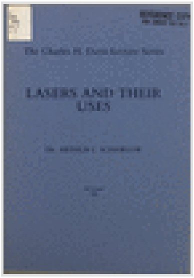

Lasers and Their Uses (1983)

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The Charles H. Davis Lecture Series

Seventh Lecture

LASERS AND THEIR USES

by

Dr. Arthur L. Schawlow
Professor of Physics
Stanford University

Presented Before the Students and Faculty
of the
Naval Postgraduate School
November 9, 1982

and

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January 10, 1983

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CONTENTS

THE
CHARLES H. DAVIS
LECTURE SERIES

AT THE CLOSE of that greatest of all contests of men and machines, World War II, Theodore von Karman could say, with deep personal conviction, that ". . . scientific results cannot be used efficiently by soldiers and sailors who have no understanding of them, and scientists cannot produce results useful for warfare without an understanding of the operations." With such simple truths fresh on their minds, von Karman and his civilian and military colleagues proceeded to forge institutional links—such as the Office of Naval Research—through which they hoped to encourage an enduring partnership between the scientific and military communities. Though the intensity of the bond has fluctuated with the ebb and flow of international relations and internal affairs, the partnership has endured to produce a military capability but dimly perceived by those who established it. But the partnership is not self-sustaining; it requires the constant vigilance of those who have not forgotten the bitter lessons of the past, the outspoken dedication of those whose vision extends beyond the next procurement cycle, and, above all, it requires open communication between the partners. It is to this latter task that the Charles H. Davis Lecture Series is dedicated.

The lecture series is named in honor of Rear Admiral Charles Henry Davis (1807–1877) whose distinguished career as a naval officer and as a scientist so epitomizes the objectives of the series, and whose clear vision of the proper role of science in human affairs redounded to the betterment of all men. The topics and the speakers in the series are chosen by a Search Committee operating under the National Research Council of the National Academy of Sciences, and two lectures are presented each year before the students and faculty of both the Naval Postgraduate School in Monterey, California, and The Naval War College at Newport, Rhode Island. The series is sponsored by the Office of Naval Research.

REAR ADMIRAL
CHARLES H. DAVIS
(1807–1877)

CHARLES HENRY DAVIS was born January 16, 1807, in Boston, Massachusetts. His education consisted of preparation at the Boston Latin School followed by two years at Harvard University (1821–1823). In 1823, Davis was appointed midshipman and sailed (1824) on the UNITED STATES to the West Coast of South America where he transferred to the DOLPHIN for a cruise of the Pacific. Returning to Harvard he continued to work on a degree in mathematics and is listed with the graduating class of 1825.

In 1829 Davis became passed midshipman and was ordered to the

ONTARIO (1829–1832) of the Mediterranean squadron. Later, while serving aboard the VINCENNES (1833–1835), he was promoted to lieutenant. Aboard the INDEPENDENCE (1837–1841) Davis made a cruise to Russia and then to Brazil. Throughout these early years at sea Davis continued to study mathematics, astronomy and hydrology. During this period one of his superiors would write of him, "C. H. Davis is devoted to the improvement of his mind; and his country may expect much from him."

From 1842 to 1856 Davis undertook a number of special tasks and served on several commissions and boards. Notable among these was his participation in a survey of the New England coastal waters (1846–1849) during which he discovered several shoals that may have been responsible for a number of unexplained wrecks in the area. It was during this period in his career that Davis published "A Memoir upon the Geological Action of the Tidal and Other Currents of the Ocean" (1849) and "The Law of Deposit of the Flood Tide" (1852). He was also a prime mover in establishing the "America Ephemeris and Nautical Almanac" (1849) and supervising its publication at Cambridge, Massachusetts until 1855 and again from 1859 to 1862.

Promoted to commander in 1854, Davis resumed sea duty in command of the ST. MARYS in the Pacific (1856–1859). While he was captain of the ST. MARYS he was instrumental in securing the release of the adventurer William Walker and his followers who were beseiged at Rivas, Nicaragua.

With the outbreak of the Civil War Davis was immediately appointed to a number of important positions. He became the executive head of the new Bureau of Detail for selecting and assigning officers. He was one of three officers appointed by Secretary Gideon Welles to the Ironclad Board which passed judgment on the plans and specifications for the MONITOR and other ironclads. Promoted to captain in November 1861, Davis participated in the development of plans for blockading the Atlantic Coast, planning the operation against Hatteras Inlet and Port Royal Channel, and the early naval strategy of the war.

During the operations against Port Royal, Davis served as captain of the fleet and Chief of Staff to Admiral Samuel F. Du Pont. He shares with Du Pont a great deal of the credit for the excellent plan of attack carried out on November 7, 1861. Later, as flag officer of the Mississippi Flotilla, Davis led successful engagements against the Confederate fleet which contributed to the abandonment of Fort Pillow and the surrender of Memphis. He was promoted to commodore in July 1862, and to rear admiral on February 7, 1863.

In late 1862 Davis returned to Washington to head the newly established Bureau of Navigation. From this position he worked closely with such distinguished scientists as Joseph Henry and Alexander Bache to establish a "Permanent Commission" to advise the government on inventions and other scientific proposals which were being stimulated by the war. The Permanent Commission was established by the Secretary of the Navy on February 11, 1863 with Davis, Bache and Henry as members. However, Davis and his colleagues saw a wider need for cooperation between science and government and worked diligently for the establishment of the National Academy of Sciences. Their efforts were successful; President Abraham Lincoln signed a bill authorizing the establishment of the Academy on March 3, 1863.

