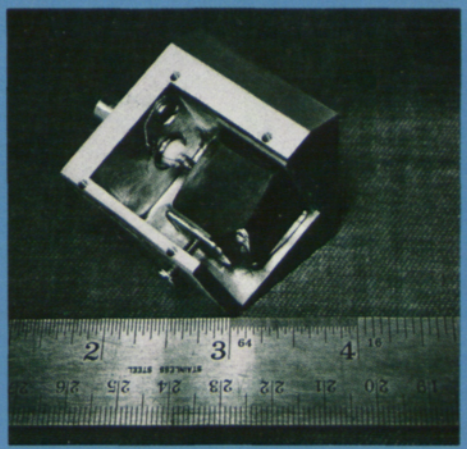
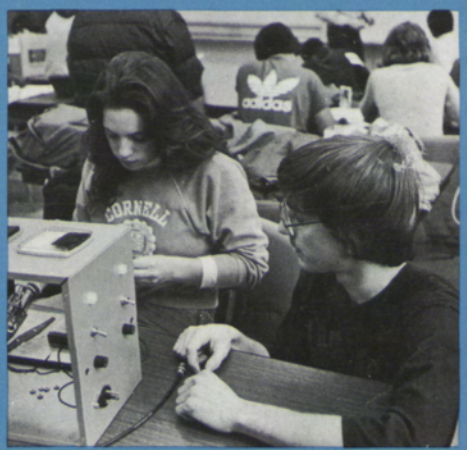
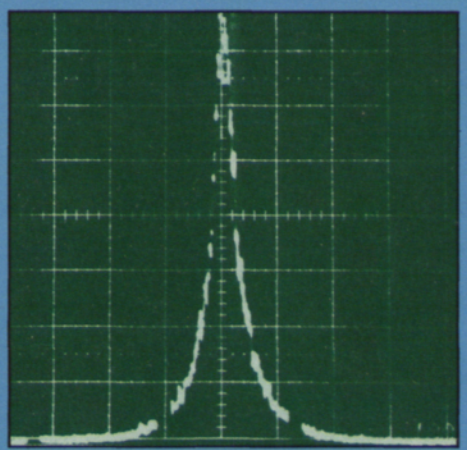
ENGINEERING

CORNELL QUARTERLY







VOLUME 19
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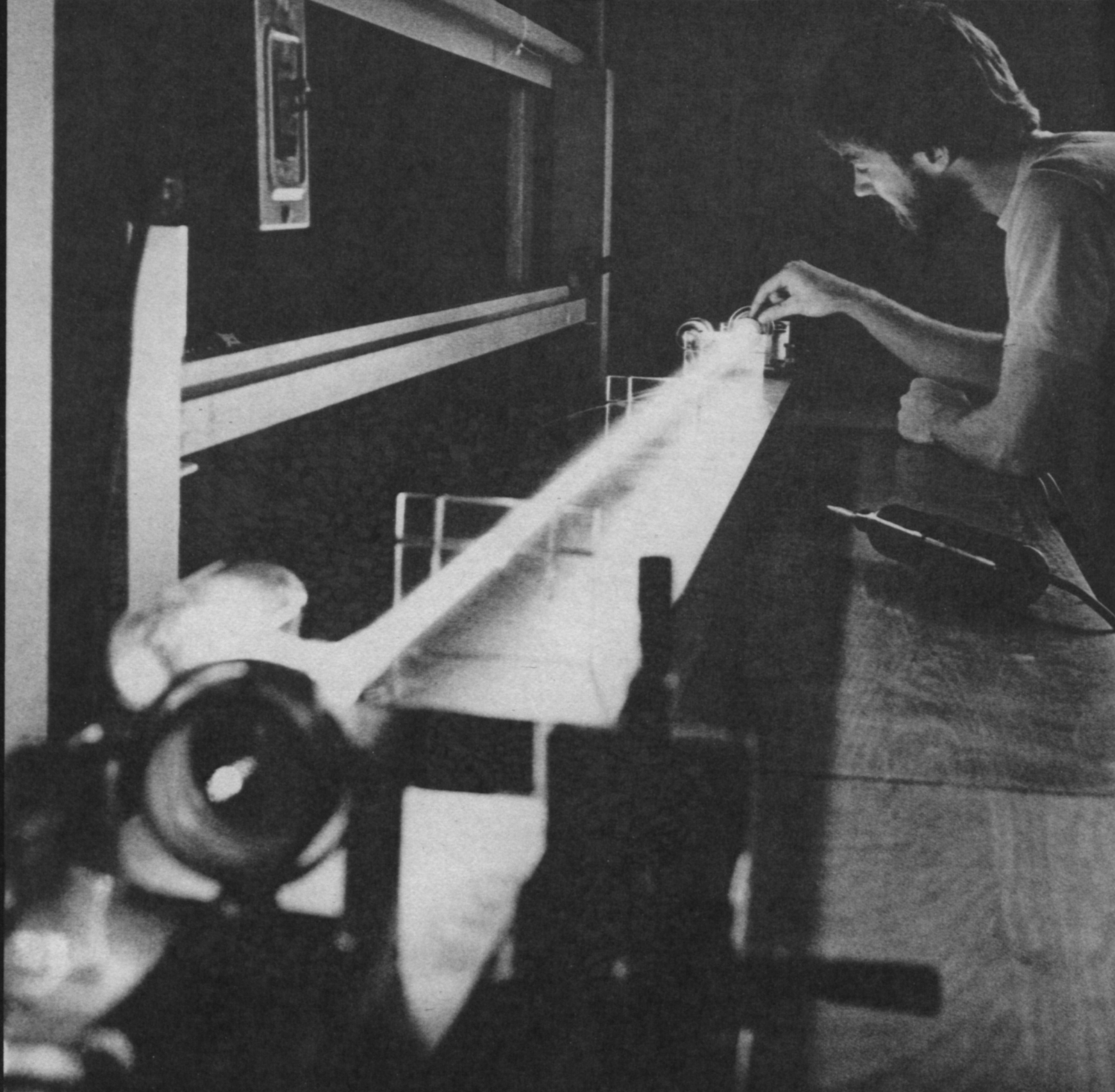
SUMMER 1984

THE POWER
OF OPTICS
FOR TECHNOLOGY



IN THIS ISSUE

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Outside cover (clockwise from noon): From George Wolga's laboratory, an experimental infrared spectroscopic sensor based on a tunable acousto-optic filter; a tunable dye laser in Clifford Pollock's laboratory; a trace of femtosecond laser pulses generated in C. L. Tang's laboratory; Cornell undergraduates learning about lasers by building them in a recently introduced course taught by Terrill Cool.

Opposite: A Cornell graduate student adjusts the spatial modes of a gas laser.

FEMTOSECOND LASERS

Key to the Measurement of Ultrafast Processes in Semiconductors and Molecules

by C. L. Tang

How fast is fast? Nothing can travel faster than the speed of light. To travel a distance of one millimeter, it takes light only about three trillionths of a second, or three picoseconds (1 picosecond = 1 trillionth of a second, or 10^{-12} second). That is fast. Or is it?

Until recently, scientists thought of "ultrafast" processes in physics and chemistry as occurring in intervals on the order of a few picoseconds. About ten years ago, scientists began to learn how to measure such "ultrafast" processes using picosecond lasers; anything faster than that was generally considered "instantaneous"—too fast to measure or study experimentally.

Within the last three years, as a result of work carried out mainly at Bell Laboratories, Cornell, IBM, and—more recently—MIT, there have been dramatic advances that promise to change the concept of what "really fast" means. New laser techniques now make it possible to measure physical and chemical processes occurring one hundred times faster than it takes light to travel a distance of one millimeter. Phenomena can be studied with a time resolution down to approximately 30 femtoseconds (1 femtosecond = 1 thousandth of a picosecond, or 10^{-15} second). What was previously considered "instantaneous" is now either measurable or, if still too fast to measure, more sharply defined by two orders of magnitude. From this new perspective, picosecond phenomena are now considered "slow"; femtosecond processes are FAST.

NEW QUESTIONS, NEW IMPLICATIONS

This opens up a whole new world of phenomena to be studied and questions to be answered. Although many of these questions might seem remote to those who are not specialists in the field, some of them are relevant to practically everyone.

What to expect from electronic devices is one example. With the current trend toward ever smaller and faster electronic devices, it is reasonable to ask what their ultimate speed is likely to be. With femtosecond lasers (see Figure 1), it is now possible to begin to

Figure 1

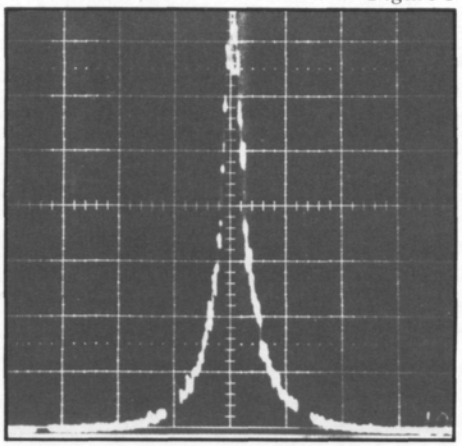


Figure 1. An autocorrelation trace of 55-femtosecond laser pulses. These pulses, obtained in Cornell research, were and still appear to be the shortest that have been generated directly from a laser. Such pulses can be further shortened by using additional pulse-compression techniques external to the laser; for example, workers at the Massachusetts Institute of Technology recently compressed a laser-generated pulse down to 15 femtoseconds, thus achieving the shortest light pulse ever generated. The Cornell work was done in late 1981 by Jean-Marc Halbout, then a graduate student of Professor Tang.

Figure 2

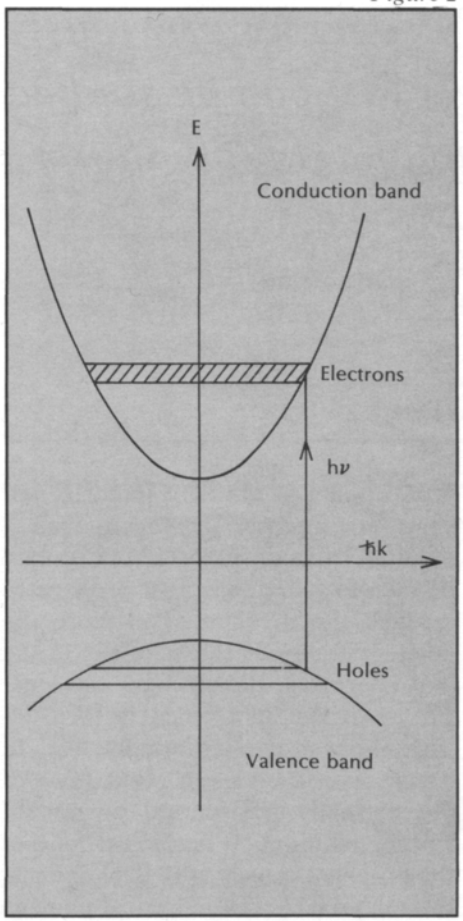


Figure 2. Schematic illustrating what happens when electrons are excited by an optical pulse. The absorption of a photon of energy (hν) will cause an electron to move from the valence band into the conduction band in a semiconductor. The solid curves show the energy (E) of an electron as a function of its momentum (ħk) in the solid.

answer this question. The ultimate speed of electronic devices is limited by how fast electrons in semiconductors can be manipulated. The intrinsic response time of semiconductors is known to be in the subpicosecond time domain, but until recently, these characteristic times could only be inferred indirectly. Now, with the femtosecond lasers, they can be measured directly.

Another question is how materials can be damaged or protected from damage by intense laser light—presumably a matter of general concern in the context of current talk about laser weapons and defense. (At Cornell we are not, of course, working on such problems directly.) Femtosecond laser techniques can be used to study the dynamic behavior of molecules agitated by intense light. Obviously, research on this and other problems associated with molecular processes is significant not only because of possible applications, but because of its basic scientific interest.

MEASURING VERY FAST PROCESSES IN MATERIALS

How are these very fast processes actually measured? It is simple in principle. Basically, one sends into the sample to be measured two short optical pulses separated by a variable delay. The first pulse "pumps" or perturbs the medium and the second pulse "probes" the disturbance produced in the medium by the first pulse. By varying the delay between the two, it is possible to measure the dynamic characteristics of the physical process responsible for the disturbance.

The difficulties are all experimental: one must generate short enough pulses, and develop good enough signal-processing techniques to detect the very small effects on the probe pulse. These problems have now been solved.

HIGH-SPEED ELECTRONS IN SEMICONDUCTORS

In the case of semiconductors, for example, the disturbance in the medium is caused by optically excited electrons (see Figure 2). When a valence electron absorbs a photon of sufficiently high energy, it acquires the energy of the photon and becomes excited. Such excited electrons are able to move about in the solid in response to applied electric fields, and so are the positively charged "holes" that are a consequence. The electrical properties of a semiconductor are determined by such mobile charged carriers.

