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Lasers

The intense, monochromatic, coherent light from these new sources shows many unfamiliar properties.

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In the last few years new light sources of enormous intensity and great spectral purity have become available. These new sources belong to the general class of molecular oscillators and amplifiers which make use of stimulated emission. Their principles of operation are based on those of the microwave amplifiers and oscillators known as masers. It is, thus, appropriate to use the term *maser* as a generic word, qualifying it by adjectives such as *infrared, optical,* or *ultraviolet* where appropriate. However, almost all masers operating in the infrared, visible, and ultraviolet regions of the spectrum make use of mode selection to provide a well-collimated beam of radiation. For such masers, the term *laser* is now commonly used.

There now exists a large and rapidly growing literature on lasers, including several books (*1*) and a considerable number of review articles (*2*). One abstracting service is now issuing cards on lasers and closely related subjects at a rate greater than 1000 per year (*3*). It is clearly impossible to summarize, or even list, all aspects of current laser research. Nor is it possible here to trace the complex history of the growth and development of this field. Instead, I shall merely describe briefly the general structures of lasers, and the resulting special characteristics of the radiation which they produce. This radiation differs in certain respects from ordinary light by many orders of magnitude. Its interaction with matter can, therefore, be very different from that of ordinary light. I shall discuss some aspects of these interactions, to illustrate some of the novel ways in which laser light might be used. Specific applications will be discussed, however, only as they serve to illustrate the phenomena.

Ordinary light sources, whether tungsten filament lamps, flames, gas-discharge tubes, or even the sun, are essentially hot bodies. That is, they have some source of energy which excites the individual electrons, atoms, or molecules. An atom in an excited state can deliver this excitation by spontaneously emitting a light quantum, and thereby making a transition to a state of lower excitation. It may again become excited, and again emit radiation. In any light source there are enormous numbers of atoms, and each of them becomes excited and radiates independently. Moreover, the atoms can emit radiation with a range of different frequencies, or even a continuum of wavelengths.

Thus, the light from any conventional source is a jumble of waves from separate atoms. Since the atoms act quite independently, there is no correlation between the phases of light from different parts of the source. From every part of the source, light spreads out in all directions. In contrast to this, a plane wave, which propagates in a single direction, has spatial coherence. The wave fronts are planes of constant phase perpendicular to the direction of propagation. If the plane wave is passed through a converging lens it remains coherent, but the wave fronts become spheres centered on the focal point.

One can get an approximately plane wave from an ordinary light source by placing a small aperture some distance away from it. Only waves traveling in the selected direction can pass from the source through the aperture. One achieves some spatial coherence in this way, at the cost of excluding most of the light. More of the light can be made into a directional beam by using a lens or mirror very much larger than the source. This is the method used in a searchlight. It achieves collimation at the expense of spreading the radiant energy over a broad beam, so that the energy density is lower than it is near the source. Similarly, somewhat greater monochromaticity can be achieved by passing the light from a conventional source through a narrow band filter. The light which lies outside the filter pass band must be rejected, so that monochromaticity is obtained at the expense of intensity.

At radio frequencies, however, we are accustomed to use electronic oscillators, which generate output at an almost pure single frequency. The output of an oscillator has a high degree of time coherence, in that the wave crests follow each other at regular intervals. This time coherence is largely lacking in conventional light sources, where the periods and phases of the waves fluctuate rapidly.

In a laser we obtain light that has a high degree of space and time coherence. We do this by forcing the individual atoms to synchronize their radiations, even though these atoms may be thousands or even millions of wavelengths apart. This synchronization is provided by stimulated emission of radiation. Stimulated emission can occur whenever there are atoms in an

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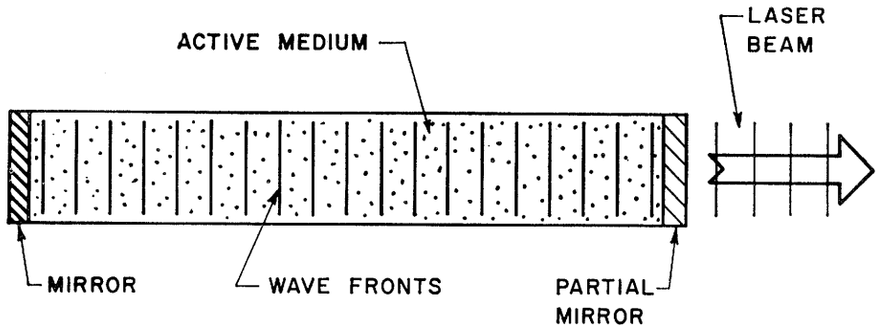


Fig. 1. Basic structure of a simple laser.

excited state. Then radiation of the proper frequency, corresponding to a transition between this state and some lower one, can stimulate emission at the same frequency. The excited atom thereby makes a transition to the lower state and delivers its energy to the wave. Moreover, the stimulated emission takes place at the frequency of the incoming wave, and with the proper phase to augment the incoming wave. Thus, if the medium contains only excited atoms, a wave grows as it passes through the medium. This process is a true negative absorption, and, if the medium is free from gross scattering imperfections, the wave grows without changing its shape or losing whatever coherence it possesses.

On the other hand, if there are atoms in the lower state, they can absorb energy from the wave. This absorption competes with amplification by stimulated emission. Whenever atoms in the lower state outnumber those in the upper state, absorption predominates. This is the case for most materials under most conditions, where some absorption of light is the rule and stimulated emission is negligible.

For substances in thermal equilibrium, there are always more atoms in the lower states and progressively fewer and fewer in excited states, whatever the temperature. Thus, substances in equilibrium may emit light spontaneously, and they may absorb light, but they never show amplification by stimulated emission. However, light sources by their very nature are not really in thermal equilibrium, as they are continually losing energy by radiation and replacing it from some source such as electricity or chemical reactions. Most light sources are not far enough from thermal equilibrium for amplification to occur, but it is now known to be surprisingly easy to get amplification by stimulated emission from electrical discharges through gases. As a rough general rule, when the discharge is more violent, conditions are farther from equilibrium and amplification occurs more strongly and at more wavelengths. Amplification by stimulated emission has now been obtained at many wavelengths in the infrared, visible, and ultraviolet portions of the spectrum. Gaseous, liquid, glass, and crystalline materials have been used. Nevertheless, absorption remains the rule in nature, and stimulated emission is exceptional. The discovery of new laser materials and of their operating conditions still requires considerable ingenuity and understanding of atomic physics.