In 1865, Admiral Davis was appointed superintendent of the Naval Observatory in Washington. In 1867 he returned to sea in command of the South Atlantic Squadron. Back in Washington in 1869 he was made a member of the Lighthouse Board and commander of the Norfolk Navy Yard. He later resumed his post as superintendent of the Naval Observatory where he served until his death on February 18, 1877.

DR. ARTHUR L. SCHAWLOW

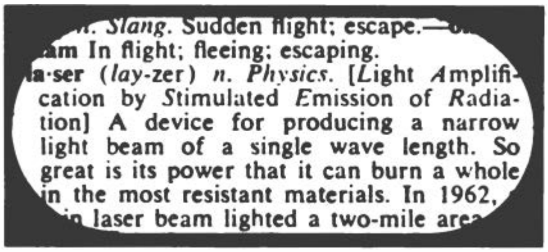
Lasers and Their Uses

Arthur L. Schawlow
Department of Physics, Stanford University

A few years ago, some of my colleagues at Stanford took a photograph at night from the hills back of the University. In the foreground you could see the lights of Palo Alto, then the darkness of the San Francisco Bay, and beyond it the lights on the eastern shore of the bay. On the far horizon there was an orange-red light, much brighter than any other in the picture. That light looked so bright, although it was not much bigger than a flashlight, because it was a laser and was extremely directional. It was aimed exactly at the observer, so if he moved a few feet to either side he would not see it at all.

In 1958, when Charles Townes and I published a paper in the *Physical Review* showing that it would be possible to build what is now known as a laser, nobody had ever heard of any such device. Yet a few years later it was such a common part of everyone's vocabulary that we could even find the music critic of the *London Times* writing, "Solti's performance deals more completely with the great moments than wildest dreams may have imagined: the first violin and viola statement of the passionate E flat theme in part two sawing through you like a beneficent laser beam. . . ." Soon you could also find the word in dictionaries, with a definition like that shown in Figure 1. I like students to see that definition with its spelling mistake, to help them learn not to believe everything they find in books, not even dictionaries.

The laser—also called initially an optical maser—was derived from an earlier device called the maser, which was invented by Townes at Columbia University. It used atoms or molecules to produce short radio waves. His original idea was that it could produce much shorter wavelengths than vacuum tubes could, but in practice it did not. The maser was useful, however, as a sensitive, low-noise amplifier for radio astronomy and satellite communications and for very precise atomic



n. Slang. Sudden flight; escape.—
am In flight; fleeing; escaping.
la·ser (*lay*-zer) *n. Physics.* [*L*ight *A*mplifi-
cation by *S*timulated *E*mission of *R*adia-
tion] A device for producing a narrow
light beam of a single wave length. So
great is its power that it can burn a whole
in the most resistant materials. In 1962,
laser beam lighted a two-mile are

FIGURE 1 An early dictionary definition of the word laser.

clocks. Townes invented this device in 1951, and by 1954 he and his associates had the first one operating.

In 1957 and 1958 Townes and I put our heads together to see if we could figure out how to make an optical maser—laser as we now call it—that would work at or near the visible region. That would mean wavelengths 20,000 to 30,000 times shorter than the microwaves produced by masers. We found that the problems were soluble, and wrote a paper saying so.

A lot of people started to build lasers. Most of them used the structure we had proposed, which is shown in Figure 2. It is a long, narrow, pencil-like column of some active medium with a mirror at each end. One mirror, the one on the left in the diagram, is a good mirror, with as high reflectivity as we can get. The other is a partial mirror, which lets some of the light leak through and reflects some of it back into the active medium. The active medium is one that can amplify light (of some wavelength or other) by stimulated emission. That is where the names come from: MASER is an acronym for Microwave (or Molecular) Amplification by Stimulated Emission of Radiation, while LASER represents Light Amplification by Stimulated Emission of Radiation. In ordinary light sources, such as a neon sign, atoms are excited somehow, perhaps by thermal agitation or by collisions with electrons in an electrical discharge. The excited atoms store energy for a brief interval, perhaps a millionth of a second, then spontaneously emit light. If, however, during the time the atoms are

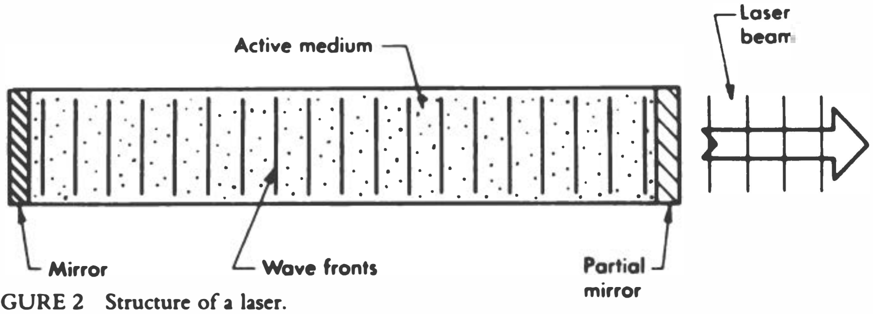


FIGURE 2 Structure of a laser.

excited, a wave of the right wavelength comes along, it can force them to emit and join a wave traveling along the axis of this system. The wave then builds up to a high intensity, until it is as strong as can be sustained by the rate at which atoms are excited. Some of the light energy stored between the mirrors leaks out through the partial mirror at the end and produces a very highly directional beam.

