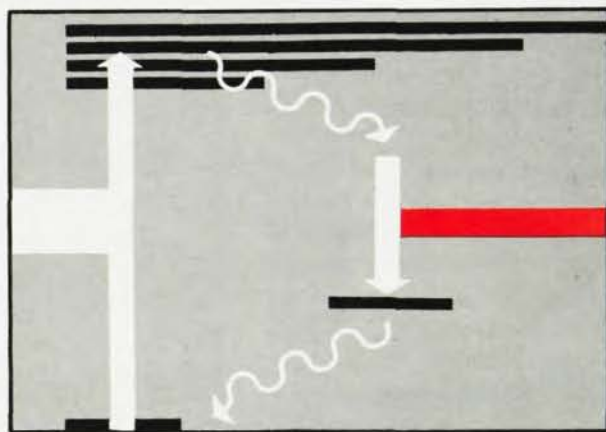


# Laser Applications

*Unique properties have made the laser an important scientific tool in applications ranging from studies of plasma light scattering and of nonlinear phenomena to the development of instruments for photography and interferometry.*

by Theodore H. Maiman



WHEN THE LASER was developed in mid-1960, it was hailed—primarily by science writers—as the solution to problems ranging from such commonplaces as television transmission and metal drilling to science-fiction tools like the instant death ray. This effort to glamorize the laser and portray it in terms of commercial and industrial application continues to occupy the bulk of the attention focused on it today. Such publicity is somewhat misleading, but the laser's role as a scientific tool is now well established.

Scientific interest in the laser is twofold. On the one hand, quantum electronics has been tremendously enlarged by the study, development and understanding of laser operation. On the other hand, the laser has contributed as an investigative tool to many areas of physics and is expected to

have an impact in chemistry, medicine and other scientific disciplines.

The effectiveness of the laser as an experimental tool lies in its many unique properties including the narrowness of its emission frequency (monochromaticity), its brightness and power density, and the pulse shortness of which it is capable. These and other qualities are found in some 50 different laser types, each varying according to wavelength, temperature, energy conversion efficiency, excitation means and other characteristics. Specialists separate lasers into three major categories; optically pumped instruments, gas lasers excited by electrical discharge and semiconductor lasers. Among the broad applications are studies of reflectance, light scattering from plasma, Rayleigh scattering and Raman spectra, nonlin-

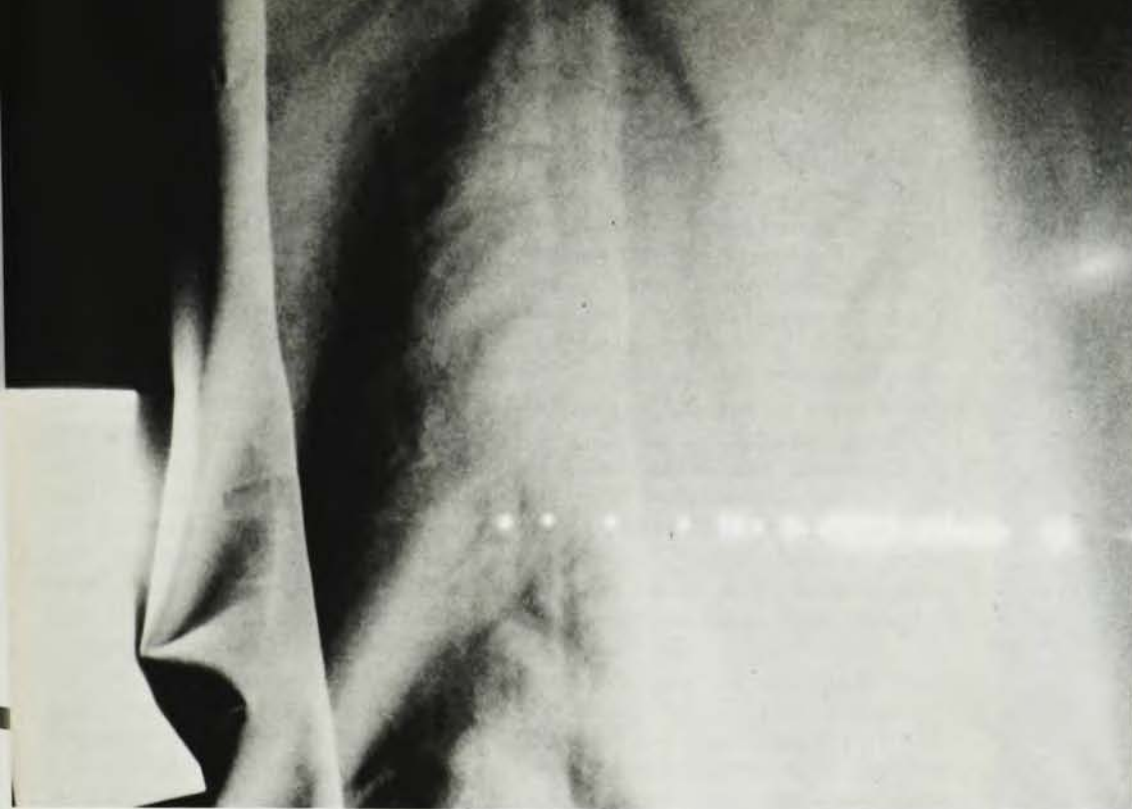
ear phenomena and creation of high plasma densities. Other important uses are found in interferometry, photography and Doppler-shift measurements.

