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► **To cite this version:**

M. Weber. LASER SOURCES TODAY AND TOMORROW. Journal de Physique Colloques, 1987, 48 (C7), pp.C7-3-C7-11. 10.1051/jphyscol:1987701 . jpa-00226906

**HAL Id: jpa-00226906**

**<https://hal.science/jpa-00226906>**

Submitted on 4 Feb 2008

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## LASER SOURCES TODAY AND TOMORROW

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ABSTRACT - Properties of current gas, liquid and solid-state laser sources are surveyed briefly, including the prospects for their further development. Of particular interest are recent advances in semiconductor diode and tunable solid-state lasers and the expanding experimental activities in x-ray lasers and free electron lasers. Improved electron beams and periodic magnetic structures (wigglers, undulators) are technologies that free electron lasers share with advanced synchrotron radiation sources. The tunable, high-brightness, partially coherent radiation from the latter will also be useful for many applications.

Introduction

The quarter of a century that has passed since the advent of the laser has witnessed an astonishing proliferation in the number and types of laser sources (1). Stimulated emission is observed from all states of matter - gases, liquids, solids and plasmas. Today one can select laser sources covering the wavelength range from microwaves to soft x-rays, operating continuously or in ultrashort pulses approaching physical limits, and having output energies and powers for oscillator-amplifier systems extending to the multiple kilojoule and terawatt ranges. Efficiencies vary from the abysmal, for x-ray lasers, to  $\approx 50\%$  for semiconductor diode lasers. Spatially, laser beams can be diffraction limited; spectrally, fractional short-term linewidths of  $\sim 10^{-16}$  have been obtained. At low powers, diode lasers have extrapolated lifetimes of 100-1000 years. The volume of active lasing media can vary from about  $1000 \mu\text{m}^3$  to many  $\text{m}^3$ . Although the costs of lasers range from relatively inexpensive to expensive, mass-produced diode lasers can be very cheap whereas lasers for fusion research and defense can be extremely expensive. A number of laser extrema are given in Table I. It is an impressive list, one resulting from several decades of intense laser research and development.

TABLE I. Extreme values of various laser properties.

Property	Value
Wavelength	5 nanometers to microwaves
Pulse duration	femtoseconds to continuous wave
Peak power	>100 terawatts
Pulse energy	>100 kilojoules
Beam quality	diffraction limited
Spectral linewidth	40 mHz (for 1 second)
Operating lifetime	>100 years
Dimensions	micrometers to kilometers
Cost	several dollars to the gross national product (limit)

Today some areas of laser science and technology are mature, while others are still emerging. In the brief space available here, one cannot comprehensively review either present or future laser sources. I shall therefore necessarily be selective in the topics and laser sources discussed.

The wavelength ranges for laser action in various media are shown in Fig. 1. Gas lasers have by far the largest range - overlapping the region of microwave oscillators and masers (e.g., CO<sub>2</sub>-laser-pumped methyl bromide lasing at 2.7 mm) and now extending into the soft x-ray region. This large range involving rotational-vibrational transitions, outer-shell electronic transitions and inner-shell electronic transitions. Although there are some gaps in the coverage, there is nearly quasi-continuum coverage in most spectral regions. Using harmonic generation, frequency mixing and Raman shifting techniques, laser radiation is available throughout the optical region. The wavelength range of condensed matter lasers is much more restricted, being limited by phonon processes (infrared absorption edge and nonradiative de-excitation) at long wavelengths and by the fundamental absorption edge of the host at short wavelengths. Although some slight extension may be possible for solid-state and liquid lasers, the only important frontier for significantly extending the wavelength range of laser sources is the x-ray region and beyond to gamma rays. Amplification by stimulated emission is in principle possible in material media at picometer wavelengths.

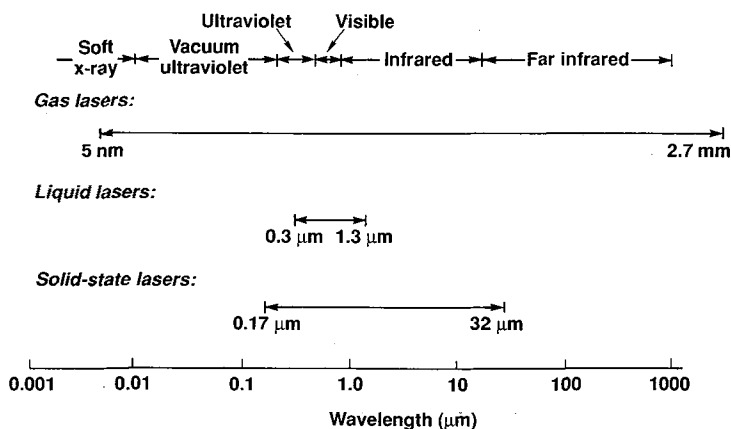


Figure 1. Wavelength ranges in which laser oscillation has been obtained for different media.