An understanding of the dynamics of these carriers is essential to an understanding of semiconductor devices. We know, for example, that in the

"Processes previously unimaginatively fast can be studied in times unimaginably short."

presence of the optically excited mobile carriers, the material becomes more transparent—or less absorbing—to the probe pulse. However, this change in transparency decreases with time after the passage of the first pulse, as more of the initially excited electrons and holes lose their energy, and this decrease provides a way of measuring the lifetime of the excited carriers. It is done by measuring the change in the absorption of successively delayed probe pulses to yield the relaxation time as a function of carrier density (see Figure 3). It is this characteristic time—the measured lifetime or relaxation time—that mainly determines the speed with which the carriers respond to applied electric fields, and it is this response time that in turn determines the ultimate speed of semiconductor devices.

In my laboratory at Cornell, the ultimate response time of gallium arsenide (GaAs), which is an important, commonly used semiconductor, has recently been measured and found to be at least as fast as 30 femtoseconds. (Collaborators in this research were Antoinette J. Taylor, a postdoctoral associate, and David J. Erskine, a graduate student.) But to take advantage of such a fast response time, the critical features of the device must be small—less than 500 Å. The technique used in this experiment has also been applied to a variety of other useful semiconductors such as germanium, aluminum gallium arsenide (AlGaAs), and cadmium selenide, and structures such as GaAs/AlGaAs quantum wells.

STUDYING THE PROBLEM OF OPTICAL DAMAGE

The connection between the dynamics of molecules and the optical-damage problem is a little more involved.

At low levels of light intensity, the optical index of refraction of most transparent materials is a constant. However, as the light intensity increases, the medium can become slightly nonlinear in the sense that the index of refraction (n) can become intensity-dependent (see Figure 4). In addition to the constant term (n_0), there is a term ($n_2 I$) that is linearly proportional to the light intensity (I). Thus, an intense light beam with a nonuniform intensity profile can create its own focusing lens as it propagates through the medium. The more the beam is focused, the stronger is the lens it creates; the stronger the lens, the more the light beam is focused. This process can eventually lead to catastrophic damage or breakdown of the normally transparent or nonabsorbing medium. It is, in fact, one of the principal causes of optical damage to materials. (The optical-damage mechanism for absorbing media is, of course, totally different; it does not involve the kind of phenomena discussed here, but is primarily thermal.)

The change in refractive index in a material can be caused by various electronic and molecular processes, the latter being more important for typical solids and liquids. In the presence of intense light, the index change occurs because the constituent molecules of the material become distorted or rotate (see Figure 5). The response time associated with such molecular distortions and rotations is extremely fast,

Figure 3

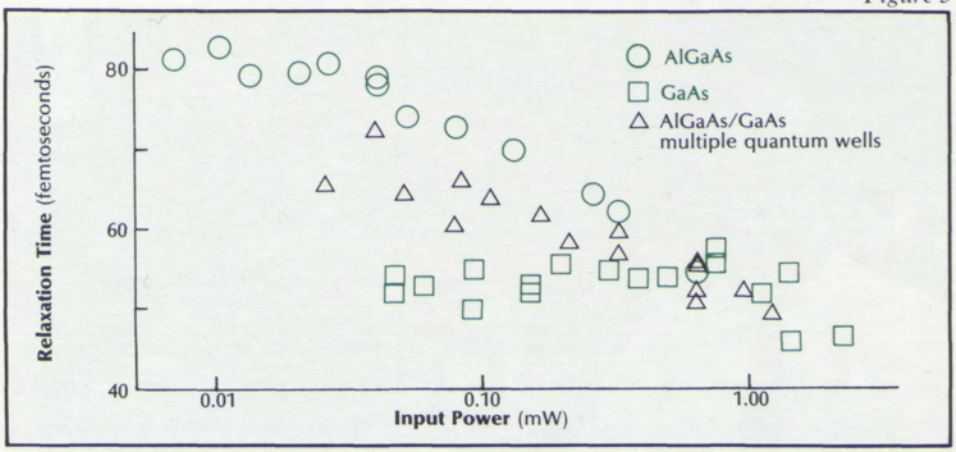
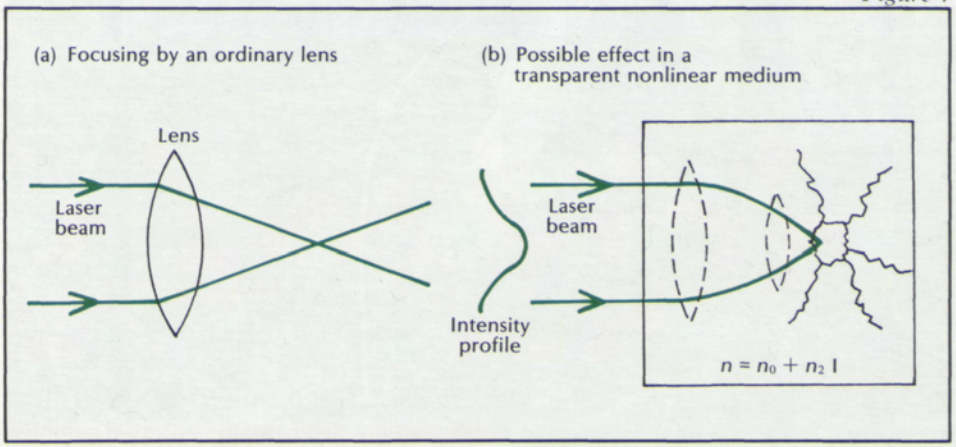


Figure 4



varying typically from tens of picoseconds down to the subpicosecond time domain.

Femtosecond laser measurements provide a way of studying the dynamics of these very fast molecular processes. The method is to induce refractive index change in the medium by exposing the material to an intense femtosecond laser pulse, and then measure the response to successively delayed probe pulses. In my laboratory, Taylor and Erskine have used such techniques to measure the fem-

Figure 5

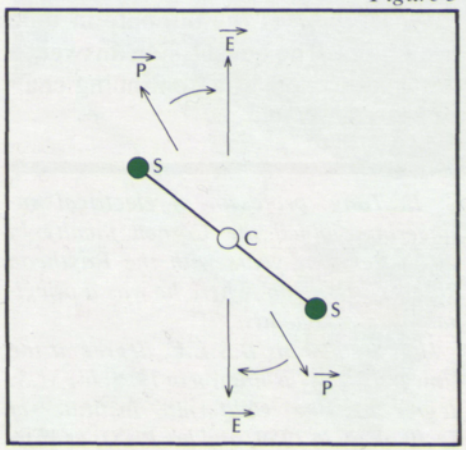


Figure 3. Experimental evidence of one of the fastest physical processes ever measured. Relaxation time, a measure of the lifetime of conduction electrons, is shown for two semiconductors and a related quantum-well structure as a function of input laser power, which is proportional to the concentration of charge carriers. The relaxation times, which are on the order of 30 to 60 femtoseconds, are a measure of how long electrons moving with a velocity of approximately 1 to 2 X 10^8 cm/sec can maintain their initial velocity.

The semiconductors measured in the experiment represented here are GaAs and $Al_{0.32}Ga_{0.68}As$. The quantum-well structure consists of alternating layers of GaAs and AlGaAs; the thicknesses of the layers is 148 Å and 360 Å, respectively.

Figure 4. Illustrations showing how self-focusing of the laser beam can lead to optical damage or breakdown of normally transparent materials. The diagram in (a) shows how an ordinary lens focuses a light beam. The diagram in (b) shows that if the index of refraction (n) of the material is dependent on intensity (I), a nonuniform beam can create its own focusing lens. As the beam propagates, the lens becomes stronger and stronger, leading ultimately to catastrophic damage or breakdown.

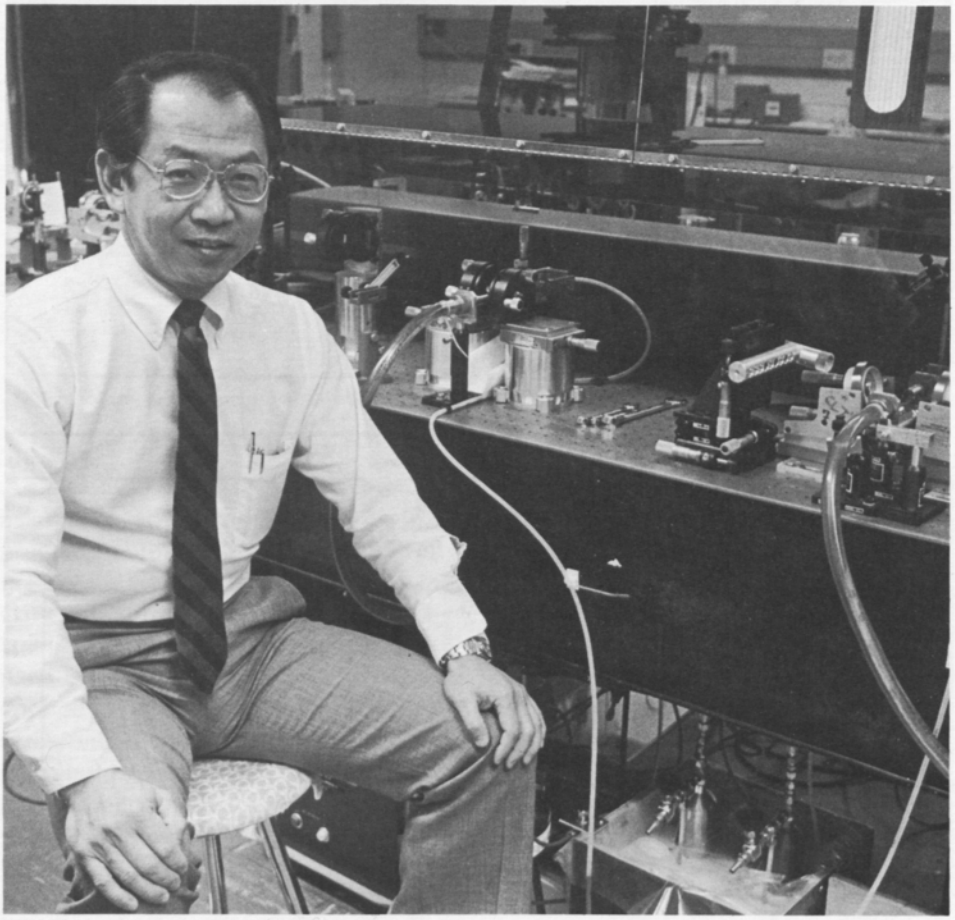
Figure 5. Optically induced molecular rotation. The electric field E of the optical wave induces a polarization P in a CS_2 molecule, which will then rotate, if it can, to lower its potential energy in the field. This leads to an alignment of the molecule by the field. The E-field in the optical wave may reverse its direction cyclically at a rate of more than 10^{14} times per second, but since any induced polarization also reverses direction, the molecule tends to rotate always in the same direction. Reorientation of the molecules or molecular distortion caused by a similar mechanism can lead to a change in the index of refraction of the medium.

tosecond vibrational relaxation of large organic molecules, and Jean-Marc Halbout, who was a graduate student at the time, studied the orientational dynamics of molecules in liquids.

A TRADITIONAL SUBJECT OF CURRENT IMPORTANCE

Cornell has a long history of research in quantum electronics and laser physics, and as the articles in this issue of the *Quarterly* demonstrate, the activity is continuing. The work in femtosecond optics and processes is part of this program of study.

The current interest in research involving femtosecond lasers derives partly from its technological implications, to be sure, but partly also from its reaching into the unknown. In time, as in space, the dimensional scale that is accessible for observation is being extended in the important direction of smallness. Processes previously unimaginably fast can be studied in times inconceivably short. Yet we must consider possibilities of even greater diminution.



What, then, is the ultimate in time resolution? The quest for an answer to this question poses a continuing challenge to our research.

C. L. Tang, professor of electrical engineering, joined the Cornell faculty in 1964 after four years with the Raytheon Research Division, where he was a principal research scientist.

He obtained his B.S.E.E. degree at the University of Washington in 1955, his M.S. degree at the California Institute of Technology in 1956, and his Ph.D. at Harvard University in 1960. As a recipient of a John Parker Traveling Fellowship from Harvard, he also studied at the Technical University in Aachen, Germany.

