Civilian benefits of X-ray laser programs

by Charles B. Stevens

At the U.S. national laboratories today, scientists are perfecting a technology—the X-ray laser—that will revolutionize our lives. First, as the basis for a second-generation defensive beam-weapon system, the X-ray laser will provide America with near invulnerability against an all-out nuclear attack, thus ending the threat of nuclear holocaust.

Second, and perhaps even more momentous, X-ray lasers will give scientists the ability to see what goes on within living cells on the subatomic level, without killing the tissues, thus bringing biology and medicine a quantum leap forward. With X-ray lasers, researchers can make 3-D motion pictures of important biological processes such as the replication of DNA or the synthesis of proteins.

In addition, the same technology has broad-based potential applications for technology and industry, from the diagnosis of fusion shock waves as they propagate, to new methods of mining and processing, as well as the generation of entirely new materials.

Some of these important applications, discussed below, include X-ray lithography for the fabrication of microelectronic components, electron spectroscopy for chemical analysis, surface and radiographic nondestructive testing of metals, microradiography, radiochemistry, X-ray crystallography, and photonuclear processes.

How lasers work

Light amplification through the stimulated emission of radiation—or the *laser*, as the process is abbreviated—has existed only since 1960. However, the scientific principles upon which it is based emerged in the early part of this century as specific applications of the fundamental advances made possible by Bernhard Riemann's relativistic physics, set forth in a series of groundbreaking papers in the mid-19th century.

Specifically, there was the work of Max Planck, the early work of Albert Einstein on the interaction of matter with electromagnetic radiation or light, and the wave mechanics of Erwin Schrödinger, which he noted was inspired by Riemann's concept of the shock wave. Schrödinger's work permitted scientists for the first time to begin to comprehend the coherent structures found on a subatomic scale.

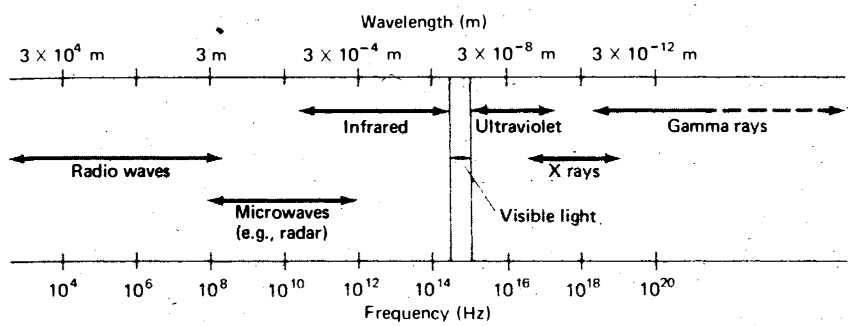
In the simplest terms, the laser is a machine that converts *incoherent energy* (light or heat or other electromagnetic radiation) into *coherent energy*, where the wavelengths are the same and the wave patterns are all traveling in step (in phase). The spectrum giving the range of electromagnetic energy by wavelength and wave frequency is shown in Figure 1.

The first systems to generate coherent electromagnetic radiation (see Figure 2), consisted of alternating current generators and electronic devices like vacuum tubes, which produced radiation at very long wavelengths. To generate the shorter-wave-length, high-frequency electromagnetic radiation, scientists have to manipulate electron motions on an atomic scale. In other words, they have to be able to access electron energy transitions within the atom itself.

Since 1960, when the first laser was created using a ruby rod, there have been many advances in laser technology. The next step, which is under way today in the national laboratories, generating X-ray radiation, involves extremely high-energy electron atomic transitions. And the next region of radiation frequencies, gamma rays, will involve energy tran-

Figure 1

Electromagnetic spectrum and the speed of electromagnetic waves



Electromagnetic waves are usually categorized as shown here, with the wavelength given at the top of the diagram in meters and the frequency along the bottom in hertz. Wavelengths at the low frequency, long wavelength end of the spectrum are the more familiar ones, such as those used to transmit radio and television signals wavelengths in the infrared range, which are mainly responsible for the heating effects of the sun. High frequency, short wavelengths—the X-ray and gamma ray range of the spectrum—are more difficult to produce but will revolutionize industrial processing, chemistry, and biology, and provide us with a defensive beam weapon system that will assure invulnerability from an all-out nuclear attack.

sitions on a nuclear scale.

All lasers consist of three elements: an *energy pump,* a *lasing medium* that the energy pump excites into activity, and a *host* material that maintains the lasing medium in a desired configuration during the lasing process.

Energy pumps can be flash lamps, electron beams, neutron beams, or even a laser beam itself—that are all external to the lasing medium. Or the energy pump can be a chemical or nuclear reaction that takes place within the medium itself. These pumps direct their energy into the lasing medium, which can be a gas, a liquid, or a solid, such as a special kind of glass.