While such an amplifying medium will preserve the coherence of a light wave, something more is needed to produce a really coherent light wave. To make a coherent oscillator from these excited atoms, one encloses them in a resonator of some kind. Then, although the resonator may be somewhat leaky and allow some light to escape, a portion of the wave is retained, and it stimulates further emission in the same phase. Thus, phase is preserved from moment to moment, and the independently excited atoms are stimulated to contribute to a coherent wave. This is the principle of the maser oscillator, as it was conceived in the early 1950's by C. H. Townes, and independently by N. G. Basov and A. M. Prokhorov. Like any other oscillator, the maser oscillator starts with some random pulse from noise or spontaneous emission. This starting pulse is amplified and some of it is retained in the resonator to control the phase of oscillation at all subsequent times.

In the microwave region, the enclosure is usually a box whose dimensions are comparable with the wavelength—that is, a few centimeters. Such a cavity resonator can be designed so that only one mode of oscillation can be sustained in it. For the optical region the wavelength is some ten thousand times shorter, and resonators are used whose dimensions are much greater than the wavelength. However, it is still possible to construct these resonators to favor one particular mode of oscillation, out of the very many modes which could occur in such a large resonator. The arrangement most commonly used consists of two small mirrors facing each other at a distance that is large compared with their diameter. The space between the mirrors contains the active medium (Fig. 1). Such an arrangement is a good resonator only for waves which travel along its axis, or very nearly so. Other waves, whose direction of propagation is inclined to this axis, are lost from the system without being reflected, or after only a few reflections, and so do not remain in the active medium long enough to be amplified much. The end mirrors, which may be either flat or slightly concave, are partly transparent, so that part of the light escapes through one or both of them. This light emerges as an extremely directional beam, and thus has a very high degree of spatial coherence. The beam is relatively powerful, because the atoms are stimulated to emit much faster than they would emit spontaneously. Moreover, since a portion of the wave in the resonator is always retained, stimulated emission continues to follow its phase. Thus, the output has time coherence, and is very nearly monochromatic. In practice, lasers sometimes produce coherent output at several different wavelengths simultaneously, although the number of different wavelengths can be reduced by further refinements when necessary. In any event the number of separate frequencies in the laser output is much smaller than the number that would be emitted spontaneously.

Thus, one would expect lasers to be much more powerful, directional, and monochromatic than ordinary light sources, and they are. When collimation is the prime requirement, lasers can be constructed to give a beam whose divergence is only that imposed by diffraction at the output aperture. Some lasers run continuously, and they have been constructed to have short-term stability as good as one part in 10^{13}, with long-term reproducibility of one part in 10^{9}. Others give very high peak power—as much as 10^{9} watts in

short pulses. Some lasers are fairly efficient, converting as much as 25 percent of the electrical input into coherent light. Lasers have generated wavelengths as short as the ultraviolet (0.34 micron) and as long as the far-infrared (337 microns), but not all wavelengths between these limits. With auxiliary devices, pulses of coherent light even farther in the ultraviolet have been produced, and coherent microwaves have been generated. Some lasers can be tuned over a frequency range as large as about 1 percent of the laser frequency—that is, through a range of more than 10^{12} cycles per second.

However, we are considering here a large family of lasers, and no one laser has all of these properties. Let us, therefore, look briefly at the several classes of lasers, to see what properties can now be obtained or expected from each. This survey is intended to give some guidance as to what sort of laser might be usable for a given scientific application. Nevertheless, even within the class of, say, optically pumped solid lasers, there is a wide range of properties. Some of them give enormous power output, while others barely reach the threshold of oscillation. Thus, a rather detailed study is still often needed to see whether a suitable laser can be found with a given wavelength, power output, and spectral purity.

Optically Pumped Lasers

The optically pumped laser was analyzed first (*4*, *5*) because its properties could be calculated most easily. The first operating laser, constructed by T. H. Maiman in 1960, was of this type (*6*). It used pink ruby—that is, an aluminum oxide crystal containing about 0.05 percent of chromic oxide. The chromium ions in ruby have broad absorption bands, so that light over a broad range of wavelengths can be absorbed to produce excited ions. Rather high light intensities are required to reach the threshold of operation, and the pumping light is ordinarily a pulsed-flash gas-discharge lamp. Continuous operation of a ruby laser has been attained by using a high-pressure mercury lamp as pumping source in an ingenious configuration (*7*).

Many optically pumped laser systems are now known. While the list includes some that use gases and liquids, almost all optically pumped lasers use solids containing rare-earth or transition-metal ions. These ions have at least some energy levels which are moderately insensitive to fluctuations in their surroundings, so that their spectra contain fairly sharp, strong, optical emission lines suitable for laser use. Pumping is provided by light from a very bright lamp, some of which is absorbed and excites atoms to the upper energy level. In most of the useful materials, pumping light can be absorbed in a number of bands which produce excitation to levels above the emitting energy level. Atoms in these higher levels very quickly give up their excess energy to the solid, and accumulate in one or a few states from which optical emission occurs.

At least 13 different ions have been used for lasers, some of them in several host materials. The output wavelength is determined primarily by the ion, but it is altered to some extent by such factors as the host crystal, the concentration, and the temperature. In some materials, laser action has been achieved at several wavelengths. Thus, in pink ruby (about 0.05 percent Cr_2O_3 in Al_2O_3) at room temperature, it is achieved at 6943 angstroms. On cooling of the crystal to liquid-nitrogen temperature, the output wavelength shifts to 6934 angstroms (*8*). With higher chromium concentrations, output can be obtained alternatively or simultaneously at this wavelength and at 7009 or 7041 angstroms (*5*, *9*).

Of these materials, ruby has been the most studied and used. Neodymium-doped glass has also been extensively investigated. Both these materials are used most for high-power pulsed operation. Both ruby and neodymium-doped–glass lasers have been made in fairly large sizes, and output flashes of up to 1000 joules or so in about 1 millisecond can be obtained from either.

Both materials have been used in continuous-wave (c.w.) operation, although some other substances require lower threshold pumping power. Neodymium-doped calcium tungstate crystals were the first to give sustained continuous-wave laser operation at room temperature (*10*).