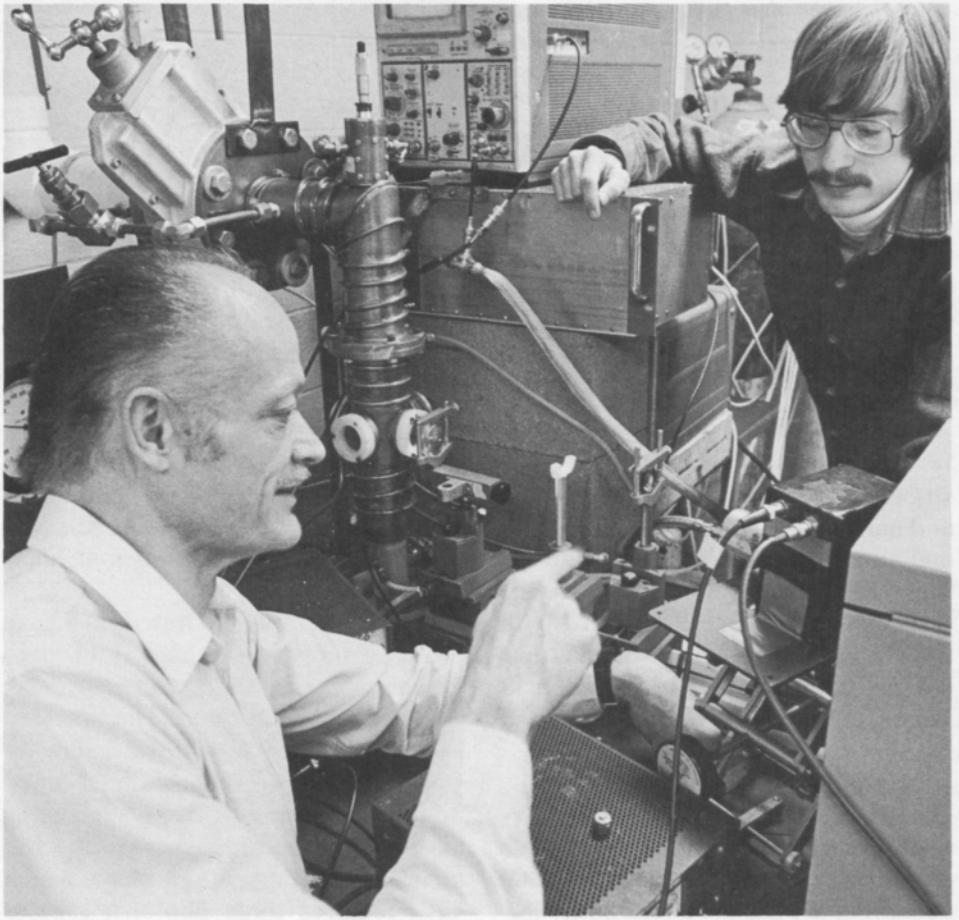
Tang is a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and of the American Physical Society. He is currently an elected member of the Administrative Committee of the IEEE Quantum Electronics and Applications Society. He chaired the Gordon Conference on Nonlinear Optics and Lasers, and this year he is co-chairman of the Program Committee of the 13th International Conference on Quantum Electronics.

LASERS FOR ULTRASENSITIVE DETECTION OF TRACE CHEMICALS

by Terrill A. Cool

The recent advent of high-energy tunable dye lasers has provided a tool for studying the smallest details of the dynamics of chemical reactions—information that is useful as well as scientifically interesting. For example, the development of more efficient ways to use our fossil fuel resources, or progress in the control of gaseous and particulate pollutants, depends on a knowledge of how hydrocarbons burn. With the new lasers, it is possible to detect and monitor the very small concentrations of active radical species that are important intermediates in the complex chemistry of hydrocarbon combustion.

In the School of Applied and Engineering Physics at Cornell University, we have been working with tunable dye lasers for many years, and in current studies we are using them to detect radical species in hydrocarbon flames. These lasers have high inten-



Professor Cool (at left) and Paul Tjossem, a graduate student, experiment with a dye laser beam focused within a low-pressure hydrocarbon flame.

Figure 1

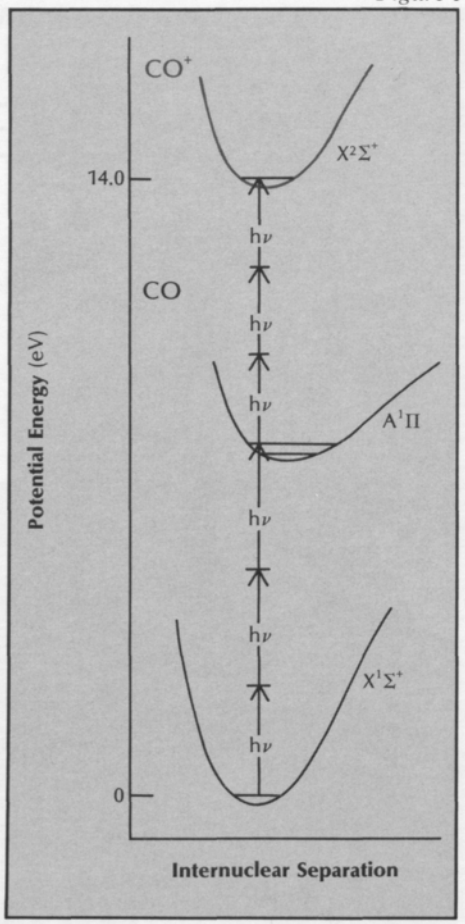


Figure 1. Detection of trace amounts of CO in a combustion gas by the laser technique of resonance enhanced multiple photon ionization (REMPI). The CO is selectively excited and then ionized by a precisely tuned laser beam.

Three electronic states of CO are shown. The ground state, CO ($X^1\Sigma^+$), is located 8 eV below the first excited singlet state, $A^1\Pi$, and 14 eV below the ground electronic state, $X^2\Sigma^+$ of the CO^+ ion. Three laser photons tuned to one of several precise wavelengths in the 4350-to-4700-Å region can be used to excite one of the low-lying vibrational levels to the CO($A^1\Pi$) state by the following resonant three-photon absorption:

$$3h\nu + CO(X^2\Sigma^+) \rightarrow CO(A^1\Pi).$$

The excited CO($A^1\Pi$) molecules are then rapidly ionized by the additional nonresonant three-photon step:

$$3h\nu + CO(A^2\Pi) \rightarrow CO^+(X^2\Sigma^+) + e^-.$$

sity (10^{10} watts per square centimeter) and narrow linewidth (less than 0.1 Å) and are capable of operation at wavelengths ranging throughout the visible to the near ultraviolet. With such lasers it is possible to detect trace species in the presence of a large background of other gases.

PHOTON IONIZATION FOR TRACE ANALYSIS

Suppose, for example, that we want to investigate the carbon monoxide (CO) content in the gas produced by hydrocarbon combustion. The technique we use for studies of this kind is *resonance enhanced multiple photon ionization* (REMPI).

The process is illustrated in Figure 1. Essentially, laser light is used to selectively excite the CO molecules and then to ionize them. The first step is accomplished by the resonant absorption of three laser photons tuned to one of several precise wavelengths in the 4350-to-4700 Å region. The nonresonant ionization step, which also requires three photons, follows rapidly. At laser intensities greater than 10^{10} watts per square centimeter, virtually every excited CO molecule is ionized before its excitation can be lost by radiative decay or collisional quenching.

The optical process is extremely nonlinear. In the CO ionization, for example, a total of six photons is required for the overall (two-step) process, and the density of CO^+ ions produced varies approximately as the sixth power of the laser intensity. Nonlinear optical processes like this can be observed only with the very high intensities provided by modern laser light sources.

WAYS OF DETECTING TRACE AMOUNTS OF CO

The detection of a trace concentration of CO may be accomplished by collecting either the CO^+ ions or the electrons produced in step 2. A mass spectrometer can be used for ion detection, and this can also provide a useful check on the identification of the ionized species. A simpler method for detecting and identifying species is to measure the electrons collected by a probe as the laser wavelength is varied.

Such an electron probe—one used by Paul Tjossem in his Ph.D. research—is illustrated in Figure 2. Designed to withstand the high-temperature oxidizing environment of hydrocarbon flames, this ionization probe is capable of detecting radical species at concentrations below the level of parts-per-million in flames at atmospheric pressure. Quantitative measurements of species densities to accuracies of ± 15 percent have been demonstrated.

Figure 2

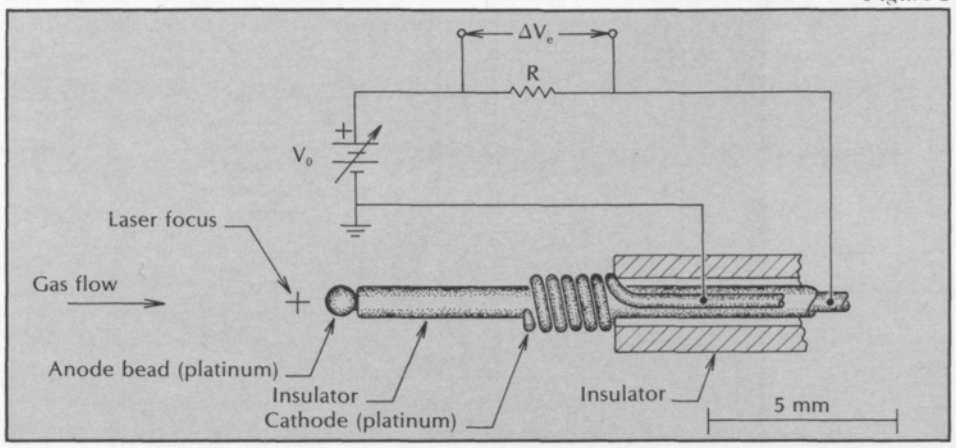


Figure 2. The electron-detection probe used at Cornell to measure trace amounts of species such as CO that are present in the gas released by hydrocarbon combustion. In accordance with the REMPI technique, the gas is exposed to precisely tuned laser light, which ionizes the CO and releases electrons. The electrons are drawn to the probe's spherical platinum anode and the current is measured. The data provide species density measurements with excellent temporal (microseconds) and spatial (submillimeter) resolution.

A REMPI ionization spectrum obtained with this probe is shown in Figure 3. CO in a CH_4/O_2 flame is being measured. The spectrum represents measurements, over a range of laser wavelengths, of the number of electrons collected by the probe; the spectrum corresponds to step 1 of the laser-interaction process. Such a spectrum serves to identify the absorbing species and also provides a direct measurement of the flame temperature to an accuracy of ±75°K.

Figure 3

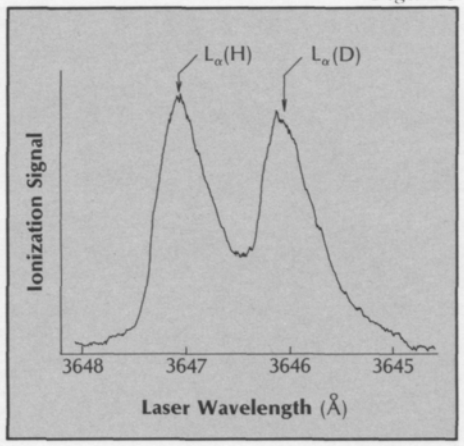


Figure 3. A spectrum obtained with the probe shown in Figure 2. This is for CO in a CH_4/O_2 flame. The spectrum corresponds to the resonant three-photon absorption between the ground vibrational level of the CO and the first vibrationally excited level, as indicated in Figure 1. The spectrum shows the clearly resolved rotational structure of this absorption band.

METHOD OF CHOICE FOR ELUSIVE SPECIES

An example of the use of the REMPI method for the detection of flame species that are difficult to monitor by any other technique is illustrated in Figure 4. In this case, hydrogen and its isotope deuterium are detected through a four-photon REMPI process. The figure shows the ionization spectra obtained at laser wavelengths in the 3645-to-3648 Å region from a $H_2/D_2/O_2$ flame. At 3647 Å, three photons per atom are absorbed in the excitation of hydrogen, and then each

Figure 4

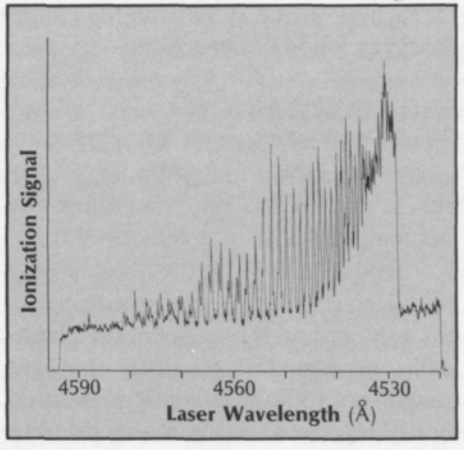


Figure 4. Detection of hydrogen and deuterium in combustion gas by the REMPI method. Three photons from 3647-Å laser light are absorbed in the Lyman-α transition H(1s)→H(2p), and the excited H(2p) atoms are then ionized by a fourth photon. The two peaks correspond to the Lyman-α resonances for H and D atoms. The peaks are separated by an isotope shift of 22.4 cm^{-1}. The substantial Stark broadening the exhibit is caused by the intensity of the electric field of the laser beam.