### Gas Lasers

Laser action has been reported for about 7000 electronic, vibrational and rotational transitions in neutral, ionized and molecular gas species. As can be seen from Fig. 2, the periodic table has been explored extensively for neutral and ion lasers, but not exhaustively; additional lasing species and transitions are therefore possible. However, out of the large number of known lasing gases, the number of useful, commercially viable sources is very much smaller. The principal commercial gas lasers are He-Ne and He-Cd (multiple lines), N<sub>2</sub>, CO<sub>2</sub>, ion (Ar, Kr) and excimer (ArF, KrF, XeCl, XeF); others of less general use including metal vapor (Cu, Au), iodine, chemical (HF, DF) and far infrared lasers. The current state-of-the-art and operating characteristics of these lasers are thoroughly surveyed in Ref. 2. Some of these lasers are technologically mature; for others one may anticipate further improvements in output power and pulse energy, efficiency and reliability (3).

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Li	Be											B	C	N	O	F	Ne																												
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Figure 2. Periodic table showing those elements (shaded) for which laser oscillation has been obtained from neutral atoms or ions in gases.

For many applications, gas lasers are being threatened by the emerging challenge of solid-state lasers which have undergone progressive and significant advances recently. Historically, vacuum tubes in electronics were replaced by solid-state devices; gas lasers in optical and optoelectronic systems may similarly be replaced by all solid-state lasers. Gas tubes continue to be used in numerous special electronics applications; gas lasers will undoubtedly play a similar role in optical applications.

### Liquid Lasers

Organic dye lasers, either laser-pumped or flashlamp-pumped, are used extensively in research and technological applications where their tunability and short-pulse characteristics are advantageous. Various families of dyes bridge the wavelength range from 0.3 to 1.3  $\mu\text{m}$  (1). As noted above, the possibility of extending this spectral range is limited. However, increasing the stability of the near-infrared dyes against photodegradation would be an important development.

Dye lasers are also threatened by advances in tunable solid-state lasers. Several crystalline paramagnetic ion and color center lasers having large tuning ranges in the visible-near IR regions have been identified and organic dye molecules have recently been incorporated into glasses with obvious lasing possibilities. Development of these lasers offers the attraction of no chemical preparation or dye circulation pumps and no risk of exposure to carcinogenic substances.

Inorganic liquid lasers were investigated in the mid-1960s through the mid-1970s. These included rare-earth chelates and rare earths in aprotic (non-hydrogen containing) solvents (1). The lasing possibilities of the former are limited by rapid nonradiative decay processes and the latter materials were frequently corrosive or toxic. Overall, prospects for these lasers were not promising and work on them has waned.

### Solid-State Lasers

The past several years have seen a renaissance of activity in solid-state lasers. This was evident in this year's CLEO Conference (4) and, to some degree, in this conference. The activity has been spurred by developments in semiconductor and insulating laser materials including high-power laser diodes and diode arrays, new tunable lasers, and more efficient pumping schemes for both small and large laser systems.

Semiconductor Lasers - These lasers illustrate both evolutionary and revolutionary advances resulting from improvements in materials, preparation methods, device structures, and operating techniques (5). Using molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD), quantum effects can be tailored in arbitrary forms of layered heterostructures (quantum well devices). This has resulted in AlGaAs diodes with CW output power  $>1$  W, phased diode arrays with outputs of tens of watts and intensities of several  $\text{kW}/\text{cm}^2$ , low-power diode efficiencies approaching 80% and diode array efficiencies of  $\sim 40\%$ , extrapolated lifetimes of 10-100 years at low power (3-5 mW) and modulation frequencies  $>16$  GHz at 300 K. Although these lasers operate in the near infrared, III-V compounds are already being developed for the 600-700 nm region and one can envision compound semiconductors eventually operating from the near-ultraviolet to the far-infrared.

