[The Journal of the Iowa Academy of Science: JIAS](http://scholarworks.uni.edu/jias)

Volume 98 | Number Article 11

1991

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Jour. Iowa Acad. Sci. 98(2):79-81, 1991

The Future of Lasers and Laser Applications

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Lasers are increasingly used in an astounding variety of scientific, engineering, medical and commercial applications. Here the prospective improvements in lasers will first be addressed, e.g., improvements in wavelength range, tunability, pulse duration, efficiency, cost, etc.

Laser applications will then be briefly surveyed, including selected topics involving basic research, materials processing, analytical and diagnostic applications, information transmission and storage, measurement and alignment and photochemical and biomedical application.

INDEX DESCRIPTORS: Lasers, Laser Applications, Laser Science, Laser Engineering

The first laser was the fixed wavelength ruby laser built in 1960. Since then a tremendous variety of lasers has been conceived and constructed which can provide any wavelength in the visible and near visible (ultraviolet (UV) and infrared (IR) regions of the electromagnetic spectrum. Moreover, lasers can be on continuously (continuous wave (CW)) or pulsed. Pulse lengths can be milliseconds (ms), microseconds (μs), nanoseconds (ns), picoseconds (ps) and even femtoseconds (fs); and high pulse repetition rates (e.g. 10,000 pulses per second) are possible. Moreover, lasers are becoming increasingly efficient, inexpensive and user friendly. Consequently lasers are increasingly applied in science, engineering, medicine and commerce. The purpose of this article is to provide my personal perspectives on the evolution of both lasers and laser applications in the coming years, especially the next decade. I will not attempt in this brief article to provide literature documentation for these perspectives; however I list some useful references which cover recent advances in laser science[1], an interesting discussion of future directions based in part on a panel discussion entitled "Lasers, the Next Thirty Years" held at the American Physical Society's Fifth Interdisciplinary Laser Science Conference (ILS-V, Stanford, August 1989)[2], a National Research Council Report on important commercial applications,[3] a popular (but now slightly dated) survey of the entire field of lasers and their applications[4] and a popular survey of the closely related area of fiber optics.[5]

LASERS

Currently, the "workhorse" lasers used in laser science include, in order of decreasing wavelength, the carbon dioxide (CO_2) laser (10.6 μm), the neodymium yttrium aluminum garnet (Nd:YAG) laser (1.06 μm), the semiconductor diode laser (e.g. ~850 nm), the helium-neon (HeNe) laser (632.8 nm), the argon ion laser (e.g. 514.5 nm or 488.0 nm), and the excimer lasers (e.g. xenon chloride (XeCl) at 308 nm, krypton fluoride (KrF) at 248 nm and argon fluoride (ArF) at 193 nm). Convenient lasers for wavelengths further in the vacuum ultraviolet (VUV) remain to be developed, although some lasers have been built (e.g. fluorine at 157 nm). Shorter wavelengths are currently more conveniently generated by nonlinear optical techniques discussed below. Although eventually important lasers in the x-ray or even the gamma-ray regions may be developed, I do not expect them to impact laser applications in the 1990s. Longer laser wavelengths than10.6 μm are also not routinely available; such wavelengths are again more conveniently generated by nonlinear optical techniques.

A key aspect of lasers is, however, tunability. This provides an ability to match the laser wavelength to absorption or transmission wavelengths of the atoms, molecules or materials under study. The lasers discussed above are relatively fixed in wavelength (although high pressure CO_2 lasers are an exception). The current "workhorse" tunable laser is the dye laser. For example, a rhodamine 6G dye laser can change color continuously from yellow-green to yellow to yellow-orange to orange to red-orange to red. However, new solid state lasers in the deep red and near infrared (e.g. alexandrite and titanium sapphire) are beginning to be used in place of dye lasers, a trend I expect to accelerate in the 1990s.

A related aspect of lasers is wavelength extension by nonlinear optical techniques, e.g. harmonic generation, sum and difference frequency mixing, and Raman shifting. For example, a Nd:YAG laser at 1.06 μm in the IR is often frequency doubled (second harmonic generation) to 532 nm in the green. Third and fourth harmonic generation to UV wavelengths of 355 and 266 nm, respectively, is also common. Howver, solid state crystals appropriate for fifth or higher harmonics do not exist presently. New crystals such as beta barium borate (BBO) have been developed to push back the limits and I expect considerable improvement here in the 1990s. Sum and difference frequency mixing (which now requires two lasers of different frequencies) is similarly limited. Gases (e.g. mixtures of rare gases and metal vapors) can be used for such nonlinear wavelength extension into the UV and VUV, but at reduced conversion efficiency.