If one wishes merely a beam of high intensity for a short flash, it is natural and still the best practice to look to solids, and in particular to neodymium glass or ruby. A typical output power from a small pulsed ruby laser might be of the order of a few kilowatts, although, with especially intense flash lamps, up to 200 kilowatts have been produced (*11*). Still higher peak powers can be obtained by the "Q-switching" or "Q-spoiling" technique first proposed by R. W. Hellwarth (*12*). In this scheme, at least one of the mirrors is detached from the laser rod, so that a shutter can be interposed between the rod and the mirror. When the pumping light flash begins, the shutter is closed, so that light cannot be reflected back to the rod. The resonant cavity is effectively broken, and its quality factor, Q, is spoiled. Thus, laser oscillations cannot begin, even when the pumping lamp has provided a considerable excess population in the upper energy state. After this is achieved, the shutter is quickly opened, and the cavity Q is restored. The amplification available is then much more than sufficient to start laser oscillations, and the stored energy is delivered in one giant pulse with a duration of a few nanoseconds. Peak powers in the range of 10 to 100 megawatts are obtained by various Q-switching techniques. Among the devices currently in use for Q-switching are electro-optical shutters, rapidly rotating mirrors or reflecting prisms, and bleachable absorbers.

Still higher peak powers have been achieved by passing the Q-switched oscillator output through a traveling-wave laser amplifier (*13*). If the amplification is to be appreciable, care must be taken to avoid reflections which would lead to independent oscillation of the amplifier section. The highest powers reported so far are of the order of 10^9 watts, and are limited chiefly by flaws in the laser materials. At such high power levels the smallest absorption can lead to catastrophic local heating. However, peak powers higher by one or even several orders of magnitude seem attainable.

Gas-Discharge Lasers

The first gas-discharge laser, constructed by A. Javan, W. R. Bennett, Jr., and D. R. Herriott (*14*), gave a continuous output of about 1 milliwatt at several wavelengths near 1 micron. It made use of a mixture of helium and neon gases. As Javan had predicted (*15*), metastable helium atoms collide with neon atoms and excite them preferentially to a few particular states which happen to have nearly the

same excitation energy as the metastable helium atoms. The laser action occurs by stimulating downward transitions of excited neon atoms to lower states, which are not so favored by the excitation process and are thus relatively empty.

Subsequent investigations showed that the helium-neon combination can give coherent laser output at many wavelengths, including several in the visible portion of the spectrum (*16*). The general spectral region can be selected by using multilayer dielectric mirrors, whose reflectivity is high only for that region. Sometimes there are several nearby wavelengths at which laser oscillation can occur. In that case, one wavelength may be selected by a dispersing prism placed between the gas-discharge tube and one of the end mirrors (*17*). The strongest visible laser line of the helium-neon mixtures is at 6328 angstroms. Continuously operating lasers at this wavelength, with power around 1 milliwatt, are now widely used.

Even when a laser oscillates on a single spectral line, its output may not consist of a single wavelength. Often oscillation occurs simultaneously at several different light frequencies which are close enough so that they all lie within the width of the spectral line. The exact frequencies are determined by the resonant frequencies of the mirror system. Such an output is very nearly monochromatic by most standards. However, a single mode of oscillation can be selected by a more complex mirror system. If the laser material has enough gain per unit length, a very short laser can be used which gives only one mode within the spectral line width. With care, the mirror spacing can be adjusted to give single-wavelength oscillation precisely at the center frequency of the spectral line; indeed this adjustment can be automated. Stability of the order of one part in 10^{12} has been obtained for a few seconds, with resettability better than one part in 10^{9} (*18*).

Although the helium-neon gas-discharge laser has been more thoroughly investigated than any other, laser action has been observed in many gases and gas mixtures. A number of selective excitation mechanisms have been identified. Continuous laser action has been obtained from the visible blue region to beyond 100 microns. With pulsed excitation, wavelengths from about 0.3 micron in the ultraviolet (*19*) to 337 microns in the far-infrared (*20*) have been obtained. It would appear that gas-discharge lasers are close to offering a solution to the classic problem of providing strong, and preferably coherent, sources throughout the submillimeter region.

Because of their lower atomic density, gases cannot store as much excitation energy per unit volume as can good solids. Thus, gases are not likely to produce such high peak-pulse powers as do solids. Peak powers of tens of watts from gas discharges have been reported, and somewhat higher powers are attainable.

Both gaseous and solid lasers usually give continuous power outputs in the milliwatt range, and both types have attained power outputs greater than 1 watt. It seems likely that discharges in ionized gases, with laser radiation from the excited ions, will soon be made to give continuous power outputs in the 10- to 100-watt range. At present, the higher-power gas lasers radiate several wavelengths simultaneously.

In comparison with solid and liquid lasers, gases have the great advantage of providing an almost ideally homogeneous medium. Thus, they can be not only very monochromatic but also very well collimated. Even the first gas laser gave an output wave whose beam divergence was close to the theoretical minimum.

Semiconductor Lasers

Both optically pumped solid lasers and gas-discharge lasers are, so far, relatively inefficient, having efficiency of, at best, a few percent and usually less than 1 percent. While the efficiency limitations of these devices are not fundamental and may be overcome eventually, semiconductor lasers (*21*) have already shown efficiencies of some tens of percent.

In a semiconductor, an electron which has been excited to the conduction band can recombine with a hole and revert to the valence band. The excitation energy, approximately equal to the energy gap, may be radiated as a light quantum. Such radiative recombination is most likely in direct-gap semiconductors such as gallium arsenide and indium antimonide. In these materials the emission of recombination radiation can be stimulated by light of the proper frequency.

In order to get enough amplification to exceed the losses and produce laser oscillation, we need to provide large numbers of electrons and holes in some region so that they can be stimulated to recombine. This can be done by making a *p-n* junction and passing a large current through it in the forward direction. Then electrons are drawn from the *n* region into the *p* region, and holes move into the *n* region. Recombination takes place strongly within a distance of a few microns on either side of the plane of the junction. The resonator mirrors are arranged perpendicular to the junction plane. Usually it is sufficient to polish, or even to cleave, two surfaces of the semiconductor crystal for mirrors. The other surfaces can be roughened to prevent specular reflection.

The power density in the junction region can be quite high. However, in most semiconductor lasers the useful region is very small, so that the overall power output is relatively limited. Peak powers of the order of 100 watts, and continuous power as high as 6 watts have been reported. The thickness of the useful region near the junction plane can be increased in some materials by modifying the doping near the junction region. Recently, laser action has been achieved throughout a layer of indium antimonide several hundred microns thick (*22*). Also, it is possible to excite a substantial thickness of the semiconductor by bombarding it with an external beam of high-energy electrons (*23*). The higher the electron energy, the greater the depth that will be penetrated and excited. However, if the electrons in the beam have energies greater than 100,000 or 200,000 electron volts, they will quickly damage the semiconductor.