Quantum well technology (6) with its ultralow threshold currents, possibility for wide spectral tunability, and device geometries appropriate for integrating optical and electronic structures is particularly promising and will make possible integrated optoelectronic circuits (IOEC) for communications and computers.

The increasing availability of diode lasers having high power, high efficiency, long lifetime, and low cost suggests that these will be the lasers of choice for the majority of applications. In addition to their use as a primary laser source, diode lasers are replacing lamps for pumping Nd:YAG and other solid-state laser materials (4). Simple, compact, robust diode-pumped Nd:YAG lasers with excellent mode control are already commercially available; with frequency doubling a Nd:YAG laser can produce blue, green and red outputs. Medium power (kW) solid-state lasers using slab geometries for efficient heat removal and high-power pulsed lasers for inertial confinement fusion research can also benefit from diode pumping. The requirements of the latter for 5-10 MJ of optical energy at a repetition rate of 5-10 Hz with an overall efficiency of  $>10\%$  now appears achievable (7).

Tunable Lasers - Tunable solid-state lasers based on phonon-terminated laser action is another area of revived interest (8). The demonstration of tunable laser action for  $\text{Cr}^{3+}$  in alexandrite has spurred the discovery of tunable  $\text{Cr}^{3+}$  lasing in low-field sites in crystals at wavelengths ranging from 0.7 to 1.1  $\mu\text{m}$ . Approximately the same spectral range has been covered by  $\text{Ti}^{3+}$ -doped  $\text{Al}_2\text{O}_3$ . Divalent V, Ni, Cu and  $\text{Ce}^{3+}$  provide tunable laser action in the region 1.1-2.5  $\mu\text{m}$  and around 0.3  $\mu\text{m}$ , respectively.

Semiconductor lasers (III-V and II-VI compounds and lead salts) cover the spectral region 0.33 to 32  $\mu\text{m}$  (1) and can be tuned by varying temperature, pressure or magnetic field. Glass lasers, because of inhomogeneous broadening of the emission, also offer some small ( $<10\%$ ) tunability.

Color center lasers generally have large tuning ranges (9); those based on  $\text{F}_2^+$  and  $\text{F}_A$  centers in alkali halides now span the range 0.8-4  $\mu\text{m}$ . Materials covering other spectral regions include  $\text{CaO:F}^+$  (350-420 nm), diamond: $\text{H}_3$  ( $\sim 500$ -600 nm) and sapphire (540-620 nm and 750-900 nm), however only isolated reports exist for these materials and further studies are needed.

Another possibility for tunable lasers arises from the ability to incorporate organic dye molecules into glasses using either sol-gel techniques or compositions having sufficiently low melting temperatures that dye decomposition does not occur. Work is currently underway on both of these approaches.

**Other Laser Possibilities** - Although paramagnetic ion lasers were among the earliest developed and a continued procession of new lasers has appeared, additional lasing possibilities exist. Elements that have lased as ions in solids are indicated on the periodic table in Fig. 3 and provide lasing from 0.17  $\mu\text{m}$  to  $\sim 5 \mu\text{m}$ . Hosts have included over 300 crystals, innumerable glasses, and glass ceramics (10). The number of commercial lasers is again very small (3). Transition and post-transition group elements are enclosed by bold lines in Fig. 3. Of the transition metals, several iron group ( $3d^n$ ) ions have lased; fluorescence from a number of palladium ( $4d^n$ ) and platinum ( $5d^n$ ) group ions is known, but only within the past few years has one of them been lased ( $\text{Rh}^{2+}$ ). Fluorescence also occurs from filled shell ions such as  $\text{Cu}^+$  ( $3d^{10}$ ). Although there have been several attempts to observe stimulated emission from  $\text{Cu}^+$  in crystals and glasses, there has been only one report of lasing to my knowledge. Many post-transition group ions having a  $ns^2$  electronic configuration (e.g.,  $\text{Sn}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Bi}^{3+}$ ) and molecular ion complexes (such as tungstates and vanadates) exhibit broad, intense fluorescence bands of interest for tunable lasers. In many cases deleterious excited-state absorption may prevent oscillation, but this remains to be quantified.

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H	IIA												III A	IV A	V A	VIA	VII	He																											
Li	Be											B	C	N	O	F	Ne																												
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Figure 3. Periodic table showing those paramagnetic elements (shaded) for which laser oscillation has been obtained in solids.