Raman shifting is another nonlinear optical wavelength extension method commony carried out by sending a laser beam with photons of energy $E_0 = h\nu_0$ into a cell of high pressure gas (e.g. hydrogen (H_2)). In such a case, new photons are generated with energies

$$E = E_0 + nh\nu_{H_2}$$

where $h\nu_{H_2}$ is the energy of the vibrational excitation of the H_2 molecule (~0.55 eV) and n is a positive or negative integer. Careful consideration of the nonlinear optics allows for significant conversion efficiency for even large n.

Using the above nonlinear techniques with a moderately tunable laser such as alexandrite, two harmonic generation crystals and four Raman cells with different gases, one can in principle cover the spectrum from the VUV to the far IR with only a single laser. I expect such flexible laser systems to appear in the 1990s and displace many of the multilaser dye-based systems in current use.

The vast range of laser pulse lengths down to femtoseconds has been alluded to above. In the 1990s, I expect fs pulses to be much more available for ultrafast studies. However, since one is approaching the ultimate limits for visible or near visible light (the shortest pulses generated are now virtually "white"), I do not expect attosecond (as) sources to be vigorously pursued unless significant breakthroughs occur in X-ray or gamma ray lasers. Note that already one can fairly readily sense the time scales (ps) on which atoms move chemically significant distances and one can approach the time scales (fs) on which electrons move atomic dimensions.

The big breakthrough in efficiency and cost has been the semiconductor diode laser. Based on extensions of semiconductor electronics technology, these primarily near infrared low power lasers are now

Table I. Some probable changes in lasers in the 1990s.

Area	Change
Wavelength coverage and tunability	• improved tunable solid state lasers • improved wavelength extension using nonlinear optics • simpler broad coverage laser systems
Pulse length	• improved femtosecond sources
Efficiency and cost	• improved electricity to light efficiencies • high power diode arrays • $1 lasers
Monochromaticity	• improvements upon 1 part in 10^{10}, 10^{15} for commercial, research lasers

setting electrical "wallplug" efficiency records (>70% at room temperature, >90% at cryogenic temperatures). No longer are lasers necessarily energy wasters, like the argon ion laser with ~0.1% efficiency. Moreover, they are now significantly superior to the best visible lamp (the low pressure sodium at 22% efficiency). While individual CW diode laser facets have recently approached 500 mW power levels, arrays of these lasers in the tens or even hundreds of watts level should become available in the 1990s. The diode lasers already exist at a wide range of near IR wavelengths, e.g. in the 700-900 nm range and near 1.3 and 1.55 μm (for optimal optical fiber transmission). Recently, red and even yellow (at 576 nm) diode lasers have been constructed. In addition, the diode lasers can be used to pump other lasers with high conversion efficiency, e.g. solid state lassers like Nd:YAG and alexandrite. Such diode pumped lasers may well be common as the 1990s end.

As the market for diode lasers grows explosively (~200 million/year currently, with an average cost of ~$3) for compact disc players, laser printers and telecommunication devices, new consumer applications such as lighting and display become economic and further price decreases and property improvements should occur.

Monochromaticity of lasers ($\Delta\nu/\nu = \Delta\lambda/\lambda$) is already commonly at the 10^{-6} = PPM level. Commercial single longitudinal mode tunable (and scannable) dye lasers are available with $\Delta\nu/\nu = 2 \times 10^{10}$ = 200 PPT. Ultranarrow diode laser frequency standards are stable to one part in 10^{+15}. I expect these frontiers will each be pushed forward in the 1990s.

In summary (Table I), my vision of laser development in the 1990s is increased quality, flexibility and increased emphasis on solid state devices.

LASER APPLICATIONS

Historically, the first important laser applications were in basic research, especially the physical sciences. To even list them now would be an ambitious undertaking.[1] Here I mention only a few of the most promising new areas (see also Table II):

1. Ultrafast Phenomena — Picosecond and now femtosecond lasers are providing fundamental information on the very fastest processes that occur for atoms, molecules and electrons, whether the process is electron-hole pair formation in semiconductors or visual photoreception on the retina.
2. Ultrasensitive Detection — Single atoms and small numbers of molecules can be detected by techniques such as laser-induced fluorescence and resonant multiphoton ionization.
3. Control of Atomic Motion by Lasers — Atoms can be cooled to microdegrees Kelvin (i.e. their velocity reduced to nearly zero), deflected, trapped, accelerated, focused and in general manipulation with lasers.
4. Optical Tweezers — Microscopic particles (e.g. single cells or even DNA strands) can be held or pulled around with strongly focused laser beams.
5. Ultraintense Electromagnetic Fields — To extend the domain of laser science from atoms, molecules and solids to nuclei and elementary particles, extremely high fields must be generated. Current fields exceed those within an atom; future fields will exceed the fields within a nucleus and will "break down" the vacuum by producing initially electron-positron pairs.
6. New Laser-Based Microscopies — The combination of high resolution and ultrahigh resolution microscopies (actually nanoscopies) such as scanning tunneling and field ionization microscopies with laser techniques promises a fascinating array of possibilities for observing events at the nm level.