Figure 5a

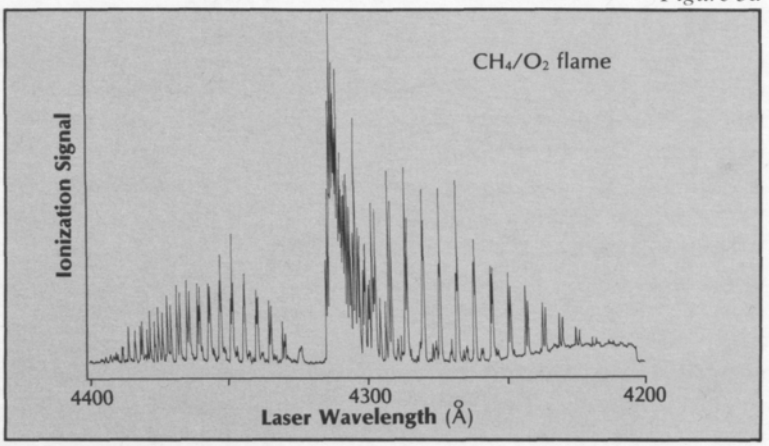


Figure 5b

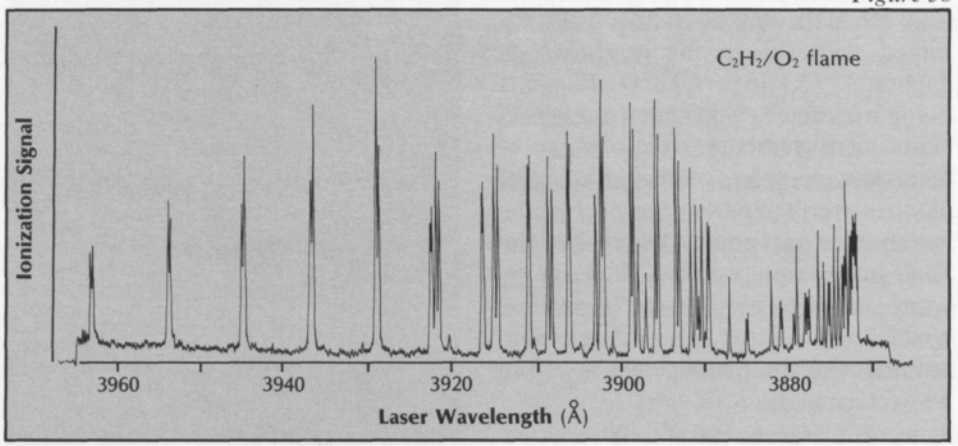


Figure 5. Ionization spectra demonstrating the enhancement of chemi-ionization in hydrocarbon flames. A tunable dye laser was used to excite CH radicals to the states CH($A^2\Delta$) and CH($B^2\Sigma^-$). The spectra correspond to the detection of electrons released by chemi-ionization following single-photon absorption. Candidate reactions capable of the observed chemi-ionization are:

$$CH(A^2\Delta, B^2\Sigma^-) + O \rightarrow CHO^+ + e^-$$

and

$$CH(A^2\Delta, B^2\Sigma^-) + C_2H_2 \rightarrow C_3H_3^+ + e^-.$$

of these excited atoms is ionized by the absorption of a fourth 3647-Å photon. The other peak reflects the resonance for deuterium atoms.

Although the use of REMPI methods for flame radical detection is now only two years old, it is clear that this approach will provide an accurate means of monitoring many species of importance in combustion chemistry. Species that have been detected by REMPI include C, O, H, PO, NO, NO_2, HCO, CH, CH_3, CO, C_2O, and CH_3O. Many others, such as CH_2 and HO_2, may prove to be feasible candidates for REMPI detection.

SOOT FORMATION IN HYDROCARBON FLAMES

Laser ionization methods may also prove useful for understanding the mechanisms of soot production in hydrocarbon flames. In the past twenty years, much study and controversy has centered on the origin of the chemically produced flame ions that are precursors to soot formation. A commonly accepted source of this primary flame ionization is the reaction between CH radicals in the ground electronic state and O atoms to produce ions and electrons. Electronically excited CH radicals have also been cited frequently as possible sources of chemi-ionization, but our work has provided the first direct proof of the existence of such reactions.

In recent experiments we have used a tunable dye laser to excite CH radicals by single-photon absorption in CH_4/O_2, C_2H_2/O_2, and C_2H_4/O_2 flames. The resulting ionization

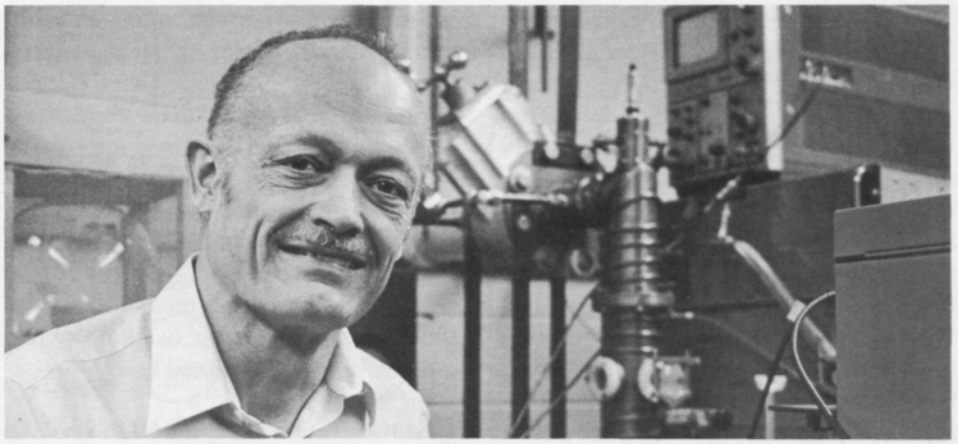
"Possible applications range from laser-based isotope separation and chemical purification to the detection and screening of cancer cells."

spectra (obtained with the probe of Figure 2) are shown in Figure 5. These data provide a direct demonstration of the enhancement of chemi-ionization attributable to electronically excited CH radicals. Further study will be needed to determine the precise chemi-ionization processes that produce the observed laser-induced ionization spectra.

THE OPENING UP OF NEW POSSIBILITIES

The laser ionization methods, such as those referred to here, are just one example of how selective interactions of laser light with matter can be put to use. Possible applications range from laser-based isotope separation and chemical purification to the detection and screening of cancer cells.

The unparalleled brightness and tunability of the laser has given us the "eyes" to distinguish subtle differences between atoms and molecules with simple methods undreamed of only a few years ago.



Terrill A. Cool, professor of applied and engineering physics, first came to Cornell as a member of the thermal engineering faculty. That was in 1965, after he had completed his doctoral work in plasma studies at the California Institute of Technology. He transferred to the School of Applied and Engineering Physics in 1973, and has served as acting director of that school, as well as graduate faculty representative in applied physics.

Cool received his undergraduate degree from the University of California at Los Angeles in 1961 and the M.S. in mechanical engineering at Cal Tech in 1962.

His work on flowing gas lasers led to the first purely chemical laser, and he has continued research into the physics of lasers. His most recent sabbatical leave was spent as a visiting fellow at the Joint Institute for Laboratory Astrophysics of the University of Colorado.

As a consultant, he has worked with the NASA Langley Research Center, the United Aircraft Research Laboratory, and the Rohm and Haas Company research laboratories.

He is a fellow of the American Physical Society and a member of the American Institute of Aeronautics and Astronautics.

TUNABLE INFRARED LASERS BASED ON COLOR CENTERS

by Clifford R. Pollock

One of the most striking ways in which lasers differ from other sources of light is that they can be made to operate at nearly a single frequency. Light from the sun, for example, is commonly described as white, meaning that its radiation covers a broad spectrum, from the ultraviolet region down to radio waves, but laser light has an extremely narrow emission linewidth. It is essentially monochromatic.

The key to the narrow linewidth of laser radiation is an effect called *stimulated emission*. An atom or molecule in an excited state can be stimulated by a photon of a certain frequency to emit a photon identical in frequency and phase. This leaves the atom or molecule in a lower energy state, but if it is again excited, or "pumped," stimulated emission can occur again. This process preferentially builds up the intensity of radiation at this one frequency, leading to the generation of monochromatic light.

Of course, the frequency linewidth of continuous-wave (cw) lasers is not infinitely small. In theory, it is limited by noise due to photons entering the beam by spontaneous emission from nonstimulated atoms. In practice, the linewidth is limited by external perturbations such as mechanical vibrations. Nevertheless, researchers in various laboratories have built lasers that actually rival the world's time standard—the atomic clock—for frequency purity, and in the near future we may find that the measurement of time is based on the oscillation frequency of well stabilized lasers.

CHOOSING FREQUENCY WITH A TUNABLE LASER

Lasers that are particularly remarkable and useful are the kind called *tunable*. Such lasers can display the same narrow linewidth and directionality of other lasers, but their exact frequency can be tuned for a particular application. In single-line lasers, radiative transitions occur between two discrete energy levels, but in tunable lasers, transitions can occur over a range of frequencies because they are based on materials that have broad energy levels. The first tunable lasers, developed in the late 1960s, were based on organic dyes. Dye lasers presently operate from about 0.4 to 1.0 micrometer (μm), which extends from the ultraviolet through the visible spectrum to wavelengths beyond the range of the human eye.

Another class of tunable laser, based on lattice defects called *color centers*, was discovered in 1974. The color-center laser was developed by a Cornell graduate, Linn F. Mollenauer of Bell Laboratories, and has prospered under his persistent and inspired research. Currently, color-center lasers operate from 0.8 μm (in the infrared) to 4.0 μm. This is an important region for the study of molecular vibrations, narrow-bandgap semiconductors, and optical communications. Our work at Cornell is directed at further development of color-center lasers and their applications.

THE PHYSICS BEHIND COLOR-CENTER LASERS

To understand how color-center infrared lasers can be used in science and technology, one needs to know how they work.

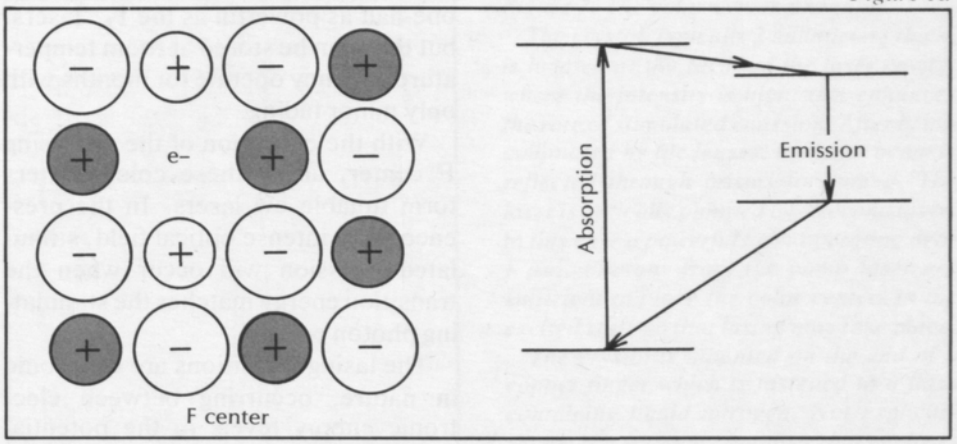
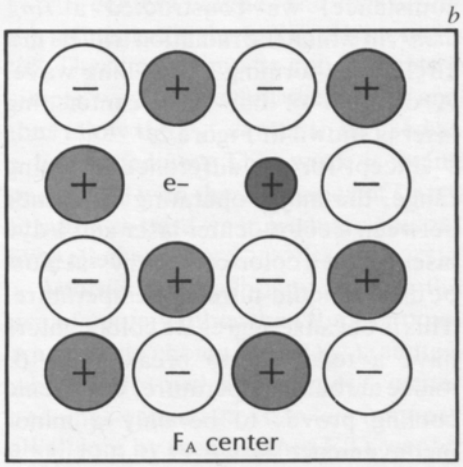
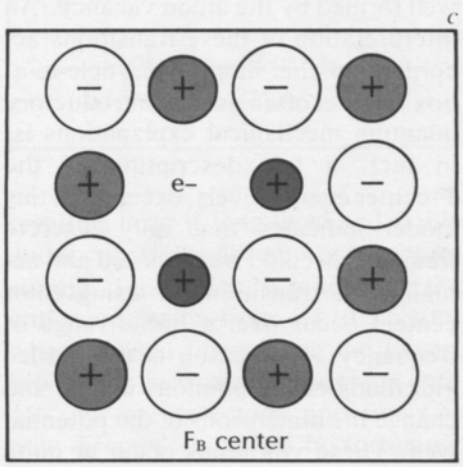
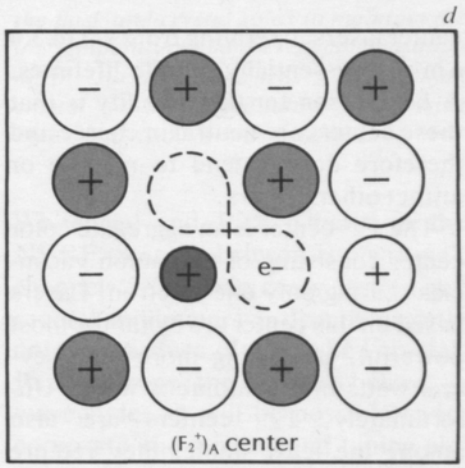


Figure 1. The basic color center and some variations. Although the basic F center does not function as a laser, all the other varieties form tunable continuous-wave lasers.