This structure, which practically all lasers use, determines the properties of laser light. The light is directional, because only the wave that goes straight back and forth along the axis of the system gets built up very much. It is powerful, because the atoms are stimulated to emit faster than they would if left to themselves. It is monochromatic, a pure single color, because of the resonance nature of the process. Finally, the light is coherent. Coherent, as in ordinary usage, means hanging together. For a laser, it means that the phase of the light all across the output window is very nearly the same, because all the atoms are stimulated to contribute their energy to the stored light wave between the mirrors. Thus if at some instant there is a wave crest at one place, it is also a crest all across the wavefront. In contrast to that, the light from an ordinary lamp comes from many different atoms radiating quite independently, so that the phase of the light at one point near the lamp has no connection with the phase at another point.

These are the properties of the light from all lasers. It is directional, powerful, monochromatic, and coherent. These properties determine the uses of lasers, but of course lasers come in all sizes. The small helium-neon laser, which I use as a pointer when showing slides, gives about a thousandth of a watt and is generally quite harmless, although it would be foolish to stare directly into the beam.

When Townes and I published our paper in December 1958, a lot of people felt that the laser would not work. Some very ingenious explanations were given of why it could not work. But some people were optimistic enough to try to build lasers, and a race started to get one operating. The person who succeeded first was Theodore H. Maiman, at the Hughes Aircraft Research Laboratories. He used a rod of pink ruby (aluminum oxide with 0.05 percent chromium impurity) for the active medium. The ends of the rod were polished flat and parallel and coated to reflect light. To excite the chromium ions in the crystal he used a xenon flashlamp, like a photographer's strobe light. When high-voltage capacitors are discharged through the lamp, there is a brilliant flash of white light. Ruby has broad absorption bands that take in a lot of the light, so that many chromium ions are excited to a level from which they can be stimulated to emit. The flash from the lamp lasts about 0.002 second, and the burst of stimulated red light lasts about 0.0005 second, or half a millisecond.

It was quite amazing that even the first of these lasers gave several thousand watts of light and had a power density of about 10,000 watts per square centimeter. This was greater than the light intensity at the surface of the sun, including all wavelengths and directions. Moreover, the light from the laser was in a narrow wavelength band in the deep red at 643 angstroms. It was also a fairly directional beam, having about .01 radian divergence, so that it could be focused with a lens onto a rather small spot. Thus even a simple lens could be used to attain a power density of millions of watts per square centimeter at the focal point. That is enough to burn a small amount of absolutely anything. For instance, when a ruby laser was fired at the surface of a block of carbon, a little of the material not only melted but actually vaporized violently enough to produce a white hot jet of carbon vapor. This is all the more remarkable because carbon has a higher melting temperature than any other substance.

It was soon found that lasers could drill very small holes. For instance, with the aid of a microscope, it was possible to drill neat holes in dried red blood corpuscles, only seven micrometers in diameter. It can be done even better now, and lasers are being used as an ultrafine surgical tool for research even at the level of chromosomes. The fineness of the cut is limited only by the wavelength of the light.

Since lasers can burn holes in a small amount of tissue, the science fiction writers—or newspaper reporters as they are sometimes known—immediately claimed that all this research was for weaponry. We were at the telephone company at the time, and we did not want to kill folks—we wanted them to stay alive and make telephone calls, preferably long distance—so we gave some thought to various kinds of countermeasures, like old-fashioned suits of shining armor. Of course, the bigger lasers that are now available would be harder to block. However, I am a little skeptical about lasers as weapons against intercontinental ballistic missiles, because you would have to score a direct hit at a distance of several thousand miles. A near miss would do nothing. Smoke screens and vapor clouds could be used for defense. So, as usual, there would be a race between those planning attack methods and those devising defenses. But it is likely that laser weapons will find some kinds of uses. Lasers do have many other applications, some of them military, as range finders and target locators. But the properties of laser light open up many kinds of applications that go far beyond brute force burning, as was envisioned by the old novelists and comic strip writers. I will discuss some of the different kinds of uses and give some examples to show how the various properties of lasers make them suitable for particular kinds of experiments and uses.

As I mentioned, when I was at Bell Telephone Labs we did not want to kill folks, we wanted them to stay alive, but when I got to Stanford we did not care so much. We had lots of students, who seemed pretty expendable, and there were plenty of professors. So we had our technician build a laser weapon. Once we had that weapon, we wanted to do some hunting. But we learned that students pay high tuition fees, and for some reason professors were off limits too. So we went looking for animals to shoot. The only place around San Francisco to find animals is the zoo, but the animals there looked rather big and fierce. So we bought a balloon for the kids. But it had a mouse balloon inside it, so we had to take our more or less trusty laser to dispose of it (Figure 3). In that experiment, the laser gives a flash of red light, just a few hundred watts for half a millisecond. The deep red light goes easily through the clear outer balloon but is absorbed by the dark blue inner balloon. The inner balloon then gets a hot spot and breaks.

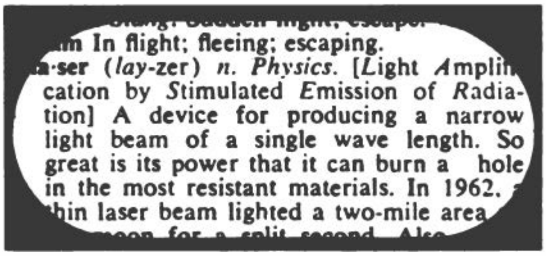
The experiment with the balloon illustrates the principle of one of the very first applications of lasers. It was not for weapons but for surgery on the retina of the eye, to prevent retinal detachment. If there is a tear or lesion that might cause the retina to become detached, the surgeon can send flashes of laser light into the eye, producing scar

FIGURE 3 A flash of light from a ruby laser breaks the blue inner balloon without harming the clear outer balloon.

tissue at the desired places to prevent the tear from growing larger. Even more, now, lasers are being used to prevent leaky blood vessels that often occur in patients with diabetes. When we were working on the laser concepts, I had no idea that there was such a thing as a detached retina. If we had been trying to help prevent blindness, I do not think we would have tried amplification of stimulated emission by atoms. Research cannot always go directly toward the goals; you sometimes have to explore and hope that something will come of it.