Semiconductor lasers are, at present, very much more efficient than the other types. They can also be tuned to some extent by changing the temperature or pressure, or by applying an external magnetic field. Moreover, the output wavelength depends on the semiconductor gap energy, and this can be shifted over a considerable range by alloying the semiconductor material.

Properties of Laser Light

Laser light differs from ordinary light chiefly in having higher coherence, both spatial and temporal, and greater intensity. At present, high coherence is most readily obtained from

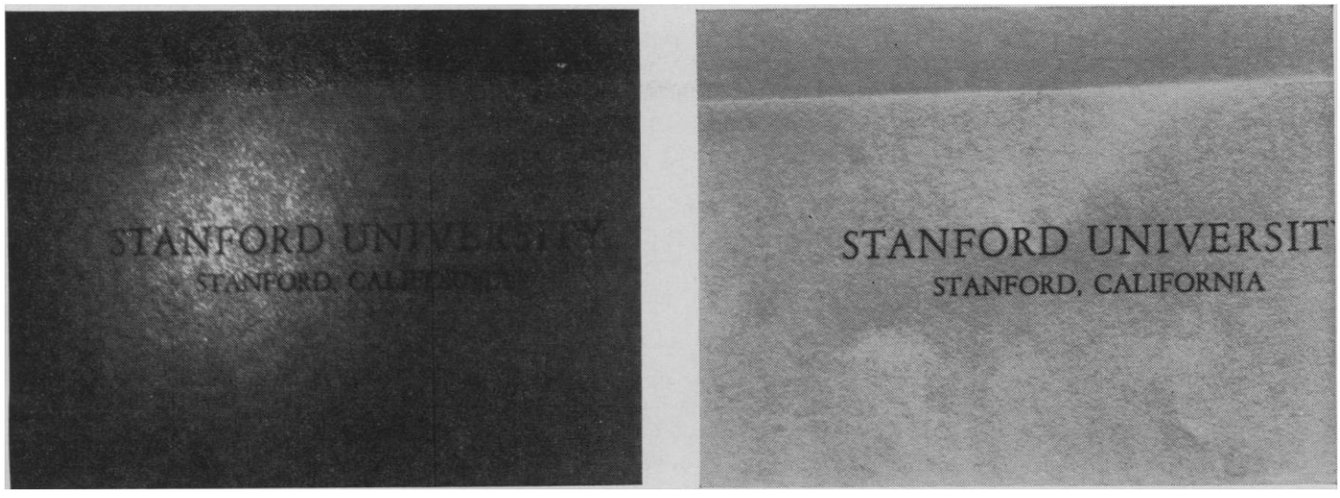


Fig. 2. (Left) A printed piece of paper illuminated by 6328-angstrom coherent light from a gas-discharge laser. (Right) The same paper illuminated by ordinary light.

a gas-discharge laser, and high intensity is most readily obtained from an optically pumped solid.

With a spatially coherent source, light from any part of the wave front can interfere, constructively or destructively, with light from any other part. The waves will cancel if they arrive out of phase, and will add if they arrive in phase. The relative phase of the waves depends on the lengths of the paths traversed, changing from in-phase to out-of-phase with a half-wavelength change of path length.

Interferometry with conventional light sources has been used for many years to make sensitive and precise measurements of length. However, the necessary coherence often must be obtained at the expense of intensity. Thus, lasers are especially convenient sources for most interferometric techniques (*24*). In particular, they seem likely to supplant other light sources as fundamental and practical precision standards of length.

Because of its coherence, laser light even looks different from ordinary light (*25*). An object illuminated by light from a laser has a markedly grainy appearance (Fig. 2). It appears to sparkle as the bright spots shift around with slight motions of the observer's eye. This comes about because the laser beam striking the surface is a coherent, nearly plane, wave. The light scattered off the rough surface of the object has a highly irregular, but still coherent, wave form. The light reaching any one point on the retina of the eye is a sum of wavelets from a portion of the object many wavelengths in diameter, because of the finite resolving power of the eye. These wavelets may add up in or out of phase, and so produce either light or darkness. If the eye is moved slightly, a different sample of waves is brought to that point on the retina, and the intensity may increase or decrease drastically, so that the object appears to sparkle. On the other hand, if the object is moved rapidly enough, these intensity fluctuations are averaged, and the graininess disappears. This phenomenon is an example of how easily interference effects are obtained with coherent light, sometimes even when they are not wanted. Sometimes, indeed, it is useful to introduce a phase scrambler to avoid unwanted interference effects.

One of the most promising applications of coherent laser-light interference is in the process of holography, or lensless photography (*26*). If one

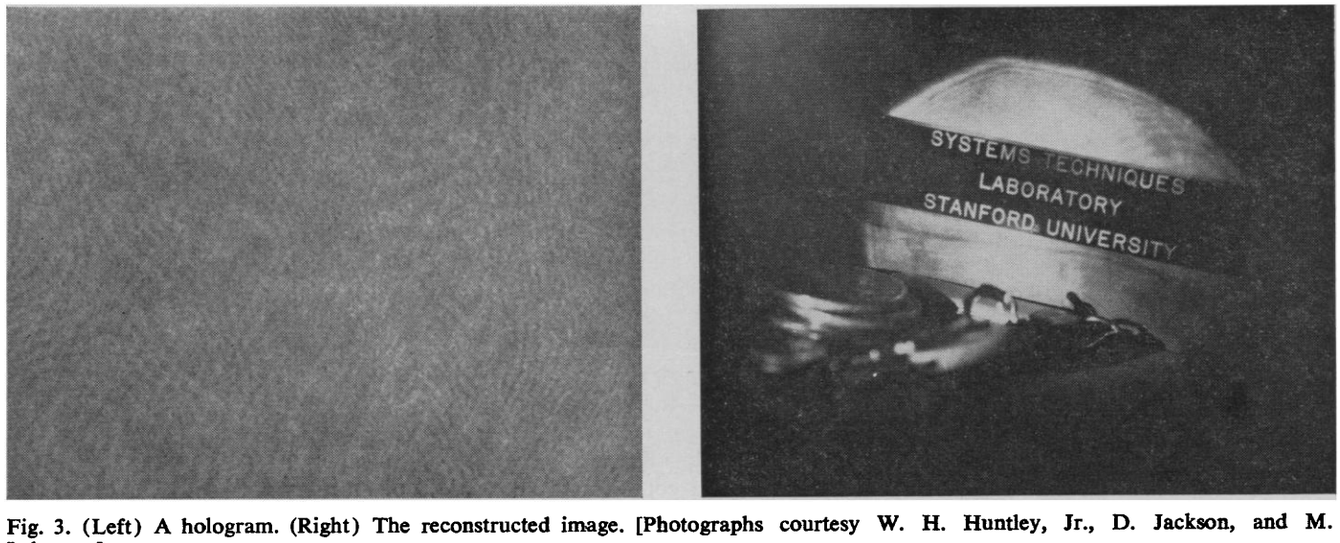


Fig. 3. (Left) A hologram. (Right) The reconstructed image. [Photographs courtesy W. H. Huntley, Jr., D. Jackson, and M. Lehmann]

