Laser technology

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Laser technology during the 20th century is reviewed emphasizing the laser's evolution from science to technology and subsequent contributions of laser technology to science. As the century draws to a close, lasers are making strong contributions to communications, materials processing, data storage, image recording, medicine, and defense. Examples from these areas demonstrate the stunning impact of laser light on our society. Laser advances are helping to generate new science as illustrated by several examples in physics and biology. Free-electron lasers used for materials processing and laser accelerators are described as developing laser technologies for the next century.

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I. INTRODUCTION

Light has always played a central role in the study of physics, chemistry, and biology. Light is key to both the evolution of the universe and to the evolution of life on earth. This century a new form of light, laser light, has been discovered on our small planet and is already facilitating a global information transformation as well as providing important contributions to medicine, industrial material processing, data storage, printing, and defense. This review will trace the developments in science and technology that led to the invention of the laser and give a few examples of how lasers are contributing to both technological applications and progress in basic science. There are many other excellent sources that cover various aspects of the lasers and laser technology including articles from the 25th anniversary of the laser (Ausubell and Langford, 1987) and textbooks (e.g., Siegman, 1986; Agrawal and Dutta, 1993; and Ready, 1997).

Light amplification by stimulated emission of radiation (LASER) is achieved by exciting the electronic, vibrational, rotational, or cooperative modes of a material into a nonequilibrium state so that photons propagating through the system are amplified coherently by stimulated emission. Excitation of this optical gain medium can be accomplished by using optical radiation, electrical current and discharges, or chemical reactions. The amplifying medium is placed in an optical resonator structure, for example between two high reflectivity mirrors in a Fabry-Perot interferometer configuration. When the gain in photon number for an optical mode of the cavity resonator exceeds the cavity loss, as well as loss from nonradiative and absorption processes, the coherent state amplitude of the mode increases to a level where the mean photon number in the mode is larger than one. At pump levels above this threshold condition, the system is lasing and stimulated emission dominates spontaneous emission. A laser beam is typically coupled out of the resonator by a partially transmitting mirror. The wonderfully useful properties of laser radiation include spatial coherence, narrow spectral emission, high power, and well-defined spatial modes so that the beam can be focused to a diffraction-limited spot size in order to achieve very high intensity. The high efficiency of laser light generation is important in many applications that require low power input and a minimum of heat generation.

When a coherent state laser beam is detected using photon-counting techniques, the photon count distribution in time is Poissonian. For example, an audio output from a high efficiency photomultiplier detecting a laser field sounds like rain in a steady downpour. This laser noise can be modified in special cases, e.g., by constant current pumping of a diode laser to obtain a squeezed number state where the detected photons sound more like a machine gun than rain.

An optical amplifier is achieved if the gain medium is not in a resonant cavity. Optical amplifiers can achieve very high gain and low noise. In fact they presently have noise figures within a few dB of the 3 dB quantum noise limit for a phase-insensitive linear amplifier, i.e., they add little more than a factor of two to the noise power of an input signal. Optical parametric amplifiers (OPAs), where signal gain is achieved by nonlinear coupling of a pump field with signal modes, can be configured to add less than 3 dB of noise to an input signal. In an OPA the noise added to the input signal can be dominated by pump noise and the noise contributed by a laser pump beam can be negligibly small compared to the large amplitude of the pump field.

II. HISTORY

Einstein (1917) provided the first essential idea for the laser, stimulated emission. Why wasn't the laser invented earlier in the century? Much of the early work on stimulated emission concentrates on systems near equilibrium, and the laser is a highly nonequilibrium system. In retrospect the laser could easily have been conceived and demonstrated using a gas discharge during the period of intense spectroscopic studies from 1925 to 1940. However, it took the microwave technology developed during World War II to create the atmosphere for the laser concept. Charles Townes and his group at Columbia conceived the maser (microwave amplification by stimulated emission of radiation) idea, based on their background in microwave technology and their interest in high-resolution microwave spectroscopy. Similar maser ideas evolved in Moscow (Basov and Prokhorov, 1954) and at the University of Maryland (Weber, 1953). The first experimentally demonstrated maser at Columbia University (Gordon *et al.*, 1954, 1955) was based on an ammonia molecular beam. Bloembergen's ideas for gain in three level systems resulted in the first practical maser amplifiers in the ruby system. These devices have noise figures very close to the quantum limit and were used by Penzias and Wilson in the discovery of the cosmic background radiation.

Townes was confident that the maser concept could be extended to the optical region (Townes, 1995). The laser idea was born (Schawlow and Townes, 1958) when he discussed the idea with Arthur Schawlow, who understood that the resonator modes of a Fabry-Perot interferometer could reduce the number of modes interacting with the gain material in order to achieve high gain for an individual mode. The first laser was demonstrated in a flash lamp pumped ruby crystal by Ted Maiman at Hughes Research Laboratories (Maiman, 1960). Shortly after the demonstration of pulsed crystal lasers, a continuous wave (CW) He:Ne gas discharge laser was demonstrated at Bell Laboratories (Javan *et al.*, 1961), first at 1.13 μm and later at the red 632.8 nm wavelength lasing transition. An excellent article on the birth of the laser is published in a special issue of Physics Today (Bromberg, 1988).