The balloon demonstration also illustrates the principle of one of my favorite inventions, the laser eraser. Since laser light has a pure color, some substances, such as white paper, just reflect the light while others, such as dark ink, absorb it and become hot. Thus when a 1-joule flash of light from a laser strikes a typewritten letter, the ink becomes white hot and vaporizes, while the paper remains unaffected. Even the paper directly under the letters is not damaged, because the process happens so quickly that there is no time for the heat to reach the paper before it is carried away by the vaporization. I had the idea of a laser eraser in 1963. I thought everyone would want to start making them because, while nobody knew how to make million-joule lasers for weapons, the laser eraser could be built easily. It could be incorporated into a typewriter: you would backspace to the error, press the zap key, and off it would go.

There ought to be a big market, because there are millions of typewriters being operated by millions of people who cannot spell. The eraser works reasonably well, and it gets around the problems of the dust from the old rubber gum erasers, which were a principal cause of typewriter malfunction. Of course, with the advent of word processors I am not going to make money from laser erasers. The problem is that everything in the laser business is made by hand, so the laser eraser would have to sell for about $2,000. There is not much of a market for $2,000 erasers, and in the 20 years since that invention there has been no progress at all toward making a suitable laser any cheaper. But the laser eraser did permit us to fix our dictionary (Figure 4).



In flight; fleeing; escaping.
a·ser (*lay*-zer) *n. Physics.* [*L*ight *A*mpli
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tion] A device for producing a narrow
light beam of a single wave length. So
great is its power that it can burn a hole
in the most resistant materials. In 1962,
hin laser beam lighted a two-mile area

FIGURE 4 Dictionary definition, after the w in *whole* has been removed by a laser eraser.

Lasers often do not work the way you think they might. I used to get my demonstration balloons from the San Francisco Zoo, labeled on the outside with the name of the zoo. People wanted to know if you could break the outer balloon by shooting at the black letters on it. In fact, if the balloon is not too tightly inflated, you can erase a part of the letters without breaking the balloon (Figure 5). With this enormous laser power density, the outer layer of ink vaporizes so quickly that it carries away heat. As in the process of ablation, which cools spacecraft nose cones during reentry, it all happens so quickly that there is no time for conduction, so the balloon stays cool.

FIGURE 5 Balloon after the laser eraser has erased a spot from the letter N.

A lot of interesting, subtle, and sophisticated things happen when laser light interacts with surfaces. The most widely used laser for machining and welding uses a carbon dioxide gas discharge. Commercial carbon dioxide lasers are available with continuous outputs of tens of kilowatts. The light they produce is deep in the infrared, with a wavelength around 10 micrometers. Metals tend to reflect light rather than absorb it, especially in the infrared. But at high intensity, additional absorption can arise in a number of ways. When the surface begins to become hot, its resistivity rises and the absorption increases. If it melts, there may be an abrupt rise in absorption because keyholing can occur. That is, when a hole begins to develop, light entering it is reflected back and forth between the walls until it is all absorbed. There can also be a thin plasma layer over the surface. If it is thin enough, then there is a discharge close to the surface, producing ultraviolet light, which transmits the heat to the metal surface. The plasma layer may, however, be so thick that it shields the surface very well. Then the laser could vaporize only a little bit from the surface before the plasma layer prevents any further damage. It has even been suggested that under intense laser light there may be phase transitions to a nonmetallic form, and that there can be hot electrons out of thermal equilibrium with the rest of the metal. The physics of laser interactions with materials is rich in possibilities for surprises.

Lasers are already being widely used in industry for welding, drilling, and hardening. They can heat a surface suddenly and very specifically. Both the place of application and the timing, which determines the depth of penetration, can be precisely controlled. For instance, in automobile manufacture, lasers could be used to heat strips along cylinders suddenly enough to harden those surfaces. The space between the strips in the cylinders would be allowed to remain soft so that it would wear enough to provide oil channels. Lasers can even harden just one edge of a gear tooth, if the gear is to be driven in only one direction. Then the surface that may wear is hard, but the rest of the metal remains ductile. I have been told that in these industrial uses lasers are proving more reliable than the machine tools they replace, because there are no tool bits to wear out. That surprises me, because around a laboratory the usual condition of lasers is not working.

The most widely used lasers up to now, however, have been the low-power ones that use an electrical discharge through a mixture of helium and neon gas. The helium-neon laser was conceived by Ali Javan at Bell Laboratories, and the first one was operated there in 1960 by Javan and his colleagues, Donald R. Herriott and William R. Bennett, Jr. It consists of a long (typically about 30 centimeters) and narrow (a few millimeters in diameter) discharge through the gas mixture. The mirrors nowadays usually form the end windows of the discharge tube. Perhaps it is worth noting here that someone who did not understand the physics of the laser might have thought of using a long, narrow column like a rifle, hoping to get a beam from it. But it does not seem likely that he or she would have thought of blocking the ends with mirrors. It is somewhat like a fire, which burns hotter when enclosed. The mirrors hold the light in, so that the light can interact more effectively with the excited atoms.