could place a photographic plate in any plane between the object and the eye and record the amplitude and phase of the light everywhere in the plane of the plate at some one instant, one would have enough information to reconstruct the image. However, the photographic process records only the intensity and not the phase. Information on phase can, however, be recovered if the plate and object are simultaneously illuminated by a suitable coherent light source. Several versions of this technique have been described, including one which provides a hologram from which a three-dimensional reproduction of the object can be reconstructed by suitably illuminating the transparency with coherent light (Fig. 3).

The time coherence of lasers makes it possible to obtain beats between two different light waves. All one needs to do is to superimpose the two beams and allow them to fall onto a fast photodetector. The light frequency is very high—of the order 10^{14} cycles per second—so that a very small fractional difference between the frequencies of the light waves gives a large absolute frequency difference. Nevertheless, it has been found possible to stabilize two separate gas lasers well enough to produce a beat frequency in the audible region, less than 10,000 cycles (*18*). This requires that the relative frequencies of the oscillators be kept constant to within one part in 10^{10} during the observations. Still greater stability is possible.

In most applications in which beats are used, they are used to obtain the difference between two frequencies derived from a single laser; thus, such high absolute frequency stability is not needed. Examples are applications in which a single laser beam is split into two parts, one of which is reflected from a moving object or transmitted through a moving medium. The two beams are then combined on a photocathode, and the velocity of the moving object or medium is inferred from the beat frequency.

Similarly, in a ring laser gyroscope or rotation sensor (*27*), two light beams circulating around a ring of mirrors in opposite senses are compared. The light traverses a laser amplifier section somewhere in its passage. Sustained optical oscillations occur in two modes corresponding to clockwise and counterclockwise circulation. If the ring is stationary, the light beams in these modes have the same frequency. If it rotates, the beam traveling in the direction of rotation has a lower frequency than the other. The beat frequency between these two beams measures the rate of rotation.

Gas lasers which give nearly monochromatic light of relatively high intensity are almost ideal sources for Raman and Brillouin scattering. The narrow beam can be made to traverse a transparent sample several or many times. The light frequency of some of the scattered light is shifted upward or downward by the frequency of an internal vibration. Raman shifts are typically of the order of a few hundred per centimeter, so the extreme monochromaticity of laser sources is rarely needed. However, lasers do provide intense sources at wavelengths which could not previously be used for Raman spectroscopy (*28*). This may well be useful in studies of materials which are opaque in the green, blue, and ultraviolet regions. Moreover, the laser light is directional and can be polarized, so that it is convenient for studies of directional Raman scattering and polarization.

In Brillouin scattering the light shifts arise from scattering by "acoustic" vibrations of relatively long wavelength and low frequency—that is, of the order of 10^{10} cycles (rather than the 10^{12} to 10^{13} cycles typical of Raman frequency shifts). For these small Brillouin frequency shifts, it is essential that the source be nearly monochromatic, so a gas laser is particularly suitable (*29*).

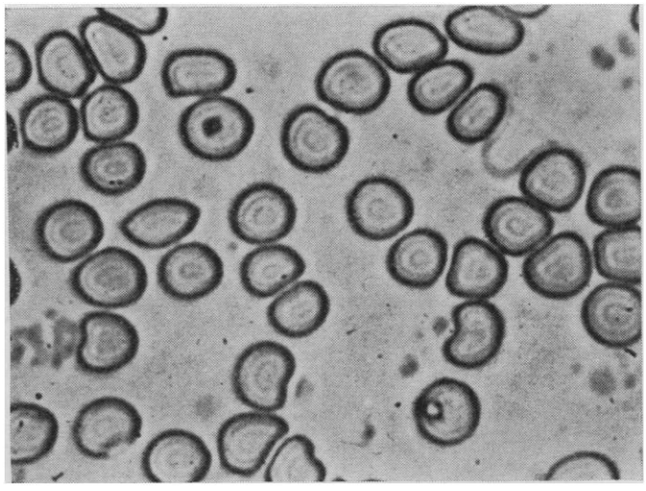
At the high light intensities obtainable from giant-pulse lasers, it is no longer possible to think of the light beam as merely probing the vibrations already present in the specimen. The intense laser light can force the various kinds of vibrations, and lead to much greater scattering at some frequencies. I shall discuss these effects after examining some of the simpler phenomena associated with high-intensity laser light.

The power densities produced by giant-pulse lasers are very high indeed. Moreover, since the output is a well-collimated beam, it can be focused to a small spot. Ideally, a single-mode laser beam can be focused to a diameter of approximately the wavelength of light—this is, to about 10^{-4} centimeter. Even with somewhat less than ideal collimation in a high-power laser, the beam could be focused to a spot of area about 10^{-6} square centimeter. In such a spot the power density would be about 10^{15} watts per square centimeter. This corresponds to an electric field of about 3×10^{8} volts per centimeter, and an associated magnetic field of about 10^{6} gauss, at optical frequencies. Such high electric fields cannot be attained at lower frequencies or at zero frequency, as cold emission from electrodes limits the attainable field. At optical frequencies, the highest field is produced at the focus, which can be far away from any surfaces.

What effects can be expected from such high power densities and field strengths? In the first place, even small lasers, when focused, can produce extremely rapid and intense heating. Even a very modest ruby or neodymium-glass laser can deliver an output power of about 1000 watts (for example, ½ joule in 5×10^{-4} second) into a beam with divergence of 0.01 radian or less, which is easily focused into a spot of area 10^{-3} square centimeter. Thus, in the focal spot, the power density from such a small laser is 10^{6} watts per square centimeter.