The maser and laser initiated the field of quantum electronics that spans the disciplines of physics and electrical engineering. For physicists who thought primarily in terms of photons, some laser concepts were difficult to understand without the coherent wave concepts familiar in the electrical engineering community. For example, the laser linewidth can be much narrower than the limit that one might think to be imposed by the laser transition spontaneous lifetime. Charles Townes won a bottle of scotch over this point from a colleague at Columbia. The laser and maser also beautifully demonstrate the interchange of ideas and impetus between industry, government, and university research.

Initially, during the period from 1961 to 1975 there were few applications for the laser. It was a solution looking for a problem. Since the mid-1970s there has been an explosive growth of laser technology for industrial applications. As a result of this technology growth, a new generation of lasers including semiconductor diode lasers, dye lasers, ultrafast mode-locked Ti:sapphire lasers, optical parameter oscillators, and parametric amplifiers is presently facilitating new research breakthroughs in physics, chemistry, and biology.

III. LASERS AT THE TURN OF THE CENTURY

Schawlow's "law" states that everything lases if pumped hard enough. Indeed thousands of materials have been demonstrated as lasers and optical amplifiers resulting in a large range of laser sizes, wavelengths, pulse lengths, and powers. Laser wavelengths range from the far infrared to the x-ray region. Laser light pulses as short as a few femtoseconds are available for research on materials dynamics. Peak powers in the petawatt range are now being achieved by amplification of femtosecond pulses. When these power levels are focused into a diffraction-limited spot, the intensities approach 10^{23} W/cm^2. Electrons in these intense fields are accelerated into the relativistic range during a single optical cycle, and interesting quantum electrodynamic effects can be studied. The physics of ultrashort laser pulses is reviewed is this centennial series (Bloembergen, 1999).

A recent example of a large, powerful laser is the chemical laser based on an iodine transition at a wavelength of 1.3 μm that is envisioned as a defensive weapon (Forden, 1997). It could be mounted in a Boeing 747 aircraft and would produce average powers of 3 megawatts, equivalent to 30 acetylene torches. New advances in high quality dielectric mirrors and deformable mirrors allow this intense beam to be focused reliably on a small missile carrying biological or chemical agents and destroy it from distances of up to 100 km. This "star wars" attack can be accomplished during the launch phase of the target missile so that portions of the destroyed missile would fall back on its launcher, quite a good deterrent for these evil weapons. Captain Kirk and the starship Enterprise may be using this one on the Klingons!

At the opposite end of the laser size range are microlasers so small that only a few optical modes are contained in a resonator with a volume in the femtoliter range. These resonators can take the form of rings or disks only a few microns in diameter that use total internal reflection instead of conventional dielectric stack mirrors in order to obtain high reflectivity. Fabry-Perot cavities only a fraction of a micron in length are used for VCSELs (vertical cavity surface emitting lasers) that generate high quality optical beams that can be efficiently coupled to optical fibers (Choquette and Hou, 1997). VCSELs may find widespread application in optical data links.

Worldwide laser sales in the primary commercial markets for 1997 (Anderson, 1998; Steele, 1998) are shown schematically in Fig. 1. Total laser sales have reached 3.2 billion dollars and at a yearly growth rate of nearly 27% will exceed 5 billion dollars by the year 2000. The global distribution of laser sales is 60% in the U.S., 20% in Europe, and 20% in the Pacific. Semiconductor diode lasers account for nearly 57% of the 1997 laser market. Diode lasers in telecommunications alone account for 30% of the total market.

Materials processing is the second largest market with applications such as welding, soldering, patterning, and cutting of fabrics. CO_2 lasers with average powers in the 100 W range account for a large fraction of the revenues in this category. High power diode lasers with power output levels between 1 and 20 W and wavelengths in the 750 to 980 nm range are now finding a wide variety of applications in materials processing as well as ophthalmic and surgical applications, instrumentation and sensing.

Growth in medical laser applications is largely due to cosmetic laser procedures such as skin resurfacing and hair removal. A large fraction of medical lasers are still used in ophthalmological and general surgical applications. Frequency-doubled Nd:YAG lasers and diode la-