A helium-neon laser gives a narrow, highly directional pencil of light that can be made visible by some kind of dust, as from chalkboard erasers. The beam looks like an ideal ray of the kind we talk about in discussing lens and mirror optics. Indeed, it makes teaching optics rather fun, as we can easily demonstrate such things as the way a lens brings light rays to a focus (Figure 6).

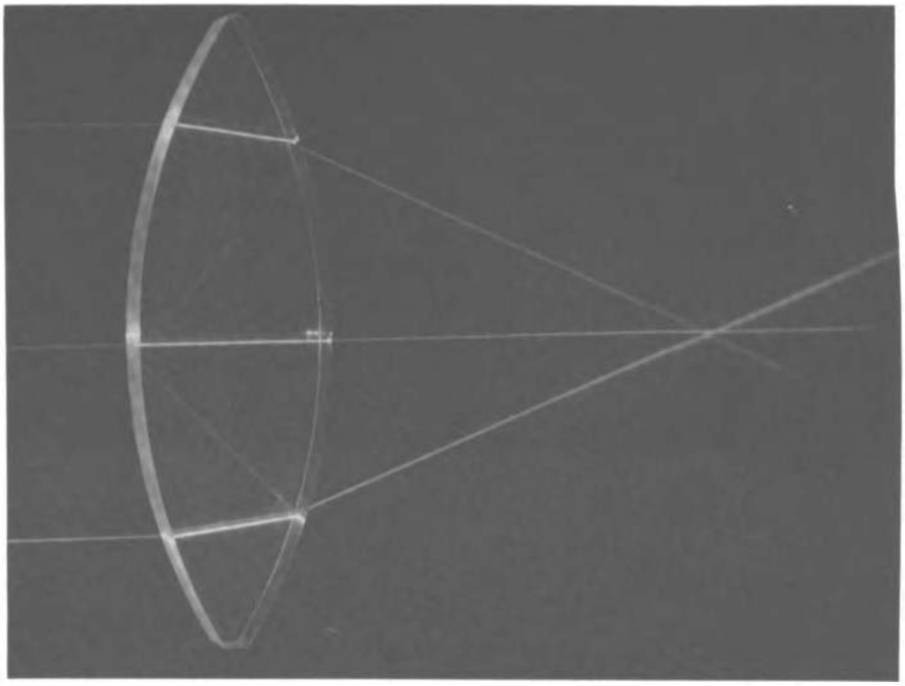

FIGURE 6 Rays of light from a laser focused by a plastic lens and made visible by chalk dust in the air.

A small visible laser of this sort can also provide a nearly ideal straight line for leveling, alignment, or surveying. For instance, lasers now help farmers to level their fields. A small tower is equipped with a laser, accurately aligned so that its beam comes out vertically. At the top there is a mirror or prism that sends the light out horizontally. As the prism rotates, the laser beam goes around in a horizontal fan. The grading machine carries a little photocell on the top of a pole. The grader picks up the light and moves the pole and its blade up and down to hold the photocell in the center of the beam. If preferred, the fan of light can be tilted from the horizontal by one or two degrees or whatever is needed for proper drainage. By using this method, farmers can get a field absolutely level very quickly.

From the beginning, we hoped that lasers would be useful for communications. After all, light waves have frequencies 20,000 or more times that of even the shortest microwaves. Since the waves follow each other in such rapid succession, each can be made different from the one before, larger or smaller, and an enormous amount of information can be transmitted. Indeed, quite early the Army Signal Corps laboratory demonstrated the transmission of seven television channels on one light beam. But rain, snow, and fog can disrupt laser beams just as they can stop ordinary light. Thus for reliable communications, it seemed for a time that we might have to wait until it was economically practical to protect the laser beams from the weather in carefully aligned underground pipes. Everyone knew, of course, that light can be guided around corners by fiber optics light pipes. The principle is shown by the curved plastic rod in Figure 7, which is guiding the light beam by total internal reflection at the surfaces. Such light guides, each as small as a human hair, were already being used in aligned bundles to see into inaccessible places, such as the stomach. But these fibers would carry the light only for short distances. About half of it would be lost in just 7 feet, and very little would survive after 100 feet. Around 1970, researchers at several laboratories were able to make glass pure enough to reduce the absorption drastically. Now there are fibers available that can convey light over distances of many kilometers. They are being used for telephone cables, both local and long distance. In big cities, where there is no more room for conventional broadband cables, the hair-thin fibers can carry television and picture phone signals as well as fast computer communications. They can be extremely useful for internal communications on ships and planes, because they are immune to electrical interference and because they do not radiate signals that others could intercept.

The coherence of laser light is another property far more subtle than anything envisioned in the old science fiction dreams of death rays. Because of it, when light from two parts of the wavefront are brought together, they may add up in phase and produce a brighter spot. But

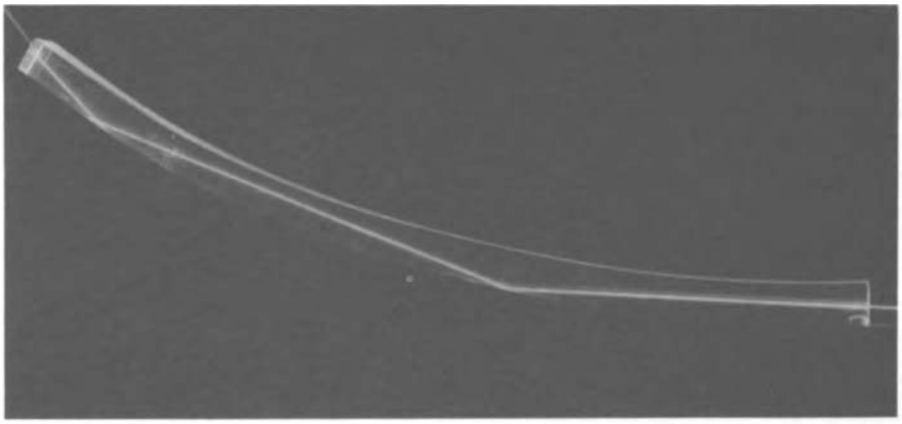

FIGURE 7 Internal reflection in a plastic rod guides light beam around a curve.