If the target is a biological specimen, a small area may be easily burned. In this manner, lasers have been used for surgery on the retina of the eye, which can ordinarily be seen but not reached. The cornea and lens of the eye are not affected because the light pulse is not focused on them, and moreover very little of the light is absorbed by their transparent material. However, the lens structure of the eye itself focuses the light on the retina.

If the target is a reasonably opaque substance, such as graphite, the light is absorbed in a surface layer less than 10^{-5} centimeter thick. In this layer the power density is, thus, greater than 10^{11} watts per cubic centimeter. If, as is quite common, the laser output consists of series of short (10^{-7}- to 10^{-6}-second) pulses, the power density during one of the pulses may be several times higher. Thus, the surface layer of the target heats very rapidly. Some of the target vaporizes almost instantaneously and emits a jet of vapor, which is sometimes brightly luminous. The spectrum of this luminous jet may be photographed; this permits spectrochemical analysis of a very small area of the target. If the jet is not itself bright enough, it can be made to pass between spark electrodes. The laser serves only to vaporize a sample of the target, while the spectrum excitation is provided by



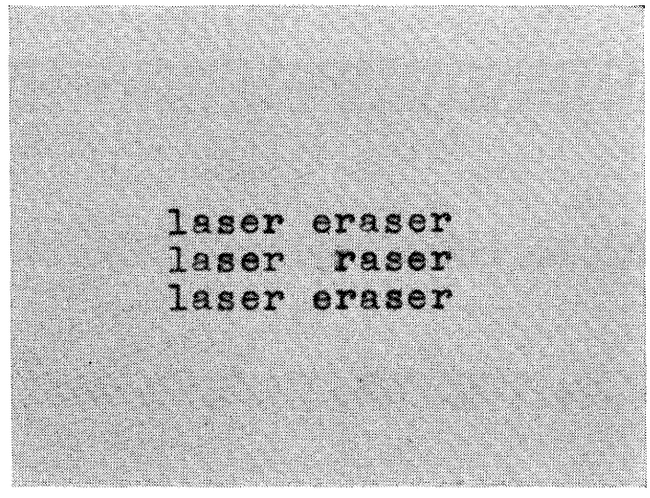


Fig. 4 (left). Red blood corpuscles with hole drilled by a laser-microscope combination. The diameter of a corpuscle is approximately 7 microns. [Corpuscles and photograph courtesy Norman Peppers, Optics Technology, Inc.] Fig. 5 (right). Laser erasing. A 1-joule flash of laser light has removed the ink pigment from one letter in the second line.

the spark (*30*). A small hole is left at the point of impact of the laser beam. If necessary, a very small hole —as small as 1 micron in diameter— can be drilled through a thin specimen (Fig. 4).

At these power levels—around 0.1 to 10 megawatts per square centimeter— the effects can be understood as, basically, rapid heating of the target. Nevertheless, the heating is so very rapid as to produce some surprising consequences. Thus, a flash of laser light can vaporize carbon ink pigment from the surface of paper without noticeably affecting the underlying paper. Exposure to about 2 kilowatts for half a millisecond is sufficient to remove a single typewritten character (Fig. 5). The liquid carrier, although it is much more volatile, does not absorb the laser light and may remain in the paper. It can sometimes still be seen with ultraviolet illumination.

Other thermal effects of surprising magnitude have been observed in studies of electron emission from laser targets. Copious electron emission has been observed to follow the light intensity with much less than a microsecond delay. Nevertheless, the effects were caused mainly by the laser's heating the surface—at a rate of 10^{10} degrees Kelvin per second! (*31*)

Moreover, there are sometimes some important indirect effects of such rapid heating. When a vapor jet is produced, the recoil delivers a sharp blow to the target, sending out strong acoustic or even shock waves in it. The occurrence of these waves in biological specimens, and some of their effects, have been noted (*32*).

If the light passes through a really transparent medium, there is little absorption, and thus little heating. However, some of the most important effects of high-power lasers are not at all thermal. High-power lasers have correspondingly high electric fields. Whereas the most intense ordinary light sources have electric fields of less than 1 volt per centimeter, the focused lasers can produce, at optical frequencies, electric fields of from 100 to 1 million volts per centimeter. These fields are not as large as the electric fields binding atoms, but they are not negligibly small either. Hence, it is not surprising that such a wave passing through any transparent medium causes the medium to act in a way quite different from its behavior at lower field strengths. Thus, the ordinary relation $D = \epsilon E$ between electric displacement D and electric field E must be replaced by

$$D = \epsilon_1 E + \epsilon_2 E^2 + \epsilon_3 E^3 + \cdots$$

This sort of nonlinear relation is well known for dielectric materials at low frequencies, but had not previously been needed at optical frequencies. The term in E^2 leads to the generation of optical harmonics having twice the frequency or half the wavelength of the original light. If waves of two different frequencies, ν_1 and ν_2, pass together through such a nonlinear medium, sum and difference frequencies, $\nu_1 + \nu_2$ and $\nu_1 - \nu_2$, are generated. Similarly, the term in E^3 leads to the production of a third harmonic wave, which has three times the input frequency, as well as to various mixing phenomena (*33, 34*).

Such effects are well-known consequences of nonlinear dielectric or magnetic properties in the audio- and radio-frequency ranges. However, when the frequencies lie in or near the visible region it is a spectacular thing to see red light change to ultraviolet on passing through a crystal, or invisible infrared produce a brilliant green.

As light waves have very short wavelengths, almost any usable nonlinear medium has dimensions many thousands of times greater than the wavelength. That is, the harmonic waves are generated throughout the medium, and not at a point. In most transparent materials a wave of higher frequency travels more slowly than one of lower frequency. Thus, the harmonic wave tends to get out of step with the fundamental wave producing it. Harmonic waves from different parts of the crystal may reach the end of the crystal with opposite phases, and so may cancel each other. As a result, only a small volume of the crystal is effective in producing optical harmonics.

It has been found, however, that in certain crystals used at just the right orientation the harmonic wave can be kept in step with the fundamental. Use is made of the fact that the harmonic can have a different polarization from the fundamental, and that this last polarization can have the same velocity as the harmonic frequency with a different polarization (*35*). By careful use of this phase-matching technique, efficiencies of up to 25 percent for harmonic generation have been observed. The higher the optical intensity, the better the harmonic generation, and so short harmonic pulses of 1-megawatt power are obtainable.