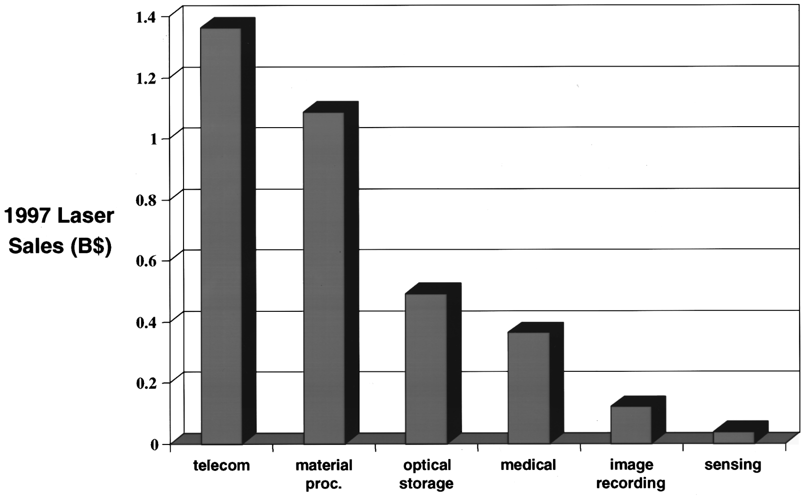

FIG. 1. World-wide laser sales in billions of dollars for laser markets in 1997.

ser systems are replacing argon-ion lasers in ophthalmology. New lasers, including the erbium-doped YAG laser, are being widely used in dermatology, dentistry, and ophthalmology.

Optical storage accounts for 10% of the market where one finds the lasers used in the compact disk (CD) players for both the entertainment and computer markets. The GaAs semiconductor laser at 800 nm wavelengths for these applications are manufactured so efficiently today that the laser costs are down to nearly $1 each. Over 200 million diode lasers, with wavelengths in the 750 to 980 nm range and powers of a few milliwatts, were sold for optical storage in 1997. The advent of digital video disks (DVDs) with 4.7 Gbytes of storage capacity and blue diode lasers (DenBaars, 1997) will lead to further growth in this field.

Image recording laser applications include desktop computer printers, fax machines, copiers, and commercial printing (Gibbs, 1998). Low power, single-mode diode lasers emitting at 780 to 670 nm wavelengths are being used in image recorders used to produce color-separation films with high sensitivity in this wavelength range. This laser-based color printing technology has combined with desktop publishing software to allow high quality page designs. Computer-to-plate technology is another important development in printing. A printing plate surface is directly imaged by exposing it with a laser beam instead of using film-based color separations. For example, photopolymer-coated plates can be exposed with frequency-doubled diode pumped Nd:YAG lasers at a wavelength of 532 nm. Most recently, thermally sensitive plates have been developed for use with near infrared patterning lasers.

Remote sensing laser markets include automotive collision avoidance, atmospheric chemical detectors, and air movement detection. Laser ranging is providing detailed elevation maps of the earth including land mass movements, biomass, cloud and haze coverage, and ice cap evolution. Laser ranging from satellites can achieve subcentimeter resolution of elevation features and land mass movement on earth. The Moon, Mars, and other planets are also being mapped by laser ranging. For the planets the measurement precision ranges between meters and centimeters. Detailed features of the ice cap on Mars as well as clouds near the edge of the ice cap have recently been mapped.

Laser applications in research, barcode scanning, inspection, art, and entertainment are small but significant markets. Lasers sold for basic research in 1997 accounted for 132 million dollars in revenues. Low power consumption, frequency-doubled diode sources emitting in the green at power levels near 10 W are being used as pump lasers for frequency tunable lasers like the Ti:sapphire laser and optical parametric amplifiers. Even a tabletop research laser can reach the petawatt peak power regime with large-volume optical amplifiers. These highly tunable, ultra short pulses are leading to advances in many research fields.

IV. LASERS IN COMMUNICATIONS

Laser light sources have revolutionized the communications industry. Voice communications increased the demand for information transmission capacity at a steady pace until the mid-1970s. The doubling time for transmission capacity during this period was approximately 8 years. The basic data rate was in the range between 10 and 80 kHz based on audio transmissions. During this period first copper wires and then microwaves were the primary communications technologies. Then in the 1980s an explosive information rate increase began, with data, fax, and images added to the information stream. The new technology of optical fiber communications using laser light sources was developed to keep pace with this new demand. The advent of the global Internet resulted in an even more surprising explosion in capacity demand. At the data source, computer terminals are used to access the Internet in homes and businesses around the world, resulting in data rates that are increasing exponentially. As workstation computer rates approach 1000 MIPS, fiber communication links to the computer in the 1000 Mb/sec range will be required. Note the coincidence of these rates and that both are increasing exponentially. It is clear that there will continue to be an exponentially increasing demand for information transmission capacity. In response to this demand, the information capacity on a single optical fiber during the past four years, between 1994 and 1998, has increased 160 fold in commercial systems from 2.5 Gbits/sec to 400 Gbits/sec. This amazing increase has been achieved by using up to 100 different laser wavelengths (dense wavelength division multiplexing, DWDM) on each fiber. The data rates at a single wavelength have increased from tens of Mbits/sec in the 1970s to 10 Gbits/sec at present, and 40 Gbits/sec will probably be in use before the turn of the century.