if there is as little as a half wavelength difference in the lengths of the paths they have traveled, they may be out of phase and cancel each other. This property makes the laser light very easy to use for precision measurements, for a distance of a half wavelength (about 20 millionths of an inch) changes the brightness drastically, and much less than that can be detected. It is worth noting that it is totally against all ordinary experience to produce a dark spot by bringing together two light beams, even from different parts of the same source. That can happen with a laser, because the light from all parts of the beam comes from atoms that have been synchronized by the wave stored between the mirrors.

The coherence of laser light is perhaps most spectacularly useful in making and viewing holograms. Holography is a marvelous method of lensless photography that was invented by Denis Gabor in 1948. It depends on the interference of light waves to produce an image with bright and dark places, and so was difficult until the advent of lasers. A few people did pioneering research on holography in the 1950s; once lasers were available there was a big advance in both the quality and the ease of making holograms.

A hologram looks like a gray piece of glass or plastic, with no evident image on it. Yet when it is illuminated by a laser, it is possible to see the image through it. The hologram actually has a microscopically fine, complex pattern of lines and spaces, which convert the laser beam into what would be coming through the window if the object were still there behind it. Since the hologram is a window, each eye sees a different point of view; the full scene is visible to either eye but with a different view. By moving your eyes around, you can see behind things and around corners, just as you might when looking through an ordinary window. The effect can be very dramatic. Objects have a very realistic three-dimensional appearance, as if they were floating in space.

To make a hologram, the light from a laser is spread out by a lens so that part of it illuminates the object and another part falls directly onto the photographic plate or film. The two beams interfere and produce the complicated pattern of light and dark that, when developed, is the hologram. A lot of uses have been found for holograms—for encoding information, for computer memories, and for retaining three-dimensional records of precious sculpture. But I am reminded of a conversation I had when a friend of mine came to Stanford in the late 1960s. He said "You know, they have finally found a use for lasers." I said, "You're kidding—lasers are inherently useless." He said, "No, it's a real use. It's called holography. Now all we have to do is find a use for holography."

Laser light is also far more nearly monochromatic, that is a pure single color, than any other kind of light. Even a simple helium-neon laser is monochromatic within one part in a hundred thousand. Some commercial lasers used for research have a spread in wavelength of less than one part in a hundred million, and others have been built with at least a thousand times narrower bandwidth. With such lasers, very high resolution laser spectroscopy is possible. We need only tune the laser across a band of wavelengths and record for which of them its light is absorbed. The laser's monochromaticity is so great that the width of the Doppler-broadened spectral lines is an immediately apparent limitation, obscuring fine details.

In the old days, people used to be taught about the Doppler effect by listening to a train whistle. The pitch of the train whistle changes as the train passes. When the source of sound is moving toward the observer, the pitch goes up; when the source is moving away from the observer, the pitch goes down. Since the atoms in a gas are all free, they are moving rapidly in all directions because of thermal agitation. The Doppler effect applies to light too, and so those atoms moving toward the observer appear to emit a little higher light frequency, while those moving away emit a lower frequency. Thus each single frequency emitted by the atoms is smeared out into a band of frequencies, and interesting details, such as those arising from interaction of the atomic nuclei with the electrons, are obscured. So it is important to eliminate the Doppler broadening for serious scientific spectroscopy.

In 1970 T.W. Hänsch at Stanford and C. Borde in Paris independently discovered an ingenious way to use the directionality and intensity of a laser to eliminate the Doppler broadening. It is shown schematically in Figure 8. The laser beam is divided into two parts by a beam splitter. The stronger beam goes through the absorbing gas, which in Hänsch and Marc Levenson's early work was iodine vapor, and saturates or bleaches a path through that cell. The other beam goes through in almost exactly the opposite direction, much more closely than the diagram shows. When a path is bleached through the cell by the saturating beam, the probe beam is better able to reach the detector. As the saturated beam is chopped on and off, the probe beam is modulated, as it is alternately more and less absorbed by the gas in the cell. This is a small modulation, but it is quite detectable. However, this only happens if the two beams interact with the same molecules, which must be molecules that are standing still or at most moving transversely. If they are moving at all along the direction of either beam, then the two beams appear to the moving molecule as Doppler shifted to different frequencies, so that the molecules cannot be resonant to both at the same time.