The rare earths, both divalent and trivalent ions, have been the most exploited elements for lasers because of their many excited states having long lifetimes and narrow emission lines (11). This year the series was completed with the lasing of  $\text{Pm}^{3+}$ . Most rare earths have lased on more than one transition; with selective excitation and cascade lasing schemes many, many more are possible and only remain to be demonstrated. Ions of the actinide series provide additional lasing possibilities, although less numerous and generally less attractive than the lanthanides (12). Coupled-ion systems involving various ion pairings result in new energy level schemes and other lasing possibilities.

### X-Ray Lasers

During the past three years lasing has been extended into the extreme ultraviolet and soft x-ray regions. The short lifetimes of inner-shell electronic transitions required the use of high-power, short-pulse lasers to create the necessary high temperature plasmas, selected ion densities, and population inversions (by collisional excitation and decay or recombination cascade processes). Lasing schemes have included 3p-3s transitions of neon-like ions ( $\text{Se}^{24+}$ ,  $\text{Y}^{29+}$ ,  $\text{Mo}^{32+}$ ), 4d-4p transitions of nickel-like ions ( $\text{Eu}^{35+}$ ,  $\text{Gd}^{36+}$ ,  $\text{Yb}^{42+}$ ) Balmer  $\alpha$  transitions of hydrogen-like ions ( $\text{C}^{5+}$ ,  $\text{O}^{7+}$ ,  $\text{F}^{8+}$ ) and 5f-3d transitions of lithium-like ions ( $\text{Ar}^{10+}$ ) (13). Preliminary results have been obtained for Ni-like Yb at 5.0 nm, the shortest wavelength laser to date (14). This is very close to the 2.3-4.4 nm "water-window" of interest for studies of biological materials.

The above lasers have used exploding foils and fibers as the amplifying medium and conditions of large single-pass gain because no mirrors were available for multipass operation. Recent developments in x-ray optics (15), such as x-ray mirrors based on synthetic multilayer structures, should make the use of resonant cavities, as for optical lasers, possible. (A double-pass amplifier has already been demonstrated (14).) This will open up the exploration of other materials and configurations having lower gain.

The use of higher Z elements and higher power lasers will lead to even shorter wavelength lasing. Lasers such as the 10-beam Nd:glass NOVA laser (7) should be sufficient to observe stimulated emission from W and Pb (14).

Beyond x-rays are gamma-ray lasers involving transitions between stationary states of nuclear isomers (16). Present efforts include nuclear spectroscopy to acquire the fundamental data on energy levels and other required characteristics of isomeric states that might be suitable for achieving stimulated emission. The rate of progress and eventual success are highly uncertain at present.

### Free-Electron Lasers

The past decade has been one of increasing activity on free-electron lasers (FEL) and progress toward the goals of high efficiency, high power and tunable radiation at variable wavelengths (17). Coherent radiation has been demonstrated from microwave to visible (525 nm) wavelengths. Efficiencies as high as 40% have been obtained at 8.6 mm; tapered wiggler magnets have increased the efficiency obtainable at shorter wavelengths. An understanding of wiggler magnetic field tolerances required to extend the technology to very long wigglers has also been obtained.

Free electron lasers involve the deflection of relativistic electrons from linear accelerators (induction or rf linacs), other accelerators and storage rings in various periodic magnetic fields. In principle they are scalable to any wavelength and lasing in the UV and VUV should be achievable soon. Optics capable of tolerating the powers generated and the synchrotron radiation that may be present are needed. Using microwave reacceleration of electrons to compensate for the gain reduction in tapered wigglers, conversion efficiencies in excess of 50% are theoretically possible.

Present FELs require large accelerators and radiation shielding, features which limit their attractiveness as a widely available tunable radiation source. The use of short-period electromagnetic wigglers could significantly reduce the electron beam energy required to reach the near-IR and visible spectral regions. Recently gyrotrons and high-power IR lasers have been proposed as wigglers for a FEL (4).

## Synchrotron Radiation

The next generation of synchrotron radiation facilities will have low-emittance electron beams and many straight sections for insertion devices (wigglers and undulators), thereby providing an alternative source of intense, tunable radiation from the infrared through the x-ray region for many applications (18, 19). These facilities share with FELs the requirements of high current and small electron beam divergence and the technology of periodic magnetic structures. High-gain FELs operating in the region of self-amplified spontaneous emission and with density modulation of the electron beam produce coherent synchrotron radiation; undulator radiation from synchrotron sources, in comparison, is usually an incoherent superposition of radiation from individual electrons.