This information revolution is reshaping the global community just as strongly as the printing press revolution and the industrial revolution reshaped their worlds. Two of the basic technologies that support the information revolution are the semiconductor diode laser and the erbium-doped fiber optical amplifier. The low noise, high intensity, and narrow line widths associated with laser oscillators and amplifiers are absolutely essential to optical fiber communications systems. Wider bandwidth incoherent sources like light emitting diodes or thermal sources fall short of the needed intensities and spectral linewidths by many orders of magnitude.

Semiconductor laser diodes were first demonstrated in 1962 at GE, IBM, and Lincoln Laboratories as homojunction devices based on III-V materials. A history of these early diode lasers and references can be found in Agrawal and Dutta (1993).When the first heterojunction GaAs/AlGaAs room temperature, continuous wave diode lasers were operated in 1970 by Hayashi and Panish (Hayashi *et al.*, 1970) at Bell Labs and Alferov (Alferov *et al.*, 1970) in Russia, their lifetimes were measured in minutes. Diode laser reliabilities have increased dramatically since that time. Diode laser lifetimes at present are estimated to be hundreds of years, and the wavelength stabilities are greater than 0.1 nm over a period of 25 years. These amazing stabilities are necessary for the new DWDM systems with over 100 wavelength channels spanning 100 nm wavelength ranges. As the optimum wavelength for low-loss in silica fiber increased in wavelength from 800 nm to 1500 nm during the 1970s, diode laser wavelengths followed by evolving from GaAs to the InGaAsP system. During the late 1980s and early 1990s, quantum wells replaced the bulk semiconductor in the active optical gain region in order to enhance the laser operating characteristics. A schematic diagram of a present-day telecommunications diode laser integrated with an electro-absorption modulator is shown in Fig. 2. The overall dimensions are less than 1 mm. An elevated refractive index region and buried distributed feedback (DFB) grating, below the active quantum wells, defines the laser optical cavity and laser wavelength, respectively.

Fiber optic communication systems also rely strongly on the erbium-doped fiber amplifier developed in the late 1980s (Urquhart, 1988). These amplifiers have high gain, typically near 25 dB, and low noise figures near the 3 dB quantum noise limit for a linear phase-insensitive amplifier. The gain in these amplifiers can be equalized over bandwidths of up to 100 nm, covering nearly a quarter of the low-loss silica fiber window between 1.2 and 1.6 μm wavelengths. Optical fiber systems can be made "transparent" over thousands of kilometers using erbium-doped fiber amplifiers spaced at distances of approximately 80 km, where fiber losses approach 20 dB.

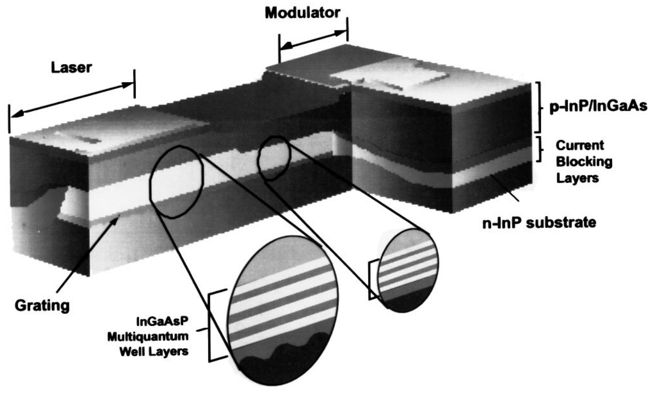

FIG. 2. A schematic diagram of a semiconductor laser diode with an electro-absorption modulator used in optical communications systems. (Courtesy of R. L. Hartman, Lucent Technologies)

As the century closes we are rapidly approaching fundamental physical limits for lasers, optical amplifiers, and silica fibers. Laser linewidths are in the 10 MHz range, limited by fundamental spontaneous emission fluctuations and gain-index coupling in semiconductor materials. The number of photons in a detected bit of information is approaching the fundamental limit of approximately 60 photons required when using coherent-state laser light fields in order to maintain an error rate of less than 1 part in 10^9. A bandwidth utilization efficiency of 1 bit/sec/Hz has recently been demonstrated. Optical amplifier bandwidths do not yet span the 400 nm width of the low-loss fiber window, but they are expanding rapidly. Fundamental limits imposed by nonlinear and dispersive distortions in silica fibers make transmission at data rates over 40 Gbits/sec very difficult over long distances. Optical solitons can be used to balance these distortions, but even with solitons fundamental limits remain for high bit rate, multiwavelength systems. The channel capacity limits imposed by information theory are on the horizon. It is clearly a challenge for the next centuries to find even more information transmission capacity for the ever-expanding desire to communicate.

V. MATERIALS PROCESSING AND LITHOGRAPHY

High power CO_2 and Nd:YAG lasers are used for a wide variety of engraving, cutting, welding, soldering, and 3D prototyping applications. rf-excited, sealed off CO_2 lasers are commercially available that have output powers in the 10 to 600 W range and have lifetimes of over 10 000 hours. Laser cutting applications include sailclothes, parachutes, textiles, airbags, and lace. The cutting is very quick, accurate, there is no edge discoloration, and a clean fused edge is obtained that eliminates fraying of the material. Complex designs are engraved in wood, glass, acrylic, rubber stamps, printing plates, plexiglass, signs, gaskets, and paper. Three-dimensional models are quickly made from plastic or wood using a CAD (computer-aided design) computer file.