In a gas laser, the host can simply be a bottle to hold the lasing gas, and in a solid laser, the host can be a slab of glass in which the atoms or ions (charged particles) of the lasing medium are embedded.

Once a significant portion of the atoms or electrons in the lasing medium are excited by the energy pump, they will begin spontaneously to emit electromagnetic radiation of a specific frequency. When this initial emission of light is continuously reflected back through the lasing medium using mirrors, it stimulates the remaining excited atoms to emit radiation coherently at the same frequency. This reflecting chamber is called the resonant cavity.

The initial laser beam can be extracted from the resonant cavity and amplified by passing the beam once through othe excited lasing mediums.

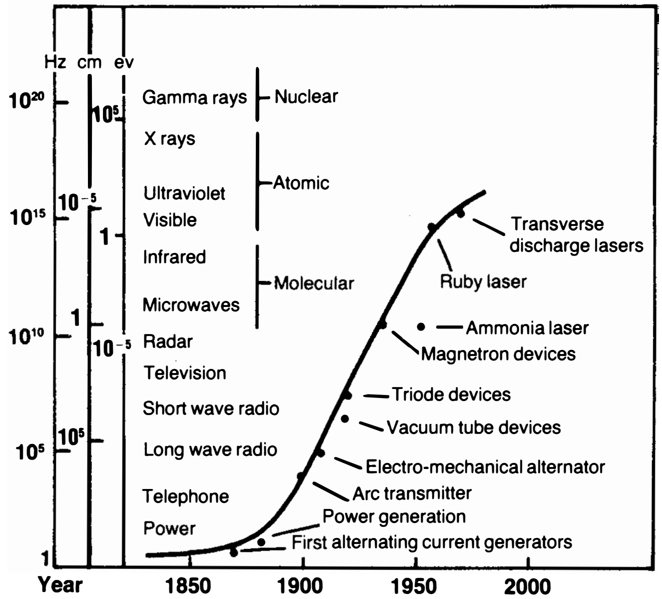
The next stage in the generation of coherent electromagnetic radiation is the X-ray laser, which will require a qualitatively new science and engineering. The shorter wavelength, higher-energy radiation of X-rays is harder to generate in a coherent form, but it provides much more penetrating power and better resolution.

The X-ray laser, in fact, makes possible the complete mastery of atomic and molecular processes. This is not only because X-rays have wavelengths comparable to the dimensions of the atom—any wavelengths larger than the atom is not capable of "seeing" it—it is also because X-rays have a high microscopic energy density that gives them an inherent capability of penetrating matter. As a result, biological specimens can be viewed *in situ* and *in vivo* without disrupting the ongoing life processes, which is not the case in ordinary optical and electrical beam microscopy. The X-ray laser will also revolutionize chemistry, allowing chemists to observe the interaction of atoms directly.

To provide a sense of how miniscule these X-rays are: conventional lasers operate in wavelengths ranging from 100,000 angstroms down to several thousand angstroms, while X-ray lasers operate in the range of hundreds of angstroms, down to 1 angstrom. An angstrom is one ten-billionth of a meter.

The next stage after the X-ray laser, the *gamma ray laser,* or *graser,* will extend this capability to the subatomic or nuclear scale, providing the key for unlocking the secrets of

Figure 2
Chronology of development of sources of coherent electromagnetic radiation



The points on the graph show the date of the first development of devices for generating coherent radiation in the range described in the list to the left of the graph line. The vertical axis, in three columns, shows the frequency (in hertz), the wavelength (in centimeters), and the photon energy (in electron volts). The development of infrared, visible light, and ultraviolet lasers increased the range of available frequencies of coherent radiation exponentially, a trend that will be continued with the development of X-ray and gamma-ray lasers.
Adapted from Baldwin, et. al, *Review of Modern Physics,* Oct. 1981.

nuclear structure and its interactions with atomic and electronic structures. The graser will also provide the unique means for directly or indirectly catalyzing nuclear energy transitions, which could lead to the creation of entirely new forms of generating nuclear energy. Theoretically, at least, the graser is projected as a direct energy source, because the nuclear transitions produced in the graser can generate more energy than the input pump energy used to catalyze them.

The full details of the status of X-ray laser development are being kept top secret at this time because of the military applications. However, it is possible from references made in the open scientific literature and published news stories in *Aviation Week* and *Laser Focus* magazines to establish the essential outlines of what is going on, as follows:

In December 1980, scientists from Lawrence Livermore National Laboratory in California used the intense incoherent X-ray output of a small nuclear explosion to demonstrate the scientific principles of an X-ray laser design. Although this highly expensive method of using a small nuclear explosion as the energy pump for an X-ray laser precludes its widespread application as a scientific diagnostic and industrial tool in the near term, many significant scientific investigations for civilian applications can be carried out as secondary experiments along with the military development tests.

