of laser sources. Lasers can be used in sensing systems to provide robotic machines with three-dimensional vision and proximity sensing capabilities. Diode lasers and diode laser arrays are strong candidates for these applications because of their small size and low-voltage excitation.

High-power lasers can be used to cut, drill, weld, and surface-treat a number of common materials. Integration of a high-power source with a robotic manipulator results in a very versatile work station with a host of advanced materials-processing capabilities (*20*). Lasers with low capital and operating costs and average power production of 100 to 10,000 W at wavelengths in the infrared and visible will be needed for these applications. Carbon dioxide and Nd:YAG are probably the best current candidates. However, free electron lasers, if perfected and commercialized, have a potential market in this area. Excimer and alexandrite devices may find some specialized robotics-related applications when shorter wavelengths or specific pulse characteristics are required.

Photochemistry. A large number of laser applications involve the use of laser photons to initiate a photochemical reaction. For example, hematoporphyrin derivative photoradiation therapy of cancerous tissue, laser separation of uranium isotopes, and photochemical deposition of metal contacts on semiconductor substrates all involve laser excitation of a molecule which then undergoes chemical reaction. These applications often require the laser radiation in a narrow spectral band. Since many molecules absorb in the ultraviolet, the 1- to 4-μm, or 8- to 12-μm band lasers that operate in those portions of the spectrum are particularly desirable. Wavelength tunability is also needed if wavelength constraints are particularly stringent or if a single source is to be used for several different photochemical processes. Excimer lasers and free electron lasers are both potentially useful in photochemistry. Cost projections for free-electron lasers suggest that one that fulfilled its technical expectations would have low enough operating costs to allow its use in some bulk chemical processing (*7*). Excimer lasers are already being used in photochemical surface processing and selected bulk chemical synthesis and purification applications.

Line-of-sight data links. Short-haul atmospheric data links are expected to grow in popularity as the technology becomes better established. A laser transmitter broadcasting to an optical receiver can provide a simple and inexpensive means of transmitting data across freeways, railroad rights-of-way, and other obstacles that complicate use of conventional transmission lines. Similar links are also needed for satellite-to-satellite communications. For terrestrial links, lasers operating with a few watts of average power at wavelengths that are easily transmitted through the atmosphere are normally used, and GaAlAs diode laser arrays, with their small size and ease of modulation, appear quite suitable. It is interesting to note that InGaAsP diode lasers operating at 1.55 μm were recently developed for fiber optic communications. This wavelength lies in a good atmospheric transmission window and also lies beyond the 1.4-μm limit at which permissible eye exposure to laser radiation increases by several orders of magnitude. Combining InGaAsP diode laser technology with the diode array concept could result in a source with good output power which penetrates the atmosphere well and is relatively safe.

Remote sensing. One of the more sophisticated applications that is still in a relatively early developmental stage involves the use of lasers to remotely measure chemical composition, temperature, or pressure (*21*). Since spectroscopic techniques are nearly always involved, laser sources that are wavelength-tunable over the absorption bands of the species of interest are needed. Tunable lasers operating in the 1- to 4-μm band should be quite useful in remote sensing. For example, almost every hydrocarbon molecule absorbs at some wavelength in this band. Although foreseeable free electron lasers are likely to be too bulky to be practical in most remote sensing work, many of the new tunable solid-state sources may be useful for these applications.

Defense applications and inertial confinement fusion. Most current R & D on free electron lasers and excimer sources is funded for defense and inertial confinement fusion. Laser sources used in directed energy weapons must be capable of delivering extremely large amounts of energy to a distant target and must be of realizable size and reasonable cost. A variety of operating wavelengths have been considered. Current emphasis is on highly efficient deuterium fluoride sources operating in the 3.8- to 4.2-μm band, but near-ultraviolet wavelengths may be more desirable. Rare gas halide excimer lasers, particularly XeF, are being considered (*22*), and issues relevant to high-energy scale-up are being explored with federal support. Although free electron lasers are as yet experimentally unproved, their potential for high-efficiency, high-power operation has stimulated substantial R & D investment by the Department of Defense.

Inertial confinement fusion also requires high-power, efficient lasers, and short laser wavelengths are preferred. The greatest success has been achieved by using very high energy Nd : glass sources followed by harmonic conversion systems to produce high-power pulses in the green or ultraviolet. Free electron lasers may be useful for fusion, but excimer lasers are a more realistic near-term option (*15*). A large excimer device that will be capable of output energies of tens of kilojoules is being built at Los Alamos National Laboratory as a step toward exploring the utility of excimer systems for initiating fusion reactions.

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Fiber-Optic Sensors for Biomedical Applications

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The development of glass or plastic fibers a fraction of a millimeter in diameter for in vivo measurements is a relatively new and potentially important endeavor. Fiber-optic sensors can be as small as electrosensors and offer several advantages. A fiber-optic device is safe, involving no electrical connection to the body; the optical leads, very small and flexible, can be included in catheters for multiple sensing; and materials suitable for long-term implantation, such as plastic, can be used. At least some of the sensors are sufficiently simple in their design to be disposable. In the case of chemical sensors there are particular advantages in long-term stability and simplification of calibration because the measurement is equilibrium-based rather than rate- or diffusion-dependent and because the specificity of the measurement is achieved by chemical instead of physical means. Reversible, specific colorimetric and fluorometric reactions are available for most chemical and biochemical constituents of interest. Electrode development, although of intense interest for many years, has not lived up to expectations for wide applicability and reliability in vivo. Fiber-optic sensors are still too new to be of proven value in most applications, but their potential is considerable.

The concept is simple. Light from a suitable source travels along an optically conducting fiber to its end, where reflection or scattering of the light returns it along the same or another fiber to a light-measuring instrument, which interprets the returned light signal. The light emanating from the sensing end of the fiber may be reflected by a tiny transducer that varies the reflectance with some parameter of interest, the light may be backscattered by the medium into which the fiber is inserted, or the returned light may arise from luminescence of something at the end of the fiber that was energized by the illuminating light. The reflected or backscattered light may be spectrally altered by passage through an indicator reagent, providing a miniaturized spectrophotometric analysis. Likewise, fluorometry or other measurement uses of luminescence may occur at the fiber end. Fiber-optic sensing allows existing optical measurement techniques to be highly miniaturized and localized. A high degree of stability can be achieved by use of the ratio method, where part of the conducted light is not affected by the measurement variable, and so can be used to correct for other optical variations.

The instrumentation associated with fiber-optic sensors is optical as well as electronic, but the optics are simple and require only standard components such as light sources, detectors, filters, and lenses. Fiber-optic connectors are a well-developed commercial item. Light intensity measurements can be processed for direct readout by standard analog and digital circuitry or a microprocessor. Because of the relative simplicity of the instrumentation, the progress of this approach is limited only by sensor development.

Three general types of in vivo fiber-optic sensing have been developed: the photometric, or bare-ended fiber; the physical sensors, in which a transducer

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