## *Significance in physics*

The laser opens many doors for the physicist and even for the radio engineer. To the physicist it is a tool for studying stimulated emission, a source that extends his available coherent radiation spectrum and a means to study natural lifetimes. For the radio engineer it is the next step in higher-frequency radiation with wavelengths much shorter than his circuit elements, and it is a low-noise source at frequencies where he did not have one before.

Laser operation has furthered theoretical and experimental work on stimulated emission in the optical spectrum. It has expanded interest in coherence concepts and caused reexamination of older ideas in this realm. That the laser is a coherent source is not as important as the extension of the coherent spectrum by a factor of  $10^4$ .

At radio frequencies, circuit elements typically are small compared with wavelength. When microwave technology was developed, new circuitry had to be devised because microwave circuit elements and wave-



AIR ARCS generated by Korad Corp.'s K-1500 ruby laser with a brightness of more than  $2.5 \times 10^{14}$  watts/cm<sup>2</sup>/steradian.

—FIG. 1

length are about the same size. Now, a new set of problems must be handled because circuit elements are much larger than the operating wavelength and, in particular, such problems as high mode densities, mode selection, etc., must be considered.

At microwave frequencies, radiationless (thermal or collisional) processes usually determine excited-state lifetimes whereas at laser wavelengths, radiative or nearly radiative lifetimes are common. Consequently, when dealing with lower-frequency stimulated-emission amplification, ambient thermal noise is a major limiting factor. At optical wavelengths, however, spontaneous emission is the dominant factor, contributing some 20 000° K per mode. If we also consider proliferation of available modes, it becomes clear why it is difficult to make a low-noise optical amplifier.

Any coherent generator has effective dimensions of the order of the wavelength. Since the optical spectrum is some  $10^4$  times higher in frequency than the high end of the microwave spectrum, it is possible in principle to concentrate energies to an area more than  $10^8$  times smaller than was formerly possible. In some lasers the radiated energy can be compressed into a very short time, a pulse of the order of  $10^{-8}$  sec or less, so

that during this pulse, peak powers of  $10^9$  watts or more are produced. Such powerful lasers have not been able to achieve the theoretical limit of concentrating the entire energy into an area of wavelength squared, but extremely large flux densities (approximately  $5 \times 10^{14}$  watts/cm<sup>2</sup>) have been attained. This implies an oscillating electric field of the order of  $3 \times 10^8$  volts/cm and an oscillating magnetic field of 1 megagauss.

These enormous field strengths have provided a tool for the study of nonlinear phenomena at optical wavelengths. In fact, nonlinear optics is a wholly new field that has been opened up by the development of the laser, and vast amounts of theoretical and experimental work have been pursued. Whereas harmonic generation at lower frequencies (radio and microwave portions of the spectrum) is commonplace, harmonic generation in the optical spectrum was attainable only in principle before the advent of the laser. Now harmonic generation has become a practical method of extending the number of available coherent wavelengths.