The area of information applications in which information is transmitted, stored, read or otherwise manipulated is the most important commercial area of application. The new field of photonics[3] in which the fundamental particles of light, photons, are used in place of or in conjunction with the electrons of electronics, is at the heart of information applications. Although the speed of light is certainly important, the primary advantages of photons are that they do not interact with each other significantly at the intensities used in photonics and they come in a continuum of colors. Thus, on the one hand, parallel tasks are readily performed (e.g. large numbers of simultaneous Fourier transforms with a single lens) and, on the other hand, information transmission rates become astronomical compared to radio or microwave frequencies (a single fiber transmitting an Encyclopedia Britannica per second). A few highlights in this area would include:

1. Fiber Optic Rewiring[5] — Not only will long distance copper cables disappear, but even individual homes and cars will be wired with optical fibers.
2. Optical Data Storage — Fueled by the audio compact disc, optical data storage will increasingly displace other technologies.
3. Display and Illumination — As high efficiency, low cost diode-laser-based technology develops throughout the visible, diode-laser-based systems will be introduced which may ultimately displace the cathode ray tube.

Table II. Some probable areas of emphasis in laser applications in the 1990s.

General Area	Areas of Emphasis
Basic Research	• ultrafast phenomena • ultrasensitive detection • control of atomic motion • optical tweezers • ultraintense fields • laser-based microscopies
Information	• fiber optic rewiring • optical data storage • display and illumination • integrated photonic devices • neural simulation
Materials Processing	• nanofabrication • chemically assisted processing • photochemical synthesis • microsurgery
Measurement and Sensing	• on-line process control • failure prediction • preventive medicine

4. Photonic Devices — Optical analogs of electronic devices and hybrid electro-optic devices will be developed for a variety of applications, especially integrated devices employing semiconductor diode lasers.
5. Neural Simulation — Optical circuitry simulating the fault tolerant logic of the brain rather than digital computer logic will increasingly be studied and may find application.

In the area of materials processing, the use of lasers to cut, drill, weld, ablate and otherwise modify bulk materials is well known. The laser is particularly useful on the microscopic level where precision focusing is possible. Some expectations in this area:

1. Nanofabrication — Although it is difficult to focus lasers to spot sizes below 1 μm, the laser will be used in conjunction with higher resolution masks, nonlinear processes, laser control of atomic motion and laser-based microscopies to fabricate devices on the nanometer scale.
2. Chemically Assisted Processing — Increasingly cleverly designed additives (chosen for both their optical and chemical properties) will be used to etch, deposit, remove particles, weld and otherwise improve on purely physical fabrication techniques.
3. Photochemical Synthesis — The use of laser photons for synthetic chemistry was studied extensively in the 1970s and found to be economic only for fine chemicals such as isotopes and pharmaceuticals. The new diode-laser-based systems promise to significantly lower capital and operating costs and significantly revive this area.
4. Microsurgery — Lasers are extensively used already in microsurgery of many kinds, e.g. in Ophthalmology. I see rapid expansion in applications involving laser lithotripsy, laser angioplasty, biostimulation and selective laser phototherapies, often in combination with microsensing (see below).

The final application area is that of measurement and sensing. On the one hand, laser ranging in outer space and across earthquake faults is well established, while on the other hand, holographic and interferometric measurements sense nanometer displacements. Virtually any physical or chemical property can be sensed in virtually any environment through which some wavelengths of light can be transmitted; the Mizushima Oil Refinery in Japan uses exclusively spark-free optical fiber sensing and data transmission. Some highlights in this area:

1. On-line Process Control — Instantaneous feedback from on-line sensors, often in harsh environments, will increasingly be used for enhanced profit, energy efficiency, and environmental control. Ultimately, this will be not only in large industries, but also in products like automobiles.
2. Failure Prediction — Optical techniques for the anticipation of failure of components from aircraft wings to artificial heart valves will find increasing application.
3. Preventive Medicine — Ultrasensitive analysis of bodily fluids and tissues will provide evidence of the very early stages of many diseases.

CONCLUSION

Modern technology is based to a large extent on the understanding, control and pervasive application of electricity and on the understanding, control and pervasive application of information. We are now in an era when the understanding, control and pervasive application of light from lasers is at hand. The tremendous synergies among electricity, information and light imply great promise and excitement in the coming years.

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