SATURATION SPECTROMETER

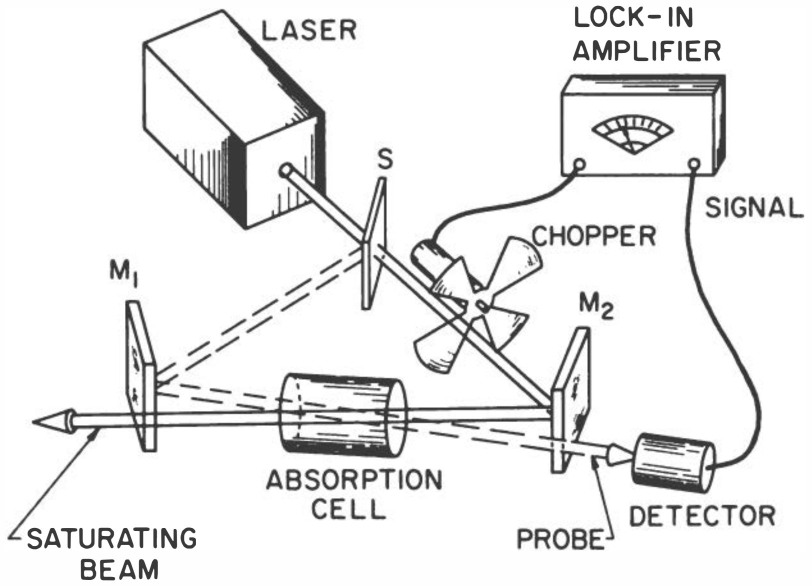

FIGURE 8 Schematic diagram of apparatus for the saturation method of laser spectroscopy without Doppler broadening.

With this powerful technique, Hänsch and Levenson resolved the complete hyperfine structure of a single line in the complex spectrum of iodine, arising from the interaction between the nucleus and the molecule (Figure 9). The line width was about one part in 100 million. If Figure 9 is projected to be about 2 meters wide on the screen, then on the same scale the visible portion of the spectrum would be over 600 kilometers wide. This was very-high-resolution spectroscopy, but much more has been done since then. The field of laser spectroscopy is extremely active and full of interesting surprises. It is possible to learn many of the details of atomic and molecular spectra that were previously quite inaccessible. We have also found systematic ways to use the unique properties of lasers to simplify complex spectra so that they can be analyzed and understood.

We also found that lasers can detect very small amounts of some substances. The beam from a tunable laser can be sent through a cell that is carefully designed with baffles to prevent any scattered light from the walls reaching a photodetector at one side of it. However, when the laser is tuned to a resonance of the gas in the cell, light is scattered from the atoms and detected by the photocell. The method can be extremely sensitive, more sensitive even than radioactive

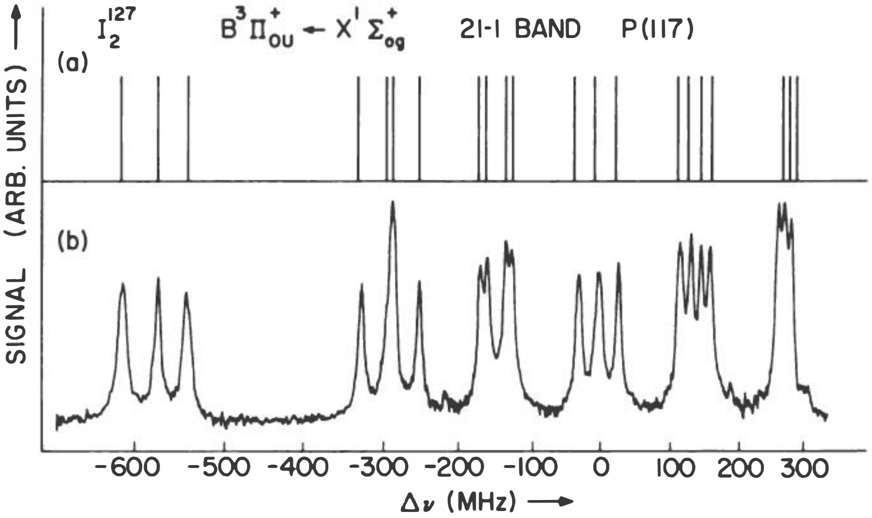

FIGURE 9 The hyperfine structure of one of the many lines in the spectrum of molecular iodine, as revealed by Doppler-free saturation spectroscopy.

methods, because many light quanta can be scattered from each atom without destroying it. One of my graduate students, William M. Fairbank, Jr., was able to measure the relative vapor density of sodium atoms at various temperatures by scattering light tuned to one of the orange-yellow resonance lines of the sodium atom. He could detect the scattered light at temperatures as low as −30°C, when there were only about 100 sodium atoms per cubic centimeter. At that temperature, there were only one or two sodium atoms in the laser beam at a time.

Thus it became apparent that laser methods could become sensitive enough to detect a single atom or molecule of any substance. Other laser techniques have been developed in a number of laboratories, including the group of S. Hurst at Oak Ridge National Laboratory, and single atom sensitivity has been confirmed. The methods are not yet universally applicable because the wavelengths needed for detecting some substances are difficult to generate. Nevertheless, it seems likely that the ability to detect single atoms or molecules will be a very important part of analytical chemistry in the future. We may someday be able to detect a single molecule in a quart of milk. How likely is it that there will not be one cancer-causing molecule in a quart of milk? Then we will really have to set limits on regulation, because complete elimination of detectable traces of harmful impurities will be impossible. We may even discover small traces of essential substances whose existence had not been known.

Lasers can be used not only for chemical analysis but also to influence chemical reactions. Chemical reactions in general go faster when they are heated up, and the laser provides a very selective way to heat things. Thus we could tune a laser to activate a chosen substance in a mixture, without affecting the rest of it. Separation of uranium isotopes by lasers is a technique that is approaching practicality. Lasers may also be used for separating long-lived fission products from the less troublesome short-lived ones. More uses for lasers in ordinary chemistry will be found, but they will not come fast, because lasers are a fairly expensive way to influence chemical reactions. Much chemistry is done with tons of materials at a few cents per pound—laser light is just too expensive to compete.