Other nonlinear phenomena are also easily accomplished with lasers. By nonlinear mixing of coherent light of different wavelengths, one can produce useful quantities of sum and dif-

ference-energy. Parametric oscillation and amplification at optical wavelengths are also possible by using the laser as a pumping source, thus further increasing the number of available wavelengths. When using the laser as a Raman source, another new phenomenon is sometimes possible: stimulated Raman emission. Thus, still another fruitful field of study and another source of additional coherent wavelengths are available.

The Raman effect is observed when electromagnetic radiation interacts with certain materials. The incoming energy is nonlinearly mixed in the material with vibrational frequencies characteristic of that medium. Scattered radiation at the sum and difference-frequencies is observed.

### *Classes of lasers*

The laser does not exist as a single device, but rather as 50 or so different types. The characteristics of some of them are shown in the table. Each has its own properties of wavelength, environmental temperature, efficiency of energy conversion, ease of modulation, excitation method, etc.

Many different time sequences are available: single-shot (at intervals of seconds or minutes), repetitively pulsed and continuous-operation. In conventional operation of pulsed la-



SUBSONIC SMOKE JET seen in the planar light from an ultraviolet nitrogen laser operated in short-pulse mode with peak power of 100 kW. —FIG. 2

sers, pulsewidths of 10–1000 microsec are typical. Operations in a Q-switched mode results in pulses in the 10–100 nanosec range. By employing mode-locking techniques, we obtain pulses shorter than  $10^{-11}$  sec.

Q-switching is a method of producing ultra-short laser pulses. A medium potentially capable of emitting stimulated optical radiation is excited but prevented from coherently emitting by means of a mechanical or electrooptical shutter. The energy stored in the excess upper state population of the medium is released in a brief transient of coherent radiation when the shutter is opened quickly-

ly—at a predetermined moment.

Of the many lasers that have been demonstrated in the laboratory, only a few have proved practical with regard to ease of operation, special material handling, efficiency, cryogenics, etc. These surviving few are available commercially or can be constructed relatively easily in the laboratory. The special types are best left to experts.

We can separate the various types of lasers into three major categories with further subdivisions. The first category is the optically pumped laser, which generally uses a fluorescent solid as the active medium (although, in special cases, liquids and gases have also been used). The excitation source that produces an inverted population and hence the stimulated emission is a pumping lamp. A number of different solid materials have proved useful, and wavelengths range roughly from 0.5 to 2.5 microns. Only three materials continue to be particularly important—ruby, which emits at 0.69 microns and neodymium-doped glass, which emits at 1.06 microns and neodymium-doped yttrium aluminum garnet (YAG), which also emits at 1.06 microns.

Both ruby and neodymium glass are most useful as short-pulse lasers although both have also been operated continuously. Neodymium-YAG is useful both as a repetitively pulsed material and a continuous source. Ruby and glass lasers can produce short pulses with peak powers in the neighborhood of  $10^9$  watts or more (figure 1). The YAG laser easily produces several watts continuously.

The second major category is gas lasers. These devices derive their excitation from an electrical discharge. Again, many different gases and gas combinations have been made to “lase.” Countless wavelengths have been produced—all the way from the near ultraviolet at 0.3 microns to the far infrared at as much as 100 microns. For most scientific applications, however, only a few gas lasers have proved practicable. Primary among these is the helium-neon laser, with strongest emissions, easily attainable, at 1.15, 3.39 and 0.63 microns. The last wavelength is the most popular because it is visible and thus more easily used. This particular laser is usually operated continuously with typi-

cal power outputs of a few milliwatts.

Another important gas laser uses singly ionized argon as the active medium. Several different wavelengths are simultaneously available from this particular laser with predominant emission in the green, blue-green, and violet. The two strongest lines are 0.4880 and 0.5145 microns. Argon lasers can be operated continuously with outputs of several watts or repetitively pulsed with average powers ranging from a milliwatt to a watt. Another similar laser has singly ionized krypton and is useful in providing additional wavelengths not available from argon. The powers and efficiencies are somewhat lower than argon.

A third class of gas lasers is typified by the carbon-dioxide laser. This type is usually made with a mixture of gases to help improve efficiency. A popular mixture uses nitrogen and helium along with the carbon dioxide. This particular laser is unusual in several aspects. First, the emitted wavelength is 10.6 microns, quite a bit longer than most other practical lasers. Further, its efficiency in producing power is some 10–15% compared with efficiencies of 0.01–1% for most other lasers. This laser is almost always operated continuously at output powers of several watts to a kilowatt or more.