The active medium of color-center lasers is quite different from that of most other lasers because the energy comes from transitions in *defects* in solids instead of from direct transitions of atoms, ions, or molecules. The color centers that have been most studied are in ionic alkali halide crystals, usually NaCl or KCl; the color center consists of a negative ion vacancy in which an electron is trapped. Such defects can be created through radiation damage with electron beams or gamma rays, or can be additively created by diffusing alkali metal into the crystals at high temperature. The term *color center* is derived from the fact that some of the associated electronic transitions of the defects occur in the visible region: the otherwise clear crystals take on a color, typically deep blue or green, that is the complement of the absorbed color.

There are several variations of the basic color center. Some are shown in Figure 1. The basic color center, usually called an F center (after the German word for color, Farben) is shown as an electron trapped in the potential well formed by a missing anion. For various reasons, the F center itself does not function as a laser medium, but perturbing the F center with adjacent impurities or defects can create many color centers that are laser-active. The F_A center consists of an F center next to a substitutional impurity such as a Li ion in KCl, and the F_B center contains two substitutional impurities. Both F_A and F_B centers have been made to lase and, in fact, they form the most stable of the color-

center lasers, operating from 2.3 to 3.4 μm with essentially infinite lifetimes. A key reason for this stability is that these centers are neutral in charge and therefore do not tend to migrate or attract other centers.

The F_2^+ center is an aggregate color center consisting of two anion vacancies sharing only one electron. Lasers based on this center are by far the most powerful, generating more than several watts in a continuous wave. Unfortunately, F_2^+ centers are also among the least stable; they require cryogenic storage and last only a few hours when actively used as lasers. The reason for this fading is not well understood, but it appears to be caused by migration of the center through the crystal until it collides with another center, thus forming a new, nonlasing, aggregate. This model of destruction seems to be confirmed by the observed stability of the $(F_2^+)_A$ center, which is an F_2^+ center pinned beside a substitutional impurity (Figure 1). The impurity is believed to pin the F_2^+ center in one spot, so that migration ceases. The $(F_2^+)_A$ lasers are presently only about one-half as powerful as the F_2^+ lasers, but they can be stored at room temperature and they operate for months with only minor fading.

With the exception of the nonlasing F center, all of these color centers form tunable cw lasers. In the presence of an intense optical field, stimulated emission will occur when the transition energy matches the stimulating photon energy.

The lasing transitions are electronic in nature, occurring between electronic energy levels in the potential well formed by the anion vacancy. An interpretation of these transitions according to the simple "particle-in-a-box" model often used in introductory quantum mechanical explanations is, in fact, a fair description of the F-center energy levels, except that this model indicates that only discrete frequencies could be observed and actually, the transitions in lasing color centers occur over a broad range of frequency. The reason is that lattice vibrations called phonons distort and change the dimensions of the potential well. These vibrations occur at quite high frequencies, on the order of 10^{13} hertz, and this means that over a period longer than 10^{-13} second, the transition will appear to cover a broad range of energy.

OUR WORK WITH COLOR-CENTER LASERS

One potential problem of broadly tunable lasers is their tendency to operate at more than one frequency simultaneously. Tuning elements such as prisms help reduce the linewidth, but it is still possible for several close frequencies to oscillate simultaneously. This not only reduces the power available at the desired frequency, but also creates a background noise. Moreover, there is a tendency for the unwanted waves to couple with and degrade the desired mode. In early work by Cornell Professor C. L. Tang, it was found that travelling-wave lasers are superior to standing-wave lasers in this respect because a travelling wave sweeps all the gain out of the medium, while a standing wave leaves an array of pockets of gain at the nodes of the wave. Taking advantage of this circumstance, we constructed a *ring laser*, in which the radiation travels in a circle, thus forming a travelling wave. A diagram of our color-center ring laser is shown in Figure 2.

Except for the difference in tuning range, the major operating difference between a color-center laser and a dye laser is that a color-center crystal must be used at liquid-nitrogen temperature. This is because aggregate color centers have a tendency to break apart or ionize at room temperature. Cryogenic cooling proves to be only a minor inconvenience, however.

Color-center lasers are the most powerful in the near infrared (those we operate generate several hundred milliwatts of power). They are also the most broadly tunable in the near infrared. They are not always the first choice for application, however, because of the poorly understood fading characteristic of some of them, mainly those based on the F_2^+ center. If we consider only long-lived color centers, we can smoothly tune from 1.0 to 3.5 μm, except for a few spectral gaps: below 1 μm, near 1.3 μm, and near 1.9 μm. These are inopportune wave-

length regions because many semiconductors of interest for optical communications have bandgaps near these energies, and we are working to fill these gaps.

One approach is to study the fading mechanism of the F_2^+ center through spectroscopic experiments. Because the fading may be due to migration of the centers during optical pumping, we are optically inducing reorientation and measuring the fading that results. Similarly, we are creating new centers such as those that would occur when two F centers collide, and measuring the influence on the fading characteristic. These experiments may indicate a simple way to prevent the fading and thus allow the F_2^+ center to be used as a laser medium. This work is being performed with the assistance of Larry Stratton, a third-year graduate student in applied physics.

Another approach is to explore the use of centers other than the F_2^+ type. An obvious choice is the $(F_2^+)_A$ center, which is formed when an F_2^+ center becomes pinned next to an impurity alkali ion; by forming the $(F_2^+)_A$ center in different alkali halides, the emission band can be shifted about. For example, in KCl doped with Na, the center lases at 1.6 to 1.9 μm, and tentative results suggest that in RbCl doped with Na, the center will lase at 1.8 to 2.1 μm. We can reach the 1.3 μm region using NaF or KF.

We have also had promising results with an entirely different kind of center—an F center formed in KCl with thallium impurities. The F electron spends most of its time around the Tl ion, creating in effect a neutral Tl atom perturbed by a color center. The resulting laser is long-lived and stable under conditions of room-temperature storage. In addition, it tunes over the important region from 1.4 to 1.6 μm, where optical fibers have the lowest loss, and where most research on optical sources, detectors, and fibers is now directed. It would be fortunate, indeed, if other similar lasers could be made at different wavelengths, using gallium or indium instead of thallium.

Since color centers can be formed by intense radiation, it is possible to create them in an alkali halide substrate using electron-beam lithography, and thereby miniaturize the actual laser resonator. William Ericson, a Master of Engineering student in our laboratory, is using this technique in project work carried out at the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell. With the help of Brian Whitehead and Rich Tiberio of the NRRFSS staff, Ericson is "writing" channels 5X5 μm in cross section and several millimeters in length directly onto the surface of a polished crystal. If, as we hope, the channels behave as waveguides, it will be possible to incorporate end mirrors and tuning elements on the substrate by creating a submicron-resolution diffraction grating along the channel. With proper dimensions, such a grating would effectively reflect only one color. Although this work is speculative right now, it holds great promise for simplifying the use and production of tunable infrared lasers.

We are also developing better switches for laser radiation. Pulsed lasers can be made to emit one short, extremely intense pulse if a shutter is placed in the laser cavity and opened only when the gain has reached its

Figure 2

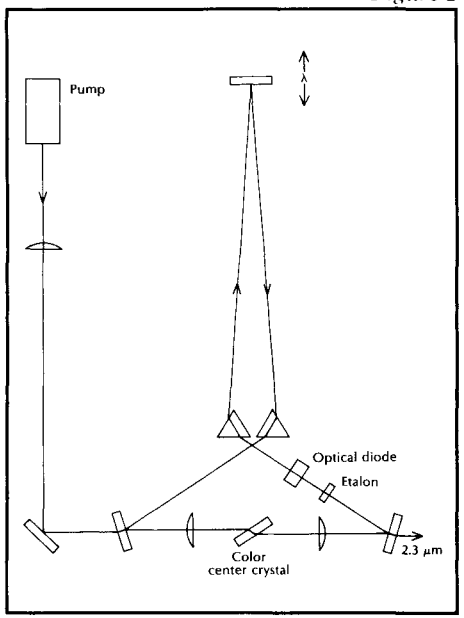


Figure 2. The color-center ring laser.

The crystal, typically 2 millimeters thick, is located at the focus of the laser cavity, where the intensity is high; this enhances the rate of stimulated emission. After being collimated by the lenses, the laser beam is reflected through prisms for tuning. The laser is optically pumped by a second laser, in this case a powerful laser operating near 1 μm. Photons from the pump laser are sufficient to place the color centers in the excited state so that lasing may take place.

The crystal is mounted on the end of a copper finger which is fastened to a flask containing liquid nitrogen. Not explicitly shown is a vacuum container that encloses the flask and crystal so as to maintain the low temperature and prevent condensation on the surfaces. Two lenses in the small crystal housing constitute the focussing optics and also serve as windows.

"Color-center lasers are the most powerful in the near infrared . . . and also the most broadly tunable."

maximum value. Various devices, called *Q switches* (because they alter the quality factor, or Q, of the laser cavity) have been used as shutters, but most of them are either lossy or very expensive. We have found that a simple room-temperature color-center crystal placed in the cavity of a ruby laser effectively Q-switches the laser, producing a narrow, powerful pulse. The nonlinear properties of color centers are the key. Initially, they absorb the laser emission, suppressing oscillation, but very rapidly the absorption saturates and the crystal becomes transparent, effectively opening the shutter. All the stored energy in the ruby is suddenly available for lasing, and a giant pulse results. Such a device promises to greatly simplify the operation of Q-switched lasers.

A NEW INTERNATIONAL STANDARD FOR LENGTH

An interesting and significant piece of work in which we participated illustrates the breadth of the possible applications of tunable lasers. This research led to the creation of a new internationally accepted definition of the meter.

Since 1678, when Roemer deduced the speed of light to be $3X10^8$ meters per second, people have tried to extend the accuracy of this fundamental constant. In 1976 scientists at the National Bureau of Standards made a measurement based on the simultaneous determination of the frequency and wavelength of an infrared gas laser. The accuracy was not limited by experimental uncertainty, but by uncertainty in the length standard, which was the 6047-Å radiation of the krypton lamp. On the basis of Einstein's postulate that the speed of light (c) is constant, it appeared that the meter could be defined in terms of the speed of light and the second. Length would then be measured using interferometry, with a source of known frequency, according to the relation $\lambda = c/f$. For this new definition of the meter to be practical, it would be necessary to accurately measure the frequency of several laser sources in the visible region.

Considering that optical frequencies are on the order of $5X10^{14}$ hertz, one can immediately realize that there is no way to directly count such a frequency. The actual measurement we performed relied on a frequency-multiplication chain that was built on the basis of well stabilized lasers and nonlinear harmonic generation, and extended from the atomic-clock frequency near 9.2 gigahertz to the 500-terahertz region. The final chain required a 2.305-μm laser with extremely narrow linewidth (better than 1 part in 10^{10}) and enough power to generate harmonics through nonlinear optics techniques. Since there was no fixed-frequency laser with these characteristics, we developed a tunable single-frequency 2.3-μm color-center laser with sufficient power and stability to complete the chain.

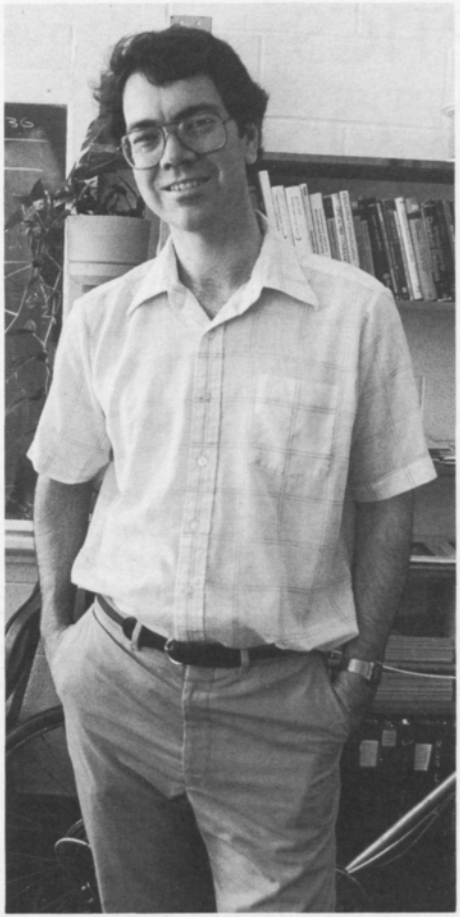
The measurement was completed in January of 1982, and as a result, the official meter is now defined as "the distance traveled by light in a vacuum during 1/299,792,458 of a second." The accuracy of the measurement was thirty times better than that of the existing standard meter.