From the point of view of quantum mechanics, second-harmonic generation is one example of a two-photon process. That is, at sufficiently high power densities, two photons may interact simultaneously with one atom (*36*). Then the usual quantum condition $E = h\nu$ can be replaced by $E = h\nu_1 + h\nu_2$, or, if $\nu_1 = \nu_2$, by $E = 2h\nu$. Some materials are transparent to the fundamental but can absorb the second-harmonic frequency. Thus, two photons arriving together can be absorbed and produce the same excitation as a single photon of the harmonic frequency. For example, high-intensity red light from a laser can be absorbed in a medium which is transparent at lower intensities. The two photons produce fluorescence which ordinarily would require, for its production, excitation by an ultraviolet photon. Again, this double quantum absorption occurs more strongly with high light intensities.

The absorption coefficient for this process is proportional to the light intensity. Thus, carbon disulfide is quite transparent to ordinary red light, but when a 1-megawatt pulsed laser was focused into it two-thirds of the power was absorbed (*37*). This was enough to produce some local boiling near the focus, whereas the ordinary linear absorption would have produced a temperature rise of less than 2°C. In this particular experiment the power density at the focus was about 3×10^9 watts per square centimeter; the exact value depends on the power level of the laser, the degree of its collimation, and the focal length of the focusing lens. The amount of double quantum absorption also depends on the particular material. For many substances it is less than it is for carbon disulfide, but for some others it can be even greater.

It is also worth noting that double quantum absorption can occur when the two quanta have different frequencies. The only essential requirement is that the two frequencies add up to the frequency of an absorption band. Only one of the waves needs to have a very high intensity. Thus, in a potassium iodide crystal, a focused ruby laser beam made possible absorption of a second quantum over a wide range of wavelengths in the ultraviolet (*38*). This induced absorption can provide useful new spectroscopic information, because those energy levels which can be reached in a double quantum absorption are those which have the same parity as the ground state. For ordinary single quantum absorption, a strong electric dipole transition occurs only when the two states have different parity. Thus, double quantum absorption may reveal energy levels which are quite hard to find by means of ordinary absorption experiments.

While absorption coefficients for double quantum processes increase linearly with the quantum flux, other kinds of power-dependent losses may appear at an abrupt threshold. Foremost among these is the coherent Raman effect. In the ordinary, incoherent Raman effect, nearly monochromatic light falls on a medium, and a tiny fraction of it is scattered with a change in wavelength. The Raman-scattered light differs in frequency from the original light by the amount of some internal motion of the scattering medium. Most often this internal motion is a vibration, but rotational and electronic Raman shifts also occur. At low temperatures, the Raman-shifted lines are always at lower frequencies than the exciting light; that is,

$$\nu_{\text{Raman}} = \nu_0 - \nu_{\text{internal}}$$

(Stokes lines). At temperatures high enough so that kT (Boltzmann's constant times absolute temperature) is at least comparable with $h\nu_{\text{internal}}$, anti-Stokes Raman frequencies may be observed, with $\nu = \nu_0 + \nu_{\text{internal}}$. Whatever the nature of the shift, the intensity of the Raman-shifted light is very small.

When the exciting light attains levels of the order of some megawatts per square centimeter, the intensity of the Raman-scattered light is greatly enhanced. Indeed, the medium becomes capable of amplifying light at the Stokes frequencies $\nu_0 - \nu_{\text{internal}}$. If, then, a column of the medium being excited under these conditions is placed between parallel end mirrors, coherent laser oscillation can occur at one or more of the Stokes frequencies. Each Stokes frequency or wavelength will have its own threshold for laser oscillation, when the gain at that frequency exceeds the resonator losses. Above the threshold, an intense coherent beam at the Stokes wavelength emerges through one or both of the end mirrors. Such coherent oscillation at the Stokes frequency was first observed when a cell containing nitrobenzene was placed between a ruby rod and the end mirror of a laser, for use as an electro-optical Q-switch. The laser mirrors served also as mirrors for the Stokes-shifted laser oscillation, the amplification coming from the nitrobenzene cell (*39*). However, a separate cell for the Raman-scattering medium may be used (*40*).

Even without mirrors, extremely intense Raman radiation is generated when a powerful laser beam traverses a suitable medium. Both Stokes and anti-Stokes lines are produced (*34, 41, 42*). Not only the first-order Stokes and anti-Stokes lines at $\nu_0 - \nu_{\text{internal}}$ and $\nu_0 + \nu_{\text{internal}}$ can be generated, but also $\nu_0 \pm 2\nu_{\text{internal}}$, $\nu_0 \pm 3\nu_{\text{internal}}$, and so on. Thus, many new frequencies are generated, and the frequency conversion efficiency may exceed 20 percent. If some of these Raman-shifted light frequencies lie within absorption bands of the material, they will be absorbed. This provides another mechanism by which high-intensity light can be absorbed by a substance. The absorption occurs even though the substance is quite transparent to low-power light of the original laser wavelength.

Thus, harmonic generation and the Raman effect can both produce absorbable light from light to which the medium is transparent. This means that, at high laser power levels, the absorption may increase much faster than the power density. This can produce rapid heating. Moreover, since some of the shifted light is in the ultraviolet, the sort of photochemical effects which ordinarily require ultraviolet light can also be produced by intense red light. These include the generation of ions and free radicals (*43*).

The high electric fields which characterize light from a high-power laser exert strong mechanical forces on any medium through which the light passes. These are electrostrictive forces, and are proportional to the square of the optical-frequency electric field. The electrostrictive force is compressive in an isotropic medium, and nearly so in other media. Moreover, since it is proportional to the square of the electric field, it does not change sign when the electric field reverses. That is, there is an average compressive force on the medium, proportional to the intensity of the light. The magnitude of this force is easily estimated to be of the order of 1 dyne per kilowatt. Thus, a light flux of 10^8 watts per square centimeter gives rise to an electrostrictive pressure of the order of

$$10^5 \text{ dyne/cm}^2 \approx 100 \text{ g/cm}^2.$$

If the intensity of the light changes,

the electrostrictive pressure follows it. Now, if there are two light frequencies, ν_1 and ν_2, traversing the medium simultaneously, they will give beats, and the instantaneous intensity at a point will rise and fall at the difference frequency $\nu_1 - \nu_2$. There will, then, be an electrostrictive force on the medium at this difference frequency, and it can set up vibrations in the medium or in the individual molecules. If this force is at a frequency corresponding to a molecular vibration frequency, the molecular vibration is driven to a relatively large amplitude and there is a very strong Raman scattering. This Raman scattering can generate more of ν_2 from a strong driving ν_1, and thus the vibrations are driven all the more vigorously. This is one way in which one can look at the process of stimulated Raman scattering.