Another special gas laser uses nitrogen as the active medium (figure 2). This laser is important because it directly generates ultraviolet at 0.3371 microns. It is operated in a repetitive short-pulse mode with peak powers of around 100 kW.

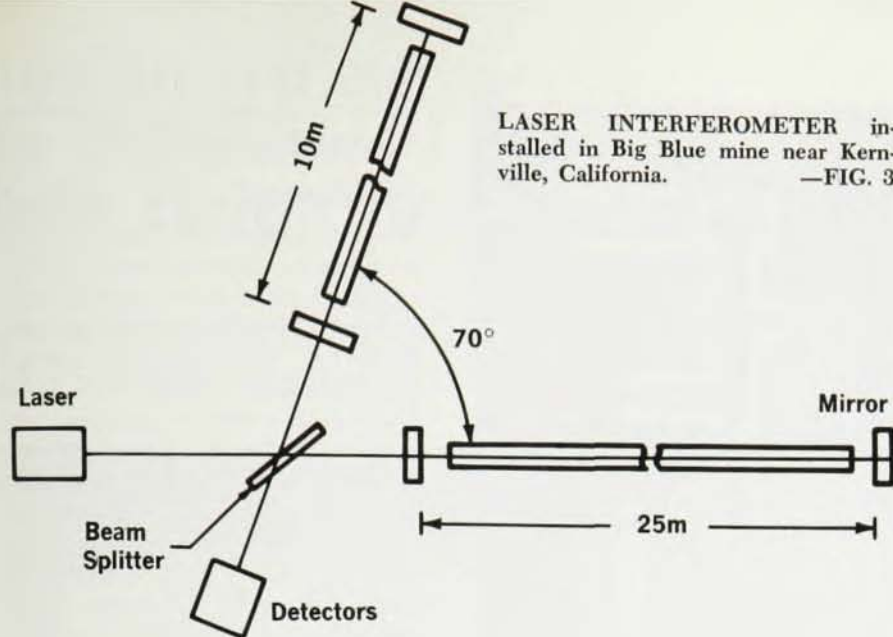
The third major category is the electron-injection semiconductor laser. Excitation is provided by electron flow across a semiconductor junction. Again, a wide number of materials have been used, covering a wavelength region from approximately 0.6 to nearly 10 microns. In this category as in the others, however, a restricted number of lasers has actually proved practical. The leading semiconductor laser uses gallium arsenide with output wavelength varying between approximately 0.84 microns (when it is operated at liquid nitrogen temperature) and 0.90 microns (when it is operated at room temperature).

When cooled well below room temperature, this type of laser can be ei-

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LASER INTERFEROMETER installed in Big Blue mine near Kernville, California. —FIG. 3



ther operated continuously or repetitively pulsed with typical average output powers of 1–10 watts. Room-temperature environment requires short-pulsed operation. Here, peak powers of 10 to 30 watts at repetition rates of 1 kilohertz are typical. Since most scientific benefits of the laser can be traced generally to its great brightness, however, and since the semiconductor laser offers low brightness when compared to other lasers, this device has limited application as a scientific tool.

#### Applications

The laser offers a wide diversity of applications, each stemming from one or

more of its characteristics. Power density and monochromaticity are exploited in studying reflectance, light scattering from plasma, Rayleigh scattering and Raman spectra and in creating high plasma densities. Enormous spectral brightness (effective temperatures of  $10^{10}$ – $10^{20}$  °K) offers advantages in the study and production of nonlinear phenomena and analysis of bodies at relatively high laboratory temperatures. Laser characteristics have also helped to create more sensitive instruments for interferometry, photography Doppler-shift measurements and for the new field of holography.

It is practical, for instance, to mea-

sure the reflectance of a hot material by using the laser as a monochromatic probe; the laser's high brightness allows the reflected light to be discerned easily from the background of the glowing body being investigated. Similarly a laser can be used to study scattering from an extremely hot plasma; the scattered light, with proper auxiliary instrumentation, stands out despite the high radiation intensity of the plasma itself.