THE VERSATILITY OF TUNABLE INFRARED LASERS

The redefinition of the meter is just one example of the kinds of research and development that require tunable, yet narrowline, sources of radiation.

Perhaps the most obvious potential application is in molecular spectroscopy. The binding energy of molecules containing light-weight atoms such as hydrogen is sufficient to cause molecular vibrations to occur at frequencies in the near infrared region, and since many molecules, including the organics, contain hydrogen, infrared lasers are useful for studies of catalysis, combustion, and many other processes involving organic chemistry. For example, a molecule can be placed in a known vibrational state by exciting it with a tunable laser, and parameters such as vibrational decay, intraband relaxation, and reactivity with surfaces or other species can be directly monitored. In our laboratory, we have used our color-center laser to probe molecules such as CO and N_2O with resolution two orders of magnitude beyond that obtained previously.

Of growing importance is the application of tunable lasers to optical-fiber communication systems. The lasers are used for research on both fibers and semiconductor devices, and also as optical sources, since they can operate at precise but separated frequencies to send tremendous amounts of data down a single fiber. A related application of broadly tunable lasers is the creation of ultrashort pulses by locking a large portion of the available bandwidth coherently together. Pulses have been formed in the infrared with durations shorter than 1 picosecond



(10^{-12} second). (Even shorter pulses have been created using dye lasers; this is described in Tang's article in this issue.) Short pulses are useful for the high-rate transmission of data on optical fibers, and as strobes to observe transient phenomena in various materials.

The needs for narrowline infrared lasers are extensive and challenging. For our part, we will concentrate on improving our understanding of the physics of laser color centers, on developing better sources of laser radiation, and on applying color-center lasers to problems in materials, in frequency standardization, and in optical communication.

Clifford R. Pollock has been an assistant professor of electrical engineering at Cornell since 1983. He came here from the National Bureau of Standards, where he spent two years on a postdoctoral fellowship from the National Research Council. He received his undergraduate and graduate education at Rice University, completing his doctoral studies in 1981.

Earlier this year, Pollock was named as one of the first recipients of the Presidential Young Investigator Award. This award, intended to attract and retain promising young researchers in academic careers, will provide from the National Science Foundation at least $25,000 a year in research support for five years; funds from industry will be matched for a total of as much as $100,000 a year.

At Cornell Pollock is associated with the Materials Science Center and the Cornell Program on Submicrometer Structures. He is a member of the Optical Society of America and of the Institute of Electrical and Electronics Engineers.

ACOUSTO-OPTICS FOR PROCESS CONTROL

by George J. Wolga

Smokestacks with built-in gas monitors may be possible with novel spectroscopic equipment under development in our laboratory at Cornell. The key instrumentation is an infrared acousto-optic sensor that will analyze gases selectively and quickly, providing the means for better combustion control.

The acousto-optic sensor, installed in the smokestack and remotely controlled by computer, would analyze the exhaust gas and supply feedback information to the combustor, allowing the plant to be operated for maximum fuel efficiency and minimum air pollution. If we succeed in developing a practical system, the dollar savings to the nation resulting from greater efficiencies in operating utility plants will be very large.

Although our current research is focused on the combustion of coal in electric-utility plants, possible applications of the instrumentation are not limited to this. The sensor promises to be useful for many problems of industrial process control, as well as for scientific investigations.

WHAT INFRARED SPECTROSCOPY REVEALS

An appreciation of what acousto-optic analysis can offer begins with an understanding of infrared spectroscopy. The word *spectroscopy* implies the spectral (frequency or wavelength) analysis of electromagnetic radiation emitted or absorbed by some form of matter. It is well known that simple gaseous molecules such as CO, CO_2, and NO absorb infrared radiation in the wavelength region of 2-10 X 10^{-6} meter. Each molecule can absorb at many different wavelengths because of changes in the rotation and vibration of the molecule, but these absorptions are discrete (separated from each other) and constitute a defined spectrum. Most importantly, the absorption spectra are characteristic and different for each molecule. This means that the presence of a particular molecule in a mixture can be detected as absorption at a particular infrared wavelength. Furthermore, measurements of the strength of absorption can be used to follow the changing concentration of a constituent.

In conventional infrared spectroscopic instruments, specific wavelengths are identified by the characteristic angle through which they are deflected, either by refraction in a prism or by diffraction from a grating. An analysis is made by passing radiation of the desired wavelength through a sample and recording absorption as a function of wavelength. In some cases, information can be obtained through spectral analysis of wavelength interference; this is done in Fourier Transform spectrometers.

However, these conventional instruments have a serious drawback for monitoring the concentration of several molecules in a gas mixture. The problem is that they are not capable of *random spectral access*, which implies the ability to change the wavelength quickly. In a conventional instrument, tuning from one wavelength to another generally entails sampling all the intermediate wavelengths, a time-consuming process that discourages the use of the technique for process control. With random spectral access, however, particular wavelengths can

". . . the dollar savings to the nation resulting from greater efficiencies in operating utility plants will be very large."

be monitored in a sequence that is fast enough to permit changing molecular concentrations of several molecules to be followed.

HOW ACOUSTO-OPTICS IMPROVES SPECTROSCOPY

A completely different technique for performing infrared analysis employs the coherent interaction of the radiation with acoustic shear waves in a suitable crystal. The process is called *acousto-optic interaction*.

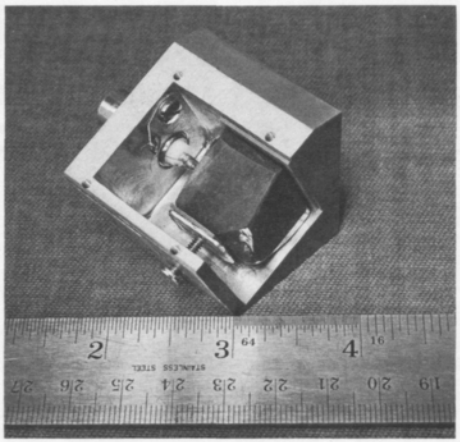
What happens is that a particular infrared wavelength changes its polarization by 90 degrees in response to acousto-optic interaction with a particular acoustic frequency in the range of 20 to 100 megahertz. There is a one-to-one relationship, called the *tuning curve*, between the wavelength of the infrared wave whose polarization is rotated and the frequency of the acoustic wave. Thus, if a polarization selector (analyzer) is placed at the output of the crystal interaction region in such a way that it blocks the infrared waves that have not had their polarization rotated, the infrared waves passing through the analyzer will have a known wavelength defined by the tuning curve and the frequency of the acoustic wave. The combination of acousto-optic crystal—the medium in which an acoustic shear wave propagates—and a polarization analyzer is called a *tunable acousto-optic filter* (TAOF).

TAOFs were first demonstrated with visible light. Subsequently, scientists at Westinghouse discovered that crystals of thallium arsenic triselenide ($ThAsSe_3$, called TAS for short) could be used for TAOFs throughout the infrared region in which simple molecules absorb.

The major benefit resulting from the use of TAOFs for infrared spectral analysis is that random spectral access is possible because of the short time it takes to establish the acoustic wave in the crystal. The crystals employed are 1 to 2 centimeters in length and acoustic waves propagate with velocities of the order of a few mm/microsecond. Thus it takes only 10 to 20 microseconds to fill the acousto-optic crystal with the appropriate acoustic wave to establish a particular point on the tuning curve—that is, to specify the infrared wavelength that will be selected by the TAOF. Since 10 to 20 microseconds is a short time compared to the characteristic time (of the order of seconds) over which process control is to be implemented, the TAOF effectively provides random spectral access. Additional advantages of the TAOF are that it is small, rugged, and capable of being remotely installed and controlled by a computer.

THE CORNELL SENSOR: A SMART INSTRUMENT

At Cornell, under the sponsorship of the Division of Basic Energy Science of the Department of Energy, we are developing the Smart Spectroscopic Sensor based on a TAOF that employs $ThAsSe_3$ (TAS) as the acousto-optic crystal. This program is being conducted in collaboration with Frederick C. Gouldin of Cornell's Sibley School of Mechanical and Aerospace Engineering. Gouldin's group is responsible for the combustion-analysis portion of the project.



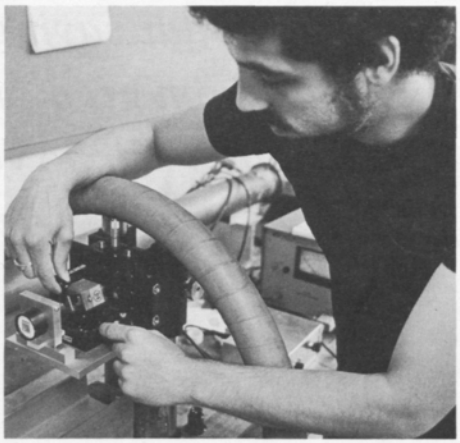


Figure 1

Right: The small SMART spectroscopic sensor based on a tunable acousto-optic filter (TAOF) could be mounted easily in a smokestack for continuous monitoring of emissions. Working with the experimental unit is Michael Bardash, a graduate student.

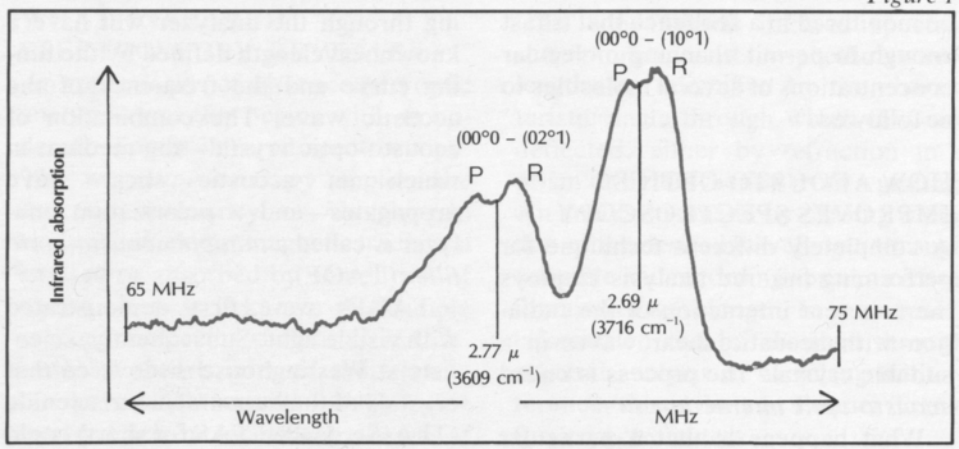


Figure 1. Two vibration-rotation infrared absorption bands of CO_2 molecules taken with the TAOF-based sensor. Each band is labelled with the quantum numbers corresponding to the initial and final vibrational states, and with the wavelength (in micrometers) and the wave number (in cm^{-1}) corresponding to the center of the band.

Specifically, our objective is to develop instrumentation capable of monitoring the concentrations of CO, CO_2, NO, and perhaps other gases, in the smokestack bearing combustion products from a coal-burning electric utility plant. Since the combustion efficiency of the plant increases as CO content in the exhaust gas decreases, optimum operation is attained by near-stoicheometric burning of the fuel to produce predominantly CO_2.

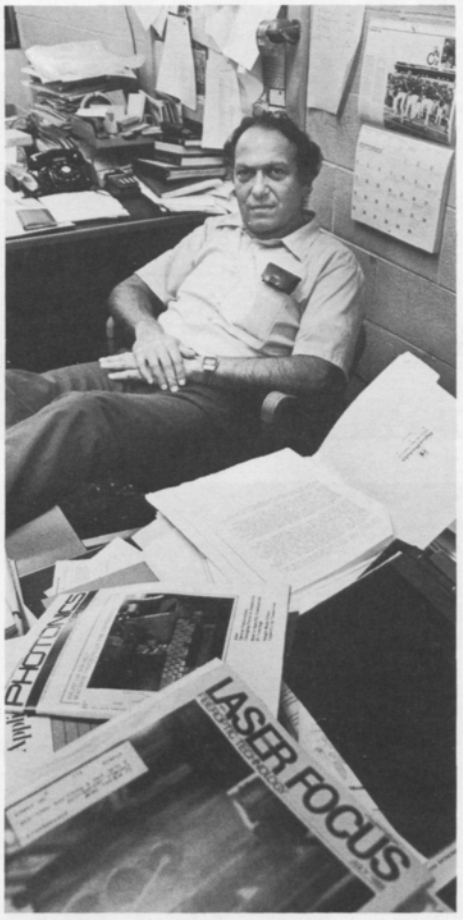
The TAOF is being instrumented with computer control of the acoustic wave frequencies that propagate in the TAS crystal. The frequencies used are, of course, those that select the infrared wavelengths to be monitored. The random-spectral-access characteristic of the TAOF will be used to measure the infrared absorption by CO and CO_2. The computer will analyze the data for gas concentrations and will supply feedback information to the coal combusters. The primary purpose is to provide a basis for adjusting the combustors so as to minimize CO concentration in the exhaust. However, other considerations—those of minimizing air pollution and characterizing the combustion process more fully—suggest that we monitor the concentration of nitrogen oxides as well.