Undulator radiation possesses many of the characteristics of laser radiation - high intensity, monochromaticity, directionality and coherence. It is highly directional with an angular divergence  $\sim 1/\gamma N^{1/2}$ , where  $\gamma$  is the electron Lorentz factor and where  $N$  is the number of periods of the magnetic undulator. The spectral bandwidth is  $\sim 1/N$ . Undulator radiation is partially coherent transversely due to finite electron-beam emittances. The longitudinal coherence length for fundamental radiation is  $\sim N\lambda$ . It can be shown (19) that the coherent power from an undulator is proportional to the beam current,  $N$ , and  $\lambda^3$  and inversely proportional to the electron beam emittances. Milliwatts of tunable, polarized, coherent power with a spatial coherence of  $\sim 1 \mu\text{m}$  should be readily achievable at 5 nm (19). However, because of the cubic dependence on wavelength, there is a rapid decrease in coherent power at shorter wavelengths.

Synchrotron radiation sources are frequently compared in terms of spectral brightness (photons/s-mm<sup>2</sup>-mrad<sup>2</sup>-0.1% bandwidth). On this basis future undulators will provide the same order of spectral brightness as the original Se<sup>24+</sup> XUV laser operating at 100 Hz (20). One must keep the intended application in mind and be careful when making such comparisons. For example, the repetition rate of XUV/x-ray lasers is presently a long way from the above assumed 100 Hz. In terms of peak spectral brightness, lasers should generally be orders of magnitude better than synchrotron sources (13, 20). If coherence length is important, lasers may again be superior because of their narrower linewidth. In addition, synchrotron radiation facilities are not laboratory sources, although efforts are underway to develop compact synchrotron sources for x-ray lithography and other applications. Thus many factors enter into the usefulness and cost effectiveness of laser versus synchrotron radiation photon sources.

## Concluding Remarks

Anticipating tomorrow's laser sources based on extrapolation is relatively easy; it is the unexpected - the surprises - that are unpredictable. The past year has witnessed an explosive growth of activity in superconductivity worldwide triggered by the discovery of high temperature materials. One may ask whether a similar development could occur in lasers.

By way of comparison, some historical milestones are compared in Fig. 4. A period of about 45 years passed between the discovery of superconductivity and a universally accepted theory; a similar period passed between the formulation of the concept of stimulated emission and Maiman's demonstration of the ruby laser. Whereas the BCS theory was followed by continued research and practical applications of superconductivity, but no significant increase in critical temperature until the past year, the ruby laser prompted a flurry of activity and a series of developments and advances that is still expanding. In this decade we may have already seen the beginning of a revolution (albeit in a quieter way and without the quantum jump that has



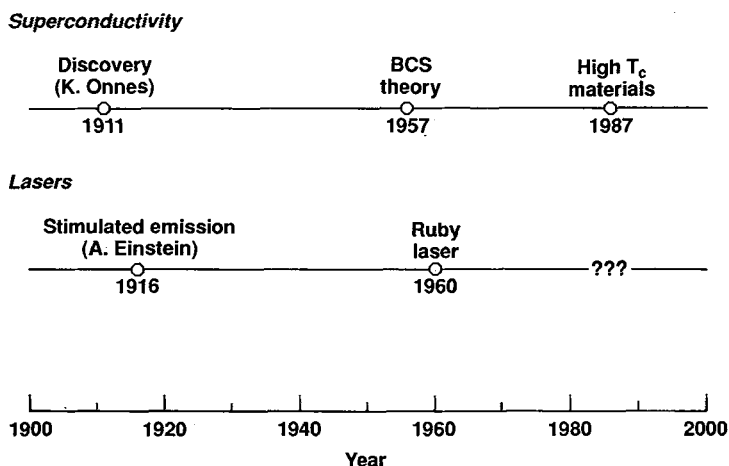


Figure 4. Important milestones in superconductivity and lasers.

occurred in superconductivity) in areas such as the production of quantum well structures and the realization of x-ray lasing. But are there other unexpected laser discoveries, say in energy storage or extraction mechanisms, that could have dramatic consequences? And what are they?

#### Acknowledgments

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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