The enormous power density that can be produced from a Q-switched, short-pulse laser leads to several applications, among which are electrical breakdown of gases (with a resultant plasma having electron densities of the order of  $10^{18}$  cm<sup>-3</sup>), thermionic emission and vaporization of materials for such fields as chemical-emission spectroscopy and mass spectroscopy.

The laser's intensity and monochromaticity offer distinct advantages in, for example, Rayleigh-scattering experiments. This application has revealed that the spectral width of the laser probe radiation, as explained by Doppler broadening in the medium under analysis, is greater than the width of the laser probe radiation.

With the laser, it is not at all difficult to generate second harmonic power outputs that are at least 10% of the fundamental output. Very powerful short pulses of 0.53-micron green light can be produced from a 1.06-micron neodymium laser, and

Laser Types and Their Characteristics

| Laser           | Wave-length<br>(microns)             | Contin-<br>uous<br>power<br>(watts) | Q-<br>spoiled<br>peak<br>power<br>(MW) | Conven-<br>tional-<br>mode<br>energy<br>(joules) | Pulse-modulation         |                      |                      | Raw<br>beam<br>angle<br>(milli-<br>radians) |
|-----------------|--------------------------------------|-------------------------------------|----------------------------------------|--------------------------------------------------|--------------------------|----------------------|----------------------|---------------------------------------------|
|                 |                                      |                                     |                                        |                                                  | Pulse<br>width<br>(μsec) | Rep<br>rate<br>(pps) | Avg<br>power<br>(mW) |                                             |
| He-Ne           | 0.6328<br>1.15<br>3.39               | 0.001–0.1                           |                                        |                                                  |                          |                      |                      | 1                                           |
| Ar <sup>+</sup> | 0.4880<br>0.5145                     | 1–10                                |                                        |                                                  | 10–100                   | 50–1000              | 1–100                | 1                                           |
| Kr <sup>+</sup> | 0.6471<br>0.5681<br>0.5208<br>0.4762 | 0.5                                 |                                        |                                                  | 10–100                   | 50–1000              | 0.5–50               | 1                                           |
| CO <sub>2</sub> | 10.6                                 | 10–1000                             | 0.01                                   |                                                  |                          |                      |                      | 1                                           |
| N <sub>2</sub>  | 0.3371                               |                                     | 0.1                                    |                                                  | 0.010                    | 1–100                | 1–100                | 2 × 20                                      |
| Ruby            | 0.6943                               | 1                                   | 10–1000                                | 1–500                                            | 1000                     | 1                    | 25 000               | 1–10                                        |
| Nd-glass        | 1.06                                 |                                     | 10–1000                                | 1–1500                                           | 0.020                    | 1–10                 | 100–1000             | 1–10                                        |
| Nd-YAG          | 1.06                                 | 1–100                               | 1–10                                   | 0.1–1                                            | 0.010                    | 1–50                 | 100–5000             | 2–5                                         |
| GaAs            | 0.84–0.9                             | 1–10                                |                                        |                                                  | 0.050                    | 100–1000             | 100–1000             | 20 × 400                                    |

similarly, powerful pulses of 0.3471-micron ultraviolet light can be produced from a 0.6943-micron ruby laser.

Raman spectra—which ordinary sources might take hours of exposure to reproduce on film—can be done in seconds or even a fraction of a second by using a laser as the source. Weak Raman lines that had not previously been observed at all have been seen with a laser and, in some cases, strong Raman lines actually have lased.

A combination of nonlinear phenomena can be used to extend further the spectrum of wavelengths obtainable from a one-stage laser. Ruby laser emission at 0.69 microns can be used, for example, to generate stimulated Raman lines in dimethylsulfoxide at 0.87 microns, and this light can in turn be passed through a harmonic generating crystal (such as potassium dihydrogen phosphate) to produce 0.43-micron radiation.