Fiber lasers (Rossi, 1997) are a recent addition to the materials processing field. The first fiber lasers were demonstrated at Bell Laboratories using crystal fibers in an effort to develop lasers for undersea lightwave communications. Doped fused silica fiber lasers were soon developed. During the late 1980s researchers at Polaroid Corp. and at the University of Southampton invented cladding-pumped fiber lasers. The glass surrounding the guiding core in these lasers serves both to guide the light in the single mode core and as a multimode conduit for pump light whose propagation is confined to the inner cladding by a low-refractive index outer polymer cladding. Typical operation schemes at present use a multimode 20 W diode laser bar that couples efficiently into the large diameter inner cladding region and is absorbed by the doped core region over its entire length (typically 50 m). The dopants in the core of the fiber that provide the gain can be erbium for the 1.5 μm wavelength region or ytterbium for the 1.1 μm region. High quality cavity mirrors are deposited directly on the ends of the fiber. These fiber lasers are extremely efficient, with overall efficiencies as high as 60%. The beam quality and delivery efficiency is excellent since the output is formed as the single mode output of the fiber. These lasers now have output powers in the 10 to 40 W range and lifetimes of nearly 5000 hours. Current applications of these lasers include annealing micromechanical components, cutting of 25 to 50 μm thick stainless steel parts, selective soldering and welding of intricate mechanical parts, marking plastic and metal components, and printing applications.

Excimer lasers are beginning to play a key role in photolithography used to fabricate VLSI (very large scale integrated circuit) chips. As the IC (integrated circuit) design rules decrease from 0.35 μm (1995) to 0.13 μm (2002), the wavelength of the light source used for photolithographic patterning must correspondingly decrease from 400 nm to below 200 nm. During the early 1990s mercury arc radiation produced enough power at sufficiently short wavelengths of 436 nm and 365 nm for high production rates of IC devices patterned to 0.5 μm and 0.35 μm design rules respectively. As the century closes excimer laser sources with average output powers in the 200 W range are replacing the mercury arcs. The excimer laser linewidths are broad enough to prevent speckle pattern formation, yet narrow enough, less than 2 nm wavelength width, to avoid major problems with dispersion in optical imaging. The krypton fluoride (KF) excimer laser radiation at 248 nm wavelength supports 0.25 μm design rules and the ArF laser transition at 193 nm will probably be used beginning with 0.18 μm design rules. At even smaller design rules, down to 0.1 μm by 2008, the F_2 excimer laser wavelength at 157 nm is a possible candidate, although there are no photoresists developed for this wavelength at present. Higher harmonics of solid-state lasers are also possibilities as high power UV sources. At even shorter wavelengths it is very difficult for optical elements and photoresists to meet the requirements in the lithographic systems. Electron beams, x-rays and synchrotron radiation are still being considered for the 70 nm design rules anticipated for 2010 and beyond.

VI. LASERS IN MEDICINE

Lasers with wavelengths from the infrared through the UV are being used in medicine for both diagnostic and therapeutic applications (Deutsch, 1997). Lasers interact with inhomogeneous tissues through absorption and scattering. Absorbers include melanin skin pigment, hemoglobin in the blood, and proteins. At wavelengths longer than 1 μm the primary absorber is water. Dyes can also be introduced into tissue for selective absorption. For example, in photodynamic therapy hematoporphyrin dye photosensitizers that absorb in the 630 nm to 650 nm wavelength range can be introduced into the system and used to treat cancer tumors by local laser irradiation in the urinary tract or esophagus. Scattering in tissue limits the penetration of radiation; for example, at a wavelength of 1 μm scattering limits the penetration depths to a few millimeters. Scattering processes are being studied in the hope of obtaining high-resolution images for breast cancer screening. Laser interaction with tissue depends on whether the laser is pulsed or CW. Short laser pulses where no thermal diffusion occurs during the pulse can be used to confine the depth of laser effects. This phenomena along with selective tuning of the laser wavelength is used in dermatology for treatment of skin lesions and in the removal of spider veins, tattoos, and hair. Nonlinear interactions also play an important role. For example, laser-induced breakdown is used for fragmentation of kidney and gallbladder stones.

Since the interior of the eye is easily accessible with light, ophthalmic applications were the first widespread uses of lasers in medicine. Argon lasers have now been used for many years to treat retinal detachment and bleeding from retinal vessels. The widespread availability of the CO_2 and Nd:YAG lasers that cut tissue while simultaneously coagulating the blood vessels led to their early use in general surgery. The Er:YAG laser has recently been introduced for dental applications with the promise of dramatic reduction in pain, certainly a welcome contribution from laser technology.