The TAOF-based infrared spectroscopic sensor we are building must be capable of being remotely installed in the smokestack of a utility plant. To permit unattended operation, we are developing self-calibration capability in the sensor that will render it insensitive to environmental factors such as

changes in air temperature or in the humidity.

Typical data obtained with our instrumentation are shown in Figure 1, the absorption spectrum of CO_2 in the 2.7-micrometer wavelength region. The two separate absorption bands correspond to two transitions between CO_2 molecules at different energy levels; in each case, molecules in the lowest energy state have been excited to a higher vibrational energy state. A similar spectrum was obtained for CO in the 4.7-micrometer wavelength region. In our figures, absorption is plotted versus the frequency of the TAOF acoustic wave drive; an interesting feature is the small range of acoustic frequency that is required to display each spectrum. Our data indicate that many infrared absorptions characteristic of the molecules of interest are accessible to our instrumentation. This will permit us to select the most appropriate ones for use in controlling combustors.

Similar instrumentation can be conceived for instituting on-line process control in chemical plants producing the raw materials for a vast number of products. Undoubtedly, each process-control application will require special characteristics of the instrumentation; nevertheless, all applications will benefit from the random-spectral-access character of the TAOF. The new sensor will extend the usefulness of infrared spectroscopy, opening up technological possibilities and providing investigators with a new tool for scientific research.



George J. Wolga, professor of electrical engineering and applied physics, is a Cornell graduate as well as faculty member; he received the B.S. degree in engineering physics (with distinction) in 1953.

He did his graduate work at the Massachusetts Institute of Technology, receiving the Ph.D. in physics in 1957, and taught there for four years before returning to Cornell in the School of Electrical Engineering. His joint appointment to the School of Applied and Engineering Physics began in 1964. He has been active in both areas; he has been graduate faculty representative for the Field of Applied Physics and has served on the policy and graduate committees for electrical engineering.

During 1969 and 1970, Wolga spent a sabbatical leave and an additional year at the Naval Research Laboratory in Washington, D.C., where he was head of the Laser Physics Branch and supervised a major portion of the laser-related activities of the laboratory. In 1964 he founded the Lansing Research Corporation in Ithaca, New York, and currently serves as vice president and consultant to that firm, which specializes in laboratory and electronic equipment. He has also been a consultant to the General Electric Company, the General Telephone and Electronics Corporation, the Naval Research Laboratory, and Itek Corporation's Applied Technology Laboratory.

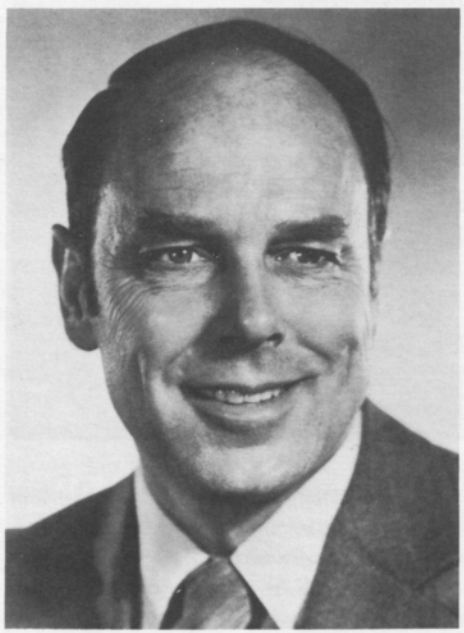
He is a member of the American Physical Society, the Optical Society, the Institute of Electrical and Electronics Engineers, and the Society for Information Display.

Everhart Leaves Deanship to Become Chancellor of Illinois at Urbana

Thomas E. Everhart, who has been dean of the College of Engineering at Cornell since January, 1979, will become chancellor of the University of Illinois at Urbana-Champaign this summer. As chancellor, he will be the chief officer of the 35,000-student campus. William B. Streett, associate dean of the College and professor of chemical engineering, will be acting dean.

At Cornell Everhart has served as the Joseph Silbert Dean of Engineering, the seventh dean in the College's history, and has also been a professor of electrical engineering. He is a specialist in electron optics and electron physics with long experience in teaching, research, and consulting. An authority on the broad aspects of submicron-structure fabrication, he has published more than eighty technical papers and holds five patents.

Cornell President Frank H. T. Rhodes characterized Everhart's administration as "dynamic," and cited such accomplishments as the establishment of the National Research and Resource Facility for Submicron



Structures, housed in the new Knight Laboratory, and the Computer-Aided Design Instructional Facility. In addition, he pointed out, Snee Hall for the Department of Geological Sciences is nearing completion, and the DeFrees Hydraulics Laboratory was dedicated in early June. "These physical facilities, plus the increased strength of the College's faculty and staff, have made his time with us highly productive," Rhodes said. "During this period, the annual research expenditures in the College increased from $14.8 million to $27.1 million. Also, the college's facilities, particularly for computing, were greatly expanded."

Everhart received the A.B. degree in physics, magna cum laude, from Harvard University in 1953. Subsequently, he studied at the University of California at Los Angeles, earning the M.Sc. in 1955, and during this period he also worked in research and development at the Hughes Aircraft Company. In 1958 he received the Ph.D. in engineering from Cambridge University, England, where he was a Marshall Scholar and helped develop the scanning electron microscope.

Before joining the Cornell faculty, Everhart was a professor at the University of California at Berkeley for twenty years. He served as chairman of the Department of Electrical Engineering and Computer Science there. During his years at Berkeley, he

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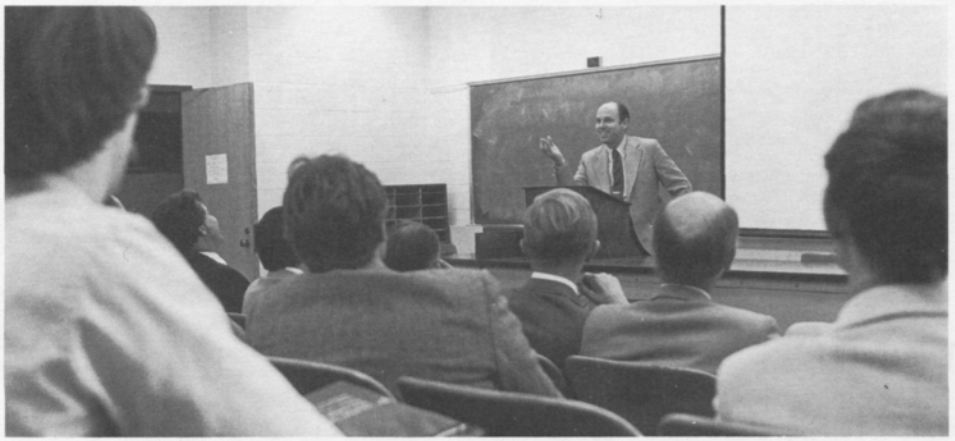

Scenes from Everhart's years at the College illustrate some of the facets of his many-sided role as dean: (1) welcoming visitors at one of many on-campus meetings; (2) greeting Chinese children during an official visit to China by Cornell leaders in 1981; (3) at the national submicron facility on the engineering campus; (4) with students during an informal class session in his home.

2

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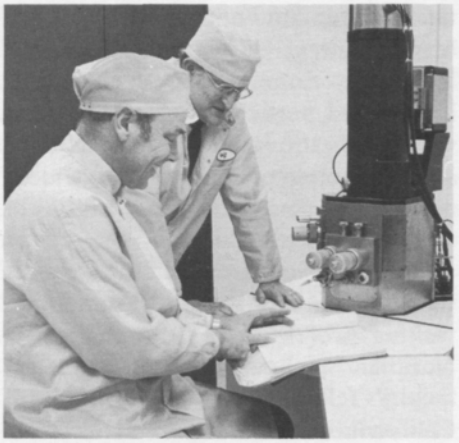


4

spent a leave at the Westinghouse Research Laboratories, conducted research at the Institut für Angewandte Physik in West Germany as a National Science Foundation senior postdoctoral fellow, and was a Guggenheim fellow at Cambridge and at Waseda and Osaka Universities in Japan.

He is a member of the National Academy of Engineering, a fellow of the Institute of Electrical and Electronics Engineers, a past president of the Electron Microscopy Society of America, and a member of a number of other professional organizations. He serves as chairman of the Lawrence Berkeley Laboratory Science and Educational Advisory Committee, and is a charter member of the Education Advisory Board of the National Academy of Engineering. Throughout his career, he has been active as an industrial consultant, and is currently chairman of the General Motors Science Advisory Committee and a member of the R. R. Donnelley and Sons Technical Advisory Committee.

Everhart and his wife, the former Doris Wentz, have four children.

Conta, Liang, Lyon Retire from Cornell Engineering Faculty

College of Engineering professors who retired this year after long careers at Cornell are *Bart J. Conta* of the Sibley School of Mechanical and Aerospace Engineering, and *Ta Liang* and *George B. Lyon* of the School of Civil and Environmental Engineering. Liang and Lyon were two of the three members of their school's Program in Environmental Sensing, Measurement, and Evaluation.

■ Conta came to Cornell as a graduate student in 1936, after graduating first in his class in mechanical engineering at the University of Rochester. He joined the faculty after earning his master's degree in 1937, and except for a year as a research engineer at the Texaco Corporation and four years on the faculty of Syracuse University, he has spent his entire career at Cornell.

His reputation is as a scientist, engineer, and teacher with a special concern for the social impacts of science and technology. His courses in thermodynamics and in energy conversion, as well as in the history of technology, are known for the presentation of fundamental information in a broad context of world history and human development. In recent years, he has had particular interest in such subjects as the relationship of science and technology, "intermediate" technology, and small-scale applications of solar energy.

Conta has spent sabbatical leaves with duPont, as a Ford Foundation visiting professor in Colombia, as a National Science Foundation science faculty fellow at the University of California at Berkeley, and as a researcher on the history of technology at the British Museum and the Science Museum in London. He has also served as an industrial consultant, as a member of national committees of the American Society for Engineering Education, and on National Science Foundation fellowship panels. He is registered as a professional engineer in New York State.

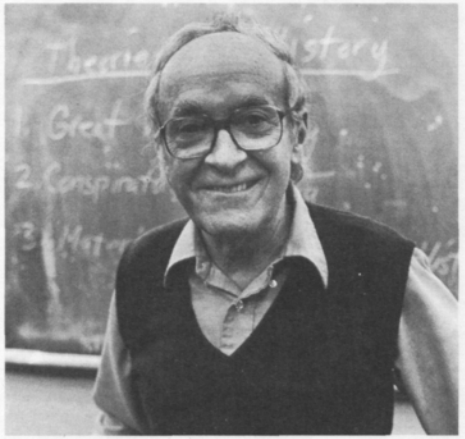
At the University, Conta has served as the graduate faculty representative in mechanical engineering and as a member of numerous committees, councils, and boards. Currently he is active in the Centre for Religion, Ethics, and Social Policy.

Conta and his wife, Ruth, plan to remain in Ithaca. "Really, nothing much has changed," he remarked. "The school has asked me to teach some courses next year and I'll be around, the same as ever."

■ Ta Liang, a pioneer in the use of aerial photographs for engineering analysis, first came to Cornell as a graduate student, stayed on as a research associate, and after three years in industry, returned to the University for twenty-seven years of teaching and research. He has used remote-sensing techniques in countries around the world for siting facilities, locating resources, and assessing agricultural and other land uses.

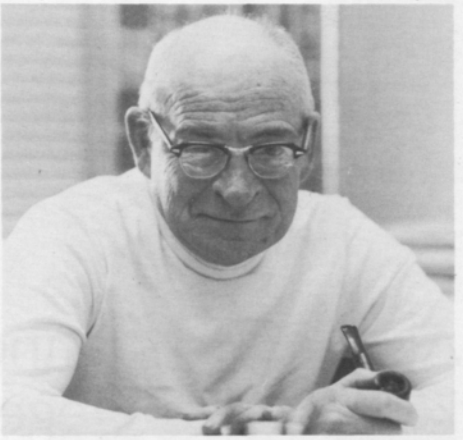
Liang received a baccalaureate degree in engineering at Tsing Hua University of China in 1937. During World War II, he was a senior engineer with the United States armed forces in the China-Burma-India theater, supervising the design and construction of roads, airports, and housing facilities.

Conta



Liang

Lyon



He received the degree of Master of Civil Engineering from Cornell in 1948, and the Ph. D. in 1952. In 1955 he became a senior soil and foundations engineer with the firm of Tippetts, Abbett, McCarthy, and Stratton, and in 1957 he returned to Cornell as a member of the faculty.