Lasers can be very powerful. Soon after the first ruby lasers were developed, Robert Hellwarth found a way to make them give pulses not at thousands of watts but at millions of watts. With such a powerful laser it becomes evident that light is not just a wave, but an electromagnetic wave. When it is focused, there is a bright flash as the high electric field of the light produces a spark breakdown in open air. Even at power levels much less than that, the response of transparent substances to the light's electric field is nonlinear, and the light is altered as an overdriven loudspeaker distorts sound. True optical harmonics or overtones can be generated in this way, having frequencies of two times or even higher multiples of the light frequency. These nonlinear optical effects can also mix two different frequencies to produce sum and difference frequencies. Thus many more frequencies or wavelengths of light can be generated. Nonlinear optics is in some ways more complex and rich in phenomena than ordinary linear optics. Discoveries in nonlinear optics and its applications to spectroscopy by Nicholaas Bloembergen were recognized by his sharing the 1981 Nobel prize in physics.

Even those powerful lasers can be amplified further, to attain peak powers of 10^{14} watts or even more for a brief instant, less than a nanosecond. Such pulses may make it possible to heat pellets of hydrogen not just white hot but to temperatures of millions of degrees, hotter even than the center of the sun. Vaporization of the surface would compress the pellet until its density would also become greater than the sun's interior. Then the hydrogen nuclei in the hot, dense pellet would collide with each other violently enough that they would fuse together to produce helium nuclei and release large amounts of energy. If these reactions can be initiated and controlled, nuclear fusion may give enough energy to supply the world's needs for a very long time.

The powerful lasers used for fusion research are extremely advanced and complex devices. In the Shiva laser at the Lawrence Livermore Laboratory, a laser oscillator's output is divided to drive 24 chains of high-power amplifiers. These are so precisely aligned and synchronized that the light pulses from each of them arrives at the target at the same time, within a billionth of a second. Such a laser reminds me that once in the early days of lasers, around 1963, I said something that I think was rather perceptive: Lasers are simple devices not only because they are simple in principle but also because we have not yet learned why and how to make them complicated. It seems from fusion research that we are now learning. Complex lasers and laser systems are also being devised for communication systems and switching. Even optical computers are envisioned.

It is gratifying to observe that lasers are also being used for artistic ends. Not only are the colored light patterns forming the basis of light shows, but lasers are also being used to carve artistic objects of wood. Perhaps in the future, lasers may be used to carve complex patterns on a large scale in stone or other hard materials. That might make it economically possible to restore decoration to buildings.

This has been only a small sample of the kinds of uses that have been found for lasers. In some ways it is still difficult to match a proposed use with an available laser. But the uses are many, and the list of them still grows rapidly.

Curriculum Vitae

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Arthur L. Schawlow is J. G. Jackson and C. J. Wood Professor of Physics at Stanford University. Born in Mount Vernon, New York, he received the Ph.D. degree from the University of Toronto in 1949. After two years as a postdoctoral fellow and research associate at Columbia University, he became a research physicist at Bell Telephone Laboratories. In 1960 he was a visiting associate professor at Columbia University. Since 1961 he has been professor of physics at Stanford University and was chairman of the Department of Physics from 1966 to 1970.

His research has been in the fields of optical and microwave spectroscopy, nuclear quadrupole resonance, superconductivity, and lasers. With C. H. Townes he is coauthor of a book, *Microwave Spectroscopy,* and of the first paper describing optical masers, which are now lasers. For this latter work Schawlow and Townes were awarded the Stuart Ballantine medal by the Franklin Institute as well as the Thomas Young medal and prize by the Physical Society and Institute of Physics. Schawlow was also awarded the Morris N. Liebmann memorial prize by the Institute of Electrical and Electronics Engineers. In 1976 he was awarded the Fredrick Ives medal of the Optical Society of America "in recognition of his pioneering role in the invention of the laser, his continuing originality in the refinement of coherent optical sources, his productive vision in the application of optics to science and technology, his distinguished service to optics education and to the optics community, and his innovative contributions to the public understanding of optical sciences." He received the Nobel prize in 1981 for his contributions to the development of laser spectroscopy.

Schawlow is a fellow of the American Physical Society, the Optical Society of America, the Institute of Electrical and Electronics Engineers, the Society of Photo-Optical Instrumentation Engineers, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and the Institute of Physics (Great Britain) and a member of the National Academy of Sciences. He was chairman of the Division of Electron and Atomic Physics of the American Physical Society in 1974, president of the Optical Society of America in 1975, and chairman of the physics section of A.A.A.S. in 1979. He was president of the American Physical Society in 1981. He was chairman of Commission C.15, Atomic and Molecular Physics and Spectroscopy, of the International Union of Pure and Applied Physics from 1978 to 1981 and chairman of the U.S. National Committee for the International Union of Pure and Applied Physics from 1979 to 1982. He has received honorary doctorates from the Universities of Ghent (Belgium), Toronto (Canada), and Bradford (England).

Schawlow has given A.A.A.S. Holiday Science Lectures in Philadelphia, Salt Lake City, and Durham and was the Richtmyer lecturer of the American Association of Physics Teachers in 1970. He was the recipient of a senior postdoctoral fellowship from the National Science Foundation. He has also been the Cherwell-Simon lecturer at Oxford University (England), the Hoxton lecturer at the University of Virginia, and the W. V. Houston lecturer at Rice University. He received the Geoffrey Frew fellowship from the Australian Academy of Science, and in 1973 he was named California scientist of the year. In 1977 he was awarded the third Marconi international fellowship.

Schawlow wrote the introductin to *Scientific American Readings on Lasers and Light* and three of the articles in that collection. He has appeared on television on the 21st Century program with Walter Cronkite and on the Experiment Series with Don Herbert as well as in films for Canadian and British TV networks.