Diagnostic procedures using the laser are proliferating rapidly. Some techniques are widely used in clinical practice. For example the flow cytometer uses two focused laser beams to sequentially excite fluorescence of cellular particles or molecules flowing in a liquid through a nozzle. The measured fluorescent signals can be used for cell sorting or analysis. Routine clinical applications of flow cytometry include immunophenotyping and DNA content measurement. Flow cytometers are used to physically separate large numbers of human chromosomes. The sorted chromosomes provide DNA templates for the construction of recombinant DNA libraries for each of the human chromosomes. These libraries are an important component of genetic engineering.

A new laser based medical imaging technique (Guillermo *et al.*, 1997) based on laser technology called optical coherence tomography (OCT) is achieving spatial resolution of tissues in the 10 μm range. Ultrasound and magnetic resonance imaging (MRI) resolutions are limited to the 100 μm to 1 mm range. The new high-resolution OCT technique is sensitive enough to detect abnormalities associated with cancer and atherosclerosis at early stages. The OCT technique is similar to ultrasound, but it makes use of a bright, broad spectral bandwidth infrared light source with a coherence length near 10 μm, resulting in at least an order of magnitude improvement in resolution over acoustic and MRI techniques. The source can be a super luminescent diode, Cr:forsterite laser, or a mode-locked Ti:Sapphire laser. OCT performs optical ranging in tissue by using a fiber optic Michelson interferometer. Since interference is observed only when the optical path lengths of the sample and the reference arms of the interferometer match to within the coherence length of the source, precision distance measurements are obtained. The amplitude of the reflected/scattered signal as a function of depth is obtained by varying the length of the reference arm of the interferometer. A cross-sectional image is produced when sequential axial reflection/scattering profiles are recorded while the beam position is scanned across the sample. Recent studies have shown that OCT can image architectural morphology in highly scattering tissues such as the retina, skin, the vascular system, the gastrointestinal tract, and developing embryos. An image of a rabbit trachea obtained using this technique coupled with a catheterendoscope is shown in Fig. 3. OCT is already being used clinically for diagnosis of a wide range of retinal macular diseases.

An elegant and novel optical technique using spin-polarized gases (Mittleman *et al.*, 1995) is being explored to enhance MRI images of the lungs and brain. Nuclear spins in Xe and ^{3}He gases are aligned using circularly polarized laser radiation. These aligned nuclei have magnetizations nearly 10^5 times that for protons normally used for MRI imaging. Xenon is used as a brain probe since it is soluble in lipids. In regions like the lungs, that do not contain sufficient water for high-contrast MRI images, ^{3}He provides the high-contrast images. One can even watch ^{3}He flow in the lungs for functional diagnostics.

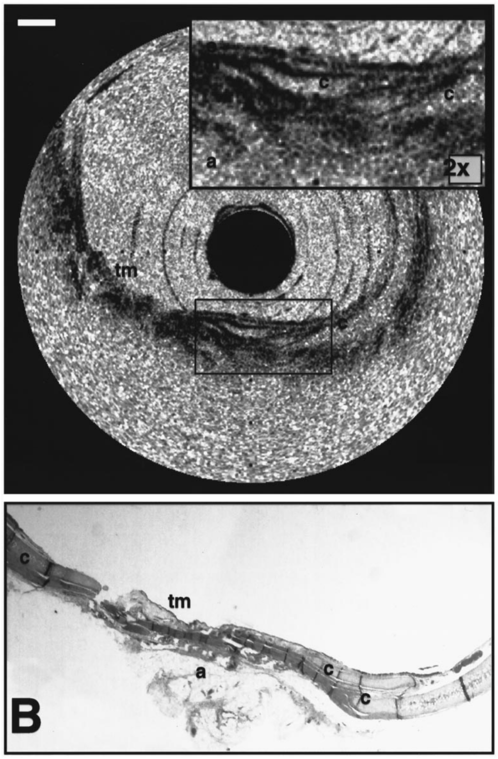

FIG. 3. Optical coherence tomography images of a rabbit trachea in vivo. (a) This image allows visualization of distinct architechtual layers, including the epithelium (e), the mucosal stroma (m), cartilage (c), and adipose tissue (a). The trachealis muscle (tm) can be easily identified. (B) Corresponding histology. Bar, 500 μm.

VII. LASERS IN BIOLOGY

Laser applications in biology can be illustrated with two examples, laser tweezers and two-photon microscopy. When collimated laser light is focused near or inside a small dielectric body like a biological cell, refraction of the light in the cell causes a lensing effect. A force is imparted to the cell by transfer of momentum from the bending light beam. Arthur Ashkin at Bell Laboratories (Ashkin, 1997) found that by varying the shape and position of the focal volume in a microscopic arrangement, a cell can be easily moved or trapped with these ‘‘laser tweezer’’ forces using light intensities near 10 W/cm^2. At these light levels and wavelengths in the near infrared, there is no significant damage or heating of cell constituents. Laser tweezers are now being used to move subcellular bodies like mitochondria within a cell (Sheetz, 1998). Tweezer techniques can also be used to stretch DNA strands into linear configurations for detailed studies. Two laser beams can be used to stabilize a cell and then a third laser beam at a different wavelength, can be used for spectroscopic or dynamic studies. Pulsed lasers are being used as ‘‘scissors’’ to make specific modifications in cell structures or to make small holes in cell membranes so that molecules or genetic materials can be selectively introduced into the cell.