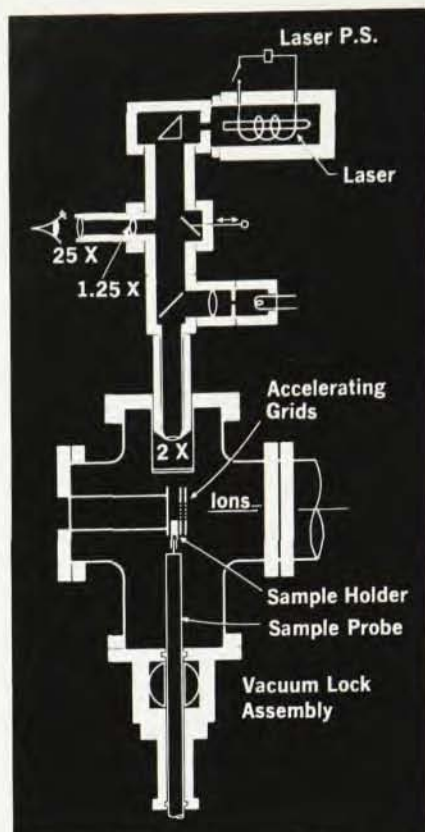
The laser also offers distinct advantages in chemical-emission spectroscopy. Since one can focus the beam to a tiny spot, only a minute portion of the material under study need be sacrificed. Further, the temperature of the heated area is at least as high as, and usually higher than, temperatures generated by conventional carbon-arc sources. And, of course, the laser greatly reduces chance of contamination. The laser also is advantageous in a time-of-flight mass spectrometer because it can serve as a precisely timed ion source (figure 4).

The laser is also being used as a probe to investigate thermal conductivity of materials; it is particularly useful when the material to be studied is hot. In this application, one delivers a short, precisely timed pulse to the sample and measures the propagation time through the material.

The laser can initiate photochemical reactions; this application exploits three of the device's characteristics: high energy density, short pulse (which permits studies of the kinetics of the reaction) and concentration of the energy at one wavelength (which permits the study of reaction selectivity as a function of wavelength).

#### Doppler-shift instruments

Laser monochromaticity permits sensitive instrumentation based on Doppler



ION SOURCE for time-of-flight mass spectrometer. Laser bursts, reflected by prism, vaporise sample, producing ions for spectrometer. —FIG. 4

shifts. In each case the scattered or reflected beam is mixed with a sample of the original beam, which acts as a reference. The two are heterodyned in a photodetector and the difference frequency detected. One example is a fluid flowmeter—a laser velocimeter. The only requirements are that the flow be through a transparent tube and that some degree of particle suspension be present in the flowing medium. Very small volumes within the total flow cross section can be examined selectively, permitting the study of flow gradients and turbulence. Because of laser brightness only a little scattering is necessary for adequate detection. Ordinary city tap water functions well.

A laser Doppler receiver can measure velocities of moving or vibrating bodies and can serve as an accelerometer by differentiation of the velocity display.

A laser arranged so that its feedback path is around a ring forms an ultra-sensitive gyro. The rotation is sensed by heterodyning the Doppler shift be-

tween the clockwise and counterclockwise traveling waves.

#### Interferometry

The very narrow spectral emission and hence long coherence lengths characteristic of lasers make possible sensitive instrumentation based on interferometry. The most obvious example is in metrology where much longer distances can now be measured with interferometric sensitivity than could be previously with nonlaser sources.

Various techniques have been devised to detect seismologic disturbances sensitively with laser interferometry (figure 3). Spectral brightness makes the laser useful as a source in Twyman-Green interferometry where one studies the effects of a prism, lens or other optical component upon a wavefront.

Holography has aroused a great deal of scientific interest because of laser availability. An object to be examined is illuminated and the scattered light allowed to interfere with a sample of the original light. The resulting interferogram is recorded on a photographic plate and retains three-dimensional information.

#### Photography

The laser also has been employed in other areas of photography. High intensity makes it useful as a source for a schlieren camera. The very short intense pulses available from Q-switched lasers enable photography of extremely fast motion.

A sophisticated technique uses the short-pulse laser as illumination for photographing and viewing objects separated from the source by scattering medium such as sea water, smoke or haze. In this case we equip the camera with a fast shutter such as a Kerr or Pockels cell. The shutter is synchronized with the laser pulse and delayed so that it does not open until the reflected light from the subject reaches the camera. By this time the backscatter has already passed beyond the camera and is not recorded. Fast circuitry is required, but, in practice, viewing distances as short as 1 meter have been successfully achieved (7-nanosecond round-trip time).

Finally the inherent collimation of the laser beam makes it suitable for aligning and autocollimating. □