Furthermore, advances in inertial confinement fusion, high-power lasers, particle beams, and magnetic fusion can provide alternative X-ray energy pump sources for the X-ray laser within the next five years, and these alternatives could make the X-ray laser sufficiently accessible and economical for general laboratory and factory use.

In fact, Livermore scientists are now carrying out experiments with the recently constructed Novette laser to generate a laboratory-scale X-ray laser, using experiments based on the concepts of Dr. Peter L. Hagelstein. The high power Novette laser is focused on a target and generates an intense burst of incoherent X-rays. This X-ray burst then hits a second target material that undergoes X-ray lasing.

The most immediate and far-ranging impact of X-ray laser diagnostics will probably occur in the microholography of living organisms. At present, the physical limitations of both optical and electron microscopy prevent observation of the most significant details of biochemical processes. Lasers permit recording of three-dimensional pictures of objects, which are called holograms. The resolution of these pictures is determined by the wavelength of the laser used. Since X-ray lasers operate with wavelengths down to one angstrom, the typical dimension of an atom, theoretically X-ray lasers will be able to make atomic-scale holograms.

X-ray microholograms will provide biological and medical researchers with their first atomic-scale pictures of what goes on within living cells. For the first time, man will be able to directly observe the structures and chemistry responsible for life itself. In order of magnitude, one can compare the potential of this to the development of the eye in biological evolution. Cancer and aging research, together with all aspects of disease and health care, will be revolutionized overnight. Genetic bioengineering will be catapulted from a hit-and-miss empirical field of research into a fully elaborated science.

These developments could emerge in the very near future, for, as noted above, many crucial experiments could be carried out in conjunction with existing weapons tests.

X-ray microholography will also revolutionize ordinary chemistry, both directly through the observation for the first time on an atomic scale of the phenomena involved, and indirectly through the application of the chemical principles learned by such minute observation of living processes.

Unleashing fusion energy

The X-ray laser can provide scientists working on the problem of fusion energy development with a crucial diagnostic tool. One of the principal avenues of experiment in fusion energy research is the method known as inertial confinement fusion. In this process, a small pellet of fusion fuel is subjected to heating and compression by bombardment from laser or particle beams, until the temperature and pressure is reached at which the atomic nuclei of the fuel pellet fuse together. This creates a new element, and an enormous release of energy.

Inertial confinement fusion is what occurs, in an uncontrolled fashion, in a hydrogen bomb. In that case, a small atomic explosion is used to set off the fusion process. The problem scientists have been grappling with is how to release this enormous energy in a controlled way, so it can be used to generate electricity and heat for industrial processes and residential users. The hope is that the X-ray laser will allow them to look inside the fuel pellet to see what is going on.

It is known that in the H-bomb, the fusion process is driven by a shock-wave compression of the fusion fuel. A portion of the radiation output of the trigger fission explosion is absorbed within a solid or plasma (superhot gas). At the same time, another portion of the radiation output irradiates the surface of this substance and generates a shock compression of the substance. As a result, the initial trapped radiation is compressed to an extremely high energy density.

This compressed radiation then irradiates an assembly of fusion fuel, resulting in high-intensity, ablation-driven compression of the fusion fuel. The shock wave acts to both increase the density of the fusion fuel, and generate a thermal spike in the center of the fusion fuel at the final stages of compression. This shock-created thermal spike is of sufficient intensity to ignite thermonuclear fusion.

Most of these phenomena can be observed indirectly, or, at best, seen with a resolution far short of that needed to capture the actual dynamics. The discrimination and penetrating capabilities of X-ray lasers will radically change this.

A revolution in mining

The use of the X-ray laser to study shock-wave propagation could have an immediate revolutionary impact on raw materials gathering, processing, and finishing. This potential application of X-ray laser diagnostics, however, is among the most highly classified ones.

As weapons scientists in particular have come to appreciate, the propagation of shock waves is not theoretically understood. As one senior researcher has described the situation: "We know what's going on in front of the shock and what's going on behind it. We don't know what's going on within the shock front itself. If you take the simple-minded Newtonian billiard ball model of molecules bouncing around in the shock front, you can't begin to explain the observed dynamics and effects of the shocks."

One example these researchers point to is the ability of a shock to generate entirely new materials. For example, when carbon is exposed to a shock wave generated by an H-bomb, a new substance, never before seen, is created. The substance has the crystalline structure of carbide tools in one direction and that of diamond in another. Because of the hardness of diamond and the thermal dissipation properties of carbide, these new materials could be extremely useful for micromachining metals and other materials.

X-ray laser diagnostics will permit researchers to observe shock-wave propagation on an atomic scale and with sufficient time resolution to capture all of the important dynamics.