Scanning confocal and two-photon optical microscopy are excellent examples of the contribution of laser technology to biology. Three-dimensional imaging of nerve cells nearly 200 μm into functioning brains and developing embryos is now a reality. Practical confocal micro-

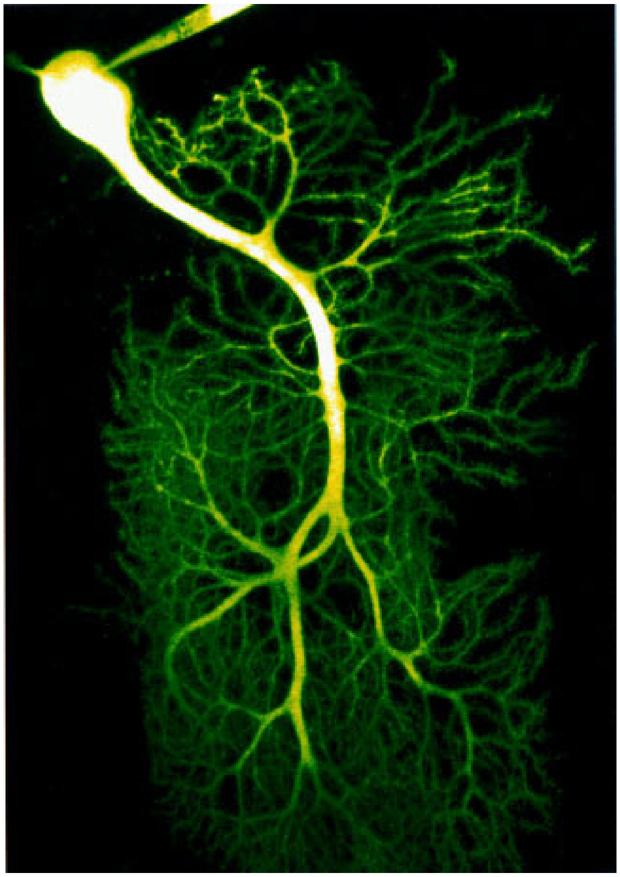

FIG. 4. (Color) Two-photon confocal microscope fluorescent image of a living Purkenji cell in a brain slice. The cell dimensions are of the order of 100 μm.

scopes came into wide use in the late 1980s as a result of reliable laser light sources. The resolution of the lens in a confocal microscope is used both to focus the light to a diffraction-limited spot and then again to image primarily the signal photons, i.e., those that are not strongly scattered by the sample, onto an aperture. Even though high-resolution 3D images are obtained, this single-photon scheme is a wasteful use of the illuminating light since a major fraction is scattered away from the aperture or is absorbed by the sample. In fluorescent microscopy, photodamage to the fluorophore is an especially limiting factor for single-photon confocal microscopy.

Multiphoton scanning confocal microscopy was introduced in 1990 and solves many of the problems of single-photon techniques. A typical two-photon microscope uses short 100 fs pulses from a Ti:sapphire mode-locked laser at average power levels near 10 mW. The high intensity at the peak of each pulse causes strong two-photon absorption and fluorescence only within the small focal volume, and all the fluorescent radiation can be collected for high efficiency. The exciting light is chosen for minimal single-photon absorption and damage, so that the two-photon technique has very high resolution, low damage, and deep penetration.

A beautiful two-photon fluorescent image of a living Purkenji cell in a brain slice is shown in Fig. 4 (Denk and Svoboda 1997). Neocortical pyrimidal neurons in layers 2 and 3 of the rat somatosensory cortex have been imaged at depths of 200 μm below the brain surface. Even more impressive are motion pictures of embryo development. Embryo microscopy is particularly sensitive to photodamage and the two-photon technique is opening new vistas in this field.

VIII. LASERS IN PHYSICS

Laser technology has stimulated a renaissance in spectroscopies throughout the electromagnetic spectrum. The narrow laser linewidth, large powers, short pulses, and broad range of wavelengths has allowed new dynamic and spectral studies of gases, plasmas, glasses, crystals, and liquids. For example, Raman scattering studies of phonons, magnons, plasmons, rotons, and excitations in 2D electron gases have flourished since the invention of the laser. Nonlinear laser spectroscopies have resulted in great increases in precision measurement as described in an article in this volume (Hänsch and Walther 1999).