Moreover, if the difference $\nu_1 - \nu_2$ is, instead, in the range of frequencies at which sound waves can be transmitted in the medium, electrostrictive forces can generate intense sound waves. Such generation of sound waves by light can occur at any frequency at which sound waves can propagate, even far above the microwave region (*42*).

One process by which very intense high-frequency sound waves have been generated is stimulated Brillouin scattering. Brillouin scattering is a process in which light is reflected by thermal sound waves in a material. Since these waves are moving with the velocity of sound, v, the reflected light is shifted in frequency by an amount of the order of $2v/c$, where c is the velocity of light. Ordinarily, Brillouin-scattered light is of low intensity. However, when high-power laser light is used, the scattered and incident light combine to produce an electrostrictive force at the difference frequency. Thus, the sound waves already present can be greatly enhanced, and this leads to further light scattering.

This stimulated Brillouin scattering of laser light has been observed in solids and in liquids. In the solids, the accompanying acoustic waves may have such a large amplitude as to shatter the crystal (*44*). This is not the only mechanism whereby high-power lasers can destroy a solid, but it is a mechanism for generating high-frequency acoustic waves of great intensity. Similarly, optical-mode vibrations can be generated by the stimulated Raman process. Such intense vibrations may have profound effects on materials, but they are just beginning to be explored.

Conclusions

Lasers now span the wavelength range from below 0.3 micron, in the ultraviolet, up to as far as 337 microns (0.34 mm) in the far-infrared. Not every wavelength within this range can now be generated coherently, but the number of available wavelengths is in the high hundreds.

Peak powers exceeding 10^9 watts have been reported, but only for a few nanoseconds. Peak flash energies so far are aound 1000 joules. Continuously operating lasers—solid, semiconductor, or gaseous—mostly have outputs in the milliwatt range and exceed 1 watt only with difficulty.

The basic problem in producing high energy, or high continuous power output, from gaseous or optically pumped solid lasers lies in the low efficiency of these devices. One can afford the luxury of wasting most of the input energy only if the total amount is not too large. Even if the cost of electricity can be ignored, the problem of rapidly removing large amounts of heat from a system of good optical quality is severe.

Some semiconductor lasers have reasonably high efficiency. However, most of them are junction devices and their working volumes are very small. Thus, very high power densities give only moderate total power. Possibly bulk semiconductor action may be achieved in a large volume with good efficiency. It would appear, however, that achievement of sustained high power from lasers will require fairly radical innovations in the devices.

I have not tried to discuss in detail the scientific or technological applications of lasers in any of the various fields. I have discussed a few applications merely to illustrate some of the special properties of laser light. Now that a reasonable variety of commercial lasers are available, the utility of lasers is being explored in many areas. Fortunately, some reviews of these special topics have appeared. It is clear, however that assimilation of the radically new properties of laser light will take some time. Much effort will be needed before the biologist, for example, can select and use a laser easily with assurance of predicting all of its effects. Meanwhile, there are very many new phenomena to explore.

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Early Man in East Africa

Recent excavations in Olduvai Gorge, Tanzania, have laid bare a new chapter in human evolution

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Olduvai Gorge in Northern Tanganyika (Republic of Tanzania) has in recent years thrown a flood of light on an early chapter in the evolution of man. Between 1955 and 1963, L. S. B. Leakey, M. D. Leakey, and their sons and helpers uncovered fossil bones representing no fewer than 14 individuals from various levels in the Olduvai strata (*1*). Although detailed descriptions are yet to be published (*2*), it is clear that earlier and lower mid-Pleistocene deposits of East Africa contain the remains of at least two different kinds of fossil hominids (that is, members of the Hominidae, the family of man). The first group of fossils fits comfortably into a well-defined category, the australopithecines, which have long been recognized as a partially hominized group, that is, a group possessing some characteristics like those of *Homo*. The second assemblage has proved most difficult to place in any existing category. After exploring every other possibility, we have been forced to attribute this second group of fossils to a new and lowly species of *Homo*, namely *Homo habilis*: this species represents a more markedly hominized lineage than the australopithecines and comprises a hitherto-unrecognized and even unsuspected transitional or intermediate form of early man (*3*).

In this article I consider the history and some of the characteristics of the new fossils, as well as their cultural and evolutionary position, and propose modifications to some existing schemes of hominid phylogeny in the light of these new discoveries.

The Olduvai Sequence

Before I review the new discoveries in detail, it may be useful to describe briefly the Olduvai stratigraphic succession (Fig. 1).

Olduvai Gorge has been cut by river action through a deep succession of old sediments, tuffs, and lavas. From the exposed strata, a remarkable series of fossils and implements has been recovered, ranging in age from Lower to Upper Pleistocene.

The strata exposed in the walls of Olduvai Gorge were divided by Hans Reck into five beds, numbered I to V, from the lowest upwards. This classification was adopted and the limits of the beds were more precisely defined by Leakey and, more recently, by Hay (*4*). It should be stressed, however, that these beds are not absolute stratigraphic units corresponding to sharp divisions in the Pleistocene sequence of events. Rather they are conveniently mappable units. Thus, as Hay has pointed out, two different marker beds have in various parts of the Gorge been regarded as the top of Bed I. Again, while Reck defined the base of Bed I as the basalt flows, Hay has preferred to include within Bed I the tuffs beneath the basalt. Hay thus regards the basalt flows as a constituent of Bed I in the eastern part of the Gorge.

Further, the newer analyses of fauna made by Leakey and his collaborators (*5*) tend to relate the fauna of the lower part of Bed II to that of Bed I and to interpret both as belonging to a final Villafranchian faunal stage. On the other hand, the fauna of the middle and upper part of Bed II is considered post-Villafranchian and so to be associated with that of Beds III and IV. The complex of Middle and Upper II, III, and IV comprises a mid-Pleistocene stratigraphic sequence.

In this presentation, the subdivision into five beds will be used to provide a background against which to consider the hominid remains.

Potassium-argon dates are available for several levels within Bed I. The span of time represented by these Beds is suggested by ages 1.75 and 1.65 million years for two levels in the lower half of Bed I. In a word, the chapters of human evolution which are dealt with here cover the period from about 2 million to about half a million years ago.

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