There are currently indications that new types of coherent matter-energy interactions are taking place within shock fronts, particularly those of high amplitude and frequency.

With X-ray laser diagnostics, scientists could, for the first time, understand how to tailor shock waves to generate specific chemical transformations. A subsidiary aspect would be the forming and shaping of finished materials such as metals and metal shock welding.

The overall effect could be the rapid realization of entirely new, extremely efficient and cheap industrial processes; a sort of near-term *fusion shock torch*. First of all, such a shock torch with its high energy density will make possible the generation of entirely new families of materials. Second, raw materials could be directly processed with the minimum number of stages and facilities needed to obtain the finished material. For example, one could develop shock techniques for processing raw ores *in situ* right in the ground. Or one could mix the raw ore ingredients needed for some finished material and "shock process" them *in situ*. Alternatively, one could envision shock processing *in situ* to make desired elements more readily accessible to other processing technologies such as chemical leaching of ores.

Because shock processing does not appear to have any limits of scale, interplanetary mining and processing on a gigantic level would also be quite practical.

Although the full projection of the new miracle materials that could be generated with shock processing must await further analysis and declassification of existing capabilities, the projections made for metallic hydrogen give us some indications. It is currently projected that stable hydrogen metal can be formed only at extremely high pressures. Once understood, shock-wave processing could provide the unique means of generating metallic hydrogen. Current theory predicts that hydrogen metal will have stupendous physical properties, compared to existing metals: Hydrogen metal could be a superconductor at room temperatures, and it could provide an extremely lightweight, strong metal capable of withstanding both high and low temperatures.

Applied to chemistry, the X-ray laser will permit highly accurate electron spectroscopy, a technique used for chemical analysis. It will revolutionize research on chemical catalysis, metallurgy, and organic compounds. A further advantage of great potential significance is the possibility of exploiting the X-ray laser beam's small diameter in microprobe analysis. Such selected area electron spectroscopy could be applied to the analysis of fracture surfaces of high-strength alloys as two-phase composite materials.

Electron spectroscopy with X-ray lasers will affect all areas of materials research and production, including microelectronics, composite materials, ceramics, and alloys.

One of the most promising applications of the X-ray laser is in the production of printed circuits, a component of all modern electronic devices. Applied to the technique known as laser lithography, the X-ray laser would improve production rates and miniaturization by orders of magnitude.

X-ray laser lithography will permit the scale of microcircuit elements to be reduced from 1 micron to 0.1 microns. This closer element spacing—reduced line widths—allows for the incorporation of new physical processes, such as the Josephson junction. In the Josephson junction, self-organized quantum effects are utilized to mimic the function of transistors, vastly increasing the speed and the number of operations per unit energy used. The incorporation of other, new microprocesses along with the Josephson junction means that the 10-fold decrease in scale made possible by X-ray laser lithography can actually generate an exponential increase in the power of modern microchips.

In terms of production rates and quality assurance, the coherent and monochromatic nature of the X-ray laser radiation vastly improves microlithography as well. The general method of microlithography is to have a mask that incorporates the microcircuit design placed over a photosensitive material that is activated when a light source is shined on it. Using long wavelength and incoherent "light" sources causes penumbral blurring that makes it necessary to keep the mask in close contact with the photosensitive resist material. This means that the functional lifetime of the mask for multi-chip production is limited. Also, physical contact between the mask and resist leads to the introduction of defects in the finished printed circuit due to mask-resist sticking.

X-ray laser lithography would permit the use of a physical gap between the resist and mask, and would significantly increase the production lifetimes of masks and vastly decrease the introduction of defects.

In combination, these effects will add up to a new computer revolution over the course of the next decade, producing computer chips thousands of times more powerful and cheaper than existing units.

The graser

The gamma-ray laser, or graser, the next generation of laser after the X-ray, presents even greater possibilities for a defensive weapons system as well as for industrial processing.

The X-ray laser could provide the unique means of pumping such a gamma-ray laser, as pointed out by both U.S. and Soviet scientists.

If realized in a practical form, the graser would be an ideal directed-energy weapon. Its short wavelength and extremely high penetrating capabilities would make it an efficient disabler of nuclear warheads over million-mile ranges.

Scientifically, the graser will provide man with the unique means to observe the structure of the nucleus. As a result, entirely new forms of nuclear energy could be discovered, such as the possibility of catalyzing latent nuclear processes, or speeding up radiation decay.

To quote a leading U.S. laser scientist, Dr. John Rather: While serving as major deterrents to total war . . . such lasers can also provide mankind with major nonfossil energy options, a quantum leap ahead in opening space for massive human endeavors, and enormous new defense and commercial opportunities in remote sensing, communications, and photochemistry."