Frequency-stabilized dye lasers and diode lasers precisely tuned to atomic transitions have resulted in ultracold atoms and Bose-Einstein condensates, also described in this volume (Wieman *et al.*, 1999). Atomic-state control and measurements of atomic parity nonconservation have reached a precision that allows tests of the standard model in particle physics as well as crucial searches for new physics beyond the standard model. In recent parity nonconservation experiments (Wood *et al.*, 1997) Ce atoms are prepared in specific electronic states as they pass through two red diode laser beams. These prepared atoms then enter an optical cavity resonator where the atoms are excited to a higher energy level by high-intensity green light injected into the cavity from a frequency-stabilized dye laser. Applied electric and magnetic fields in this excitation region can be reversed to create a mirrored environment for the atoms. After the atom exits the excitation region, the atom excitation rate is measured by a third red diode laser. Very small changes in this excitation rate with a mirroring of the applied electric and magnetic fields indicate parity nonconservation. The accuracy of the parity nonconservation measurement has evolved over several decades to a level of 0.35%. This measurement accuracy corresponds to the first definitive isolation of nuclear-spin-dependent atomic parity violation. At this accuracy level it is clear that a component of the electron-nuclear interaction is due to a nuclear anapole moment, a magnetic moment that can be visualized as being produced by toroidal current distributions in the nucleus.

Lasers are also contributing to the field of astrophysics. A Nd:YAG laser at 10.6 μm wavelength will be used in the first experiments to attempt detecting gravitational waves from sources like supernovas and orbiting neutron stars. These experiments use interferometers that should be capable of measuring a change in length between the two interferometer arms to a precision of one part in 10^{22}. A space warp of this magnitude is predicted for gravitational radiation from astrophysical sources. The terrestrial experiments are called LIGO (Light Interferometer Gravitational Wave Observatory) in the U.S. and GEO in Europe. A space-based experiment called LISA (Light Interferometer Space Antenna) is also in progress. The LIGO interferometer arms are each 4 km long. A frequency-stable, low noise, high-spatial-beam-quality laser at a power level of 10 W is required for the light source. Cavity mirrors form resonators in each interferometer arm that increase the power in the cavities to nearly 1 kW. Four Nd:YAG rods, each side pumped by two 20 W diode bars, amplify the single frequency output of a nonplanar ring oscillator from 700 mW to at least 10 W. Achieving the required sensitivity for detecting gravitational waves means resolving each interferometer fringe to one part in 10^{11}, a formidable, but hopefully achievable goal.

IX. FUTURE LASER TECHNOLOGIES

The free-electron laser and laser accelerators are examples of developing laser technologies that may have a large impact in the next century. The free-electron laser (FEL) is based on optical gain from a relativistic electron beam undulating in a periodic magnetic field (Sessler and Vaugnan, 1987). Electron beam accelerators based on superconducting microwave cavities are being developed at a new FEL center at Jefferson Laboratories. These accelerating cavities generate high fields in the 10 to 20 MeV/m range and allow very efficient generation of FEL light that can be tuned from the infrared to the deep ultraviolet with average power levels in the kilowatt range (Kelley *et al.*, 1996). At present a 1 kW average power infrared FEL is near completion and an upgrade to a powerful, deep-UV FEL is being planned. At these immense powers, a number of new technologies may be commercially interesting. Short, intense FEL pulses may allow rapid thermal annealing and cleaning of metal surfaces. Pulsed laser annealing may result in nearly an order of magnitude increase in hardness for machine tools. The high average FEL powers may be sufficient to make commercial production of laser-enhanced tools a reality. Another large market that requires high powers for processing of large volumes is polymer wraps and cloth. In this case intense FEL pulses can induce a wide range of modified polymer properties including antibacterial polymer surfaces that could be used for food wrappings and clothing with pleasing textures and improved durability. High average powers and wavelength tunability are also important for patterning of large area micromaching tools used to imprint patterns in plastic sheets.

Petawatt-class lasers may provide the basis for a new generation of particle accelerators. The frequency of microwave field accelerators being used at present will probably be limited by self-generated wakes to less than 100 GHz where the accelerating fields reach the 100 MeV/m range. Intense laser beams are being used to generate much higher fields in the 100 GeV/m range (Madena *et al.*, 1995). For example, one technique uses two laser beams whose difference frequency is tuned to the plasma frequency of a gas ionized by the laser. Accelerating fields as high as 160 GeV/m can be generated between the periodic space charge regions of the plasma wave. The propagation velocities of these gigantic fields can be engineered to match the relativistic velocities of the accelerated particles. Much work remains in order to achieve practical accelerators but proof of principle has already been achieved.

Developing laser technologies and their contributions to science are too numerous to cover adequately in this brief review. Laser communications between satellite networks, laser propelled spacecraft and laser fusion are additional examples of developing laser technologies. In the basic sciences there are many new experiments that are being enabled by laser technology including correction for atmospheric distortions in astronomy using laser reflections from the sodium layer in the upper atmosphere and studies of quantum electrodynamics using ultra-intense laser beams. Just as it was hard to envision the potential of laser technologies in the 1960s and 1970s, it seems clear that we cannot now envision the many new developments in lasers and their applications in the next century will see. Our new laser light source is sure to touch us all, both in our ordinary lives and in the world of science.

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