During his years at the University, Liang developed and taught courses in physical environment evaluation and aerial photographic studies, and he conducted and directed many research projects in remote sensing. These included the Air Force Tropical Soils Airphoto Research Project, the Land Use and Resource Inventory of Puerto Rico, and the Program in Remote Sensing sponsored at Cornell by NASA. He also served as a consultant to private, government, and international agencies in more than forty nations.

Liang and his wife, Daisy, are maintaining their home in Ithaca. He will continue his consulting activities and will help establish the newly formed Cornell unit in remote sensing and resource information.

■ George B. Lyon, who retired last January, taught civil engineering courses at Cornell since 1947; his courses covered such areas as fluid mechanics, hydrology, hydraulics, marine navigation, surveying, geodesy, and transportation. He also served as assistant director of the School of Civil and Environmental Engineering for nine years, as secretary of the College faculty, as secretary of the School faculty, and as a member of many University, College, and School committees and boards. Matters in which he had an active concern include campus traffic control, administration of the University's Division of Unclassified Students, the Engineering Cooperative Program, and the curriculum in civil and environmental engineering.

Lyon received the B.S. degree in civil engineering from the University of Illinois in 1940 and the M.S. in hydraulics from the State University of Iowa in 1942. During World War II, he served in the Army as an engineer working on hydraulic model studies for navigation locks, and then as a surveyor supervising port construction and repair in the Southwest Pacific area. After the war, he conducted water-resource studies for the Illinois State Water Survey (he is registered as a professional engineer in that state) and taught surveying at the University of Minnesota before joining the Cornell faculty.

Over the years, Lyon also taught at summer survey camps for Lehigh University and the University of Wisconsin. As a consultant, he worked with two local consulting firms: D. J. Belcher Associates, on hydrologic studies in connection with the site selection for Brasilia, capital of Brazil; and B. K. Hough on reservoir, drainage, and flood-control studies. (Both Belcher and Hough were members of the Cornell faculty.) For more than two decades, Lyon prepared ephemeris tables for surveyors, published by Keuffel and Esser, Inc.

Lyon is continuing an active association with the School. His projects include work on the School's extensive collection of antique surveying instruments and documents.

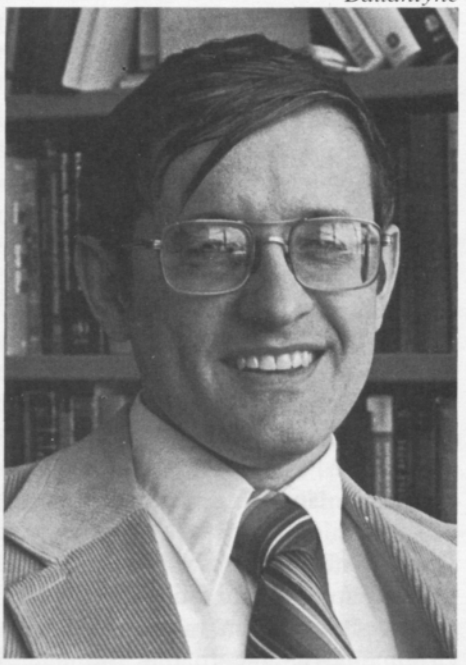
Appointments and Faculty Honors Highlight College News Notes

■ *Joseph M. Ballantyne,* director of the School of Electrical Engineering, has been named vice president for research and advanced studies at Cornell. He succeeds Robert Barker, professor of biochemistry and molecular and cell biology, who became provost.

In his new position, Ballantyne is responsible for research programs throughout the University and for building corporate liaison in the area of research. He will also work with the Graduate School in aspects of graduate education.

In commenting on the appointment, President Frank H. T. Rhodes noted Ballantyne's "distinguished record as both a research scientist and as an administrator." A specialist in photoelectronics, Ballantyne is currently conducting research on submicrometer optical devices and developing semiconductor materials for their fabrication. He was instrumental in planning and establishing the National Research and Resource Facility for Submicron Structures (NRRFSS) at Cornell, and served as its acting director in the early months of operation.

Ballantyne

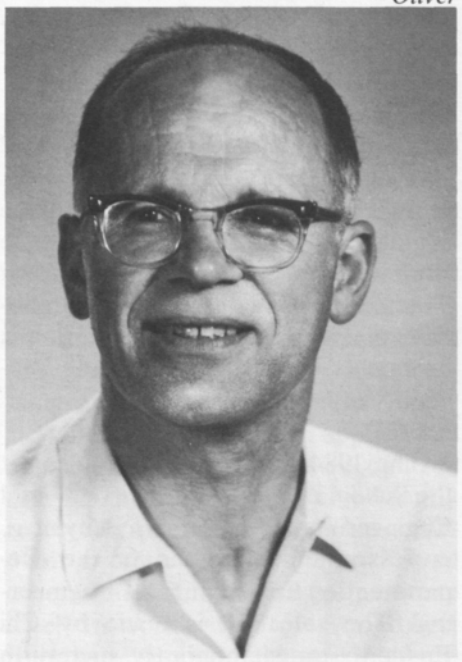


"In addition to Dr. Ballantyne's active involvement in federally supported research, his experience with industrial research will be a great asset to the University," Rhodes said. "His leadership and broad knowledge will help to assure Cornell's continued standing as one of the nation's foremost research universities."

Since coming to Cornell in 1964, Ballantyne has directed research in the areas of thin-film and solid-state lasers, far-infrared and photoelectric spectroscopy of solids, solid-state microwave detectors, and the growth of semiconducting crystals. He has presented or published more than one hundred research papers and holds several patents. Also, he has served as a consultant and held summer appointments at numerous industrial firms and government laboratories. He is an adviser to several universities on microelectronics and electrical engineering.

Ballantyne received baccalaureate degrees in both mathematics and electrical engineering from the University of Utah, and was awarded the S.M. and Ph.D. degrees by the Massachusetts Institute of Technology. He has been a National Science Foundation senior fellow at Stanford University, and was elected a senior member of the Institute of Electrical and Electronics Engineers.

Oliver



■ A Cornell geology professor, *Jack E. Oliver,* was elected to the National Academy of Sciences (NAS) this spring. Oliver, the Irving Porter Church Professor of Engineering, has been a member of the University's Department of Geological Sciences since 1971, when he came here as chairman to supervise a reorganization of the unit as an intercollege department.

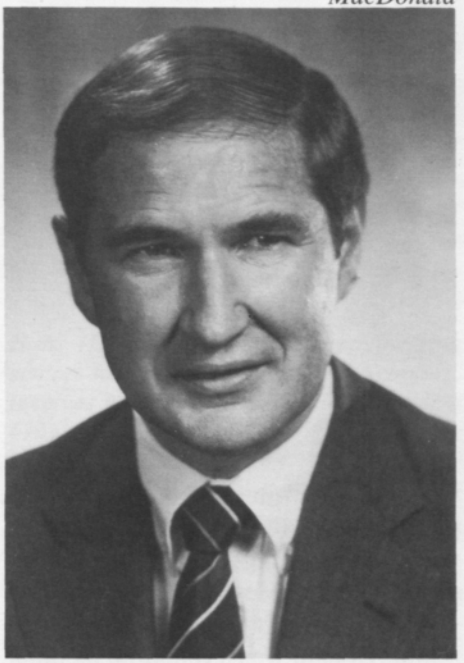
Election to the Academy, considered one of the highest honors that can be accorded to an American scientist or engineer, recognizes "distinguished and continuing achievements in original research." Oliver is a specialist in geophysics and geotectonics who has made contributions to the development of plate tectonics as a unifying concept in geology. In 1976 he was instrumental in forming the Consortium for Continental Reflection Profiling (COCORP), centered at Cornell, and in 1983 he became the founding director of the Cornell-based Institute for the Study of the Continents (INSTOC).

Oliver was educated at Columbia University, and after receiving the Ph.D. in 1953, continued to work at the Lamont-Doherty Geological Observatory there. He was a member of Columbia's Department of Geology for sixteen years, and served as chairman for two years before coming to Cornell. He has served as a consultant to government agencies and as a member of many panels of the NAS and of various international scientific organizations. He is currently a member of the Board on Earth Sciences of the National Research Council.

Other honors he has received are the Author of Classical Paper in Geophysics Award from the Society of Exploration Geophysicists (1960), the Harry Oscar Wood Award from the Carnegie Institution (1964), the Walter Bucher Medal from the American Geophysical Union (1981), and the Virgil Kauffman Gold Medal from the Society of Exploration Geophysics (1983). He has served as distinguished lecturer for the Society of Exploration Geophysics and for the Shell Development Company.

He is a former president of the Seismological Society of America, a fellow of the American Geophysical Union and the Geological Society of America, and a member of the American Association for the Advancement of Science, the Society of Exploration Geophysicists, and Sigma Xi.

MacDonald



■ The new Cornell director of the Semiconductor Research Corporation (SRC) Program on Microscience and Technology is *Noel C. MacDonald,* a specialist in electron-beam technology. He has also been appointed professor of electrical engineering.

The program was instituted in late 1982, when Cornell was selected by SRC for one of its first "centers of excellence" for promoting research essential to the development of VLSI (very-large-scale integrated) circuits. The SRC, which comprises twenty-nine semiconductor corporations, provides funding that in the first year at Cornell amounted to $1.4 million. Eighteen professors in four schools or departments (Applied and Engineering Physics, Electrical Engineering, Materials Science and Engineering, and Physics) constituted the initial Uni-

versity faculty membership in the program. Jeffrey Frey, professor of electrical engineering, served as acting director until MacDonald's appointment in May.

MacDonald was a founding member of Physical Electronics Industries, Inc., and held management positions with that firm from 1970 to 1977, when it was acquired by the Perkin-Elmer Corporation. In 1978 he became general manager of the Physical Electronics Division and in 1980 he transferred to the Semiconductor Equipment Group, where he was responsible for the worldwide technical marketing for semiconductor capital equipment. Before joining Physical Electronics, MacDonald taught for a year at Berkeley and spent two years as a member of the technical staff at the Rockwell International Science Center. He has given annual lectures on scanning electron microscopy and scanning Auger microanalysis for a short course offered by the State University of New York at New Paltz.

He received the B.S., M.S., and Ph. D. degrees in electrical engineering from the University of California at Berkeley, and later he attended the Harvard Business School's Program for Management Development. For his doctoral degree, awarded in 1967, he did research on electron-beam irradiation of metal-oxide semiconductor structures. Subsequently, he was instrumental in developing the Scanning Auger Microprobe. His current interests center on automated inspection of VLSI circuits, including modeling for process control, microfabrication, very-large-scale integration, and particle-beam instrumentation.

Among his honors are the 1973 Victor Macres Memorial Award from the Electron Microprobe Analysis Society of America for outstanding contributions in instrumentation, and the 1975 Young Engineer of the Year Award from the Institute of Electrical and Electronics Engineers (IEEE). He is a member of IEEE, the Electrochemical Society, the American Vacuum Society, the American Association for the Advancement of Science, and Sigma Xi.

■ *K. Bingham Cady,* associate professor of nuclear science and engineering, has been named to the half-time College position of associate dean for professional programs. In his capacity as dean, Cady will serve as director of the Engineering Cooperative Program and will coordinate the Master of Engineering degree program.

■ *John Bellina,* who has been director of advising and counseling for several years, is the new director of admissions. A Cornell engineering alumnus, he received the B.S. degree in 1974, the M.Eng. (Electrical) in 1975, and is completing work on the Ph. D. in electrical engineering.

■ An award for the best paper of 1982 was made to *Kenneth E. Torrance,* professor of mechanical and aerospace engineering, and a former graduate student, *Haim A. Bau,* by the Heat Transfer Division of the American Society of Mechanical Engineers. Bau is now an assistant professor at the University of Pennsylvania.

■ The 1984 Professor of the Year at the School of Civil and Environmental Engineering is *Arnim H. Meyburg,* professor and chairman of the Department of Environmental Engineering. The selection is made by Chi Epsilon, student honorary society in civil engineering.

■ *Engineering: Cornell Quarterly* has received a Citation Award from the Council for Advancement and Support of Education, for research coverage in institutional periodicals. The award was made as part of the annual CASE recognition program.

■ Six engineering students were among thirty-five Cornell seniors honored at the first Presidential Scholars Convocation held on campus May 23. They are *Hans Hallen, Edward Lu, Elizabeth McCone, Lori Rosenkopf, Luke Scrivanich,* and *Sarah Jane Skinner.*

The winners were chosen by the deans of the undergraduate schools and colleges for "qualities of intellectual curiosity and energetic leadership," as well as for outstanding

scholastic achievement. All rank in the top 5 percent of their school or college.

They were recognized by Cornell President Frank H. T. Rhodes at a convocation luncheon attended also by Larry I. Palmer, vice provost for undergraduate education, and the college deans.

In future years, the convocation will also honor the high school educators chosen by the Presidential Scholars as those who most influenced their secondary education.

Hallen, who majored in applied and engineering physics, was recognized as a student who not only consistently received grades of A or A+ (his grade-point average was 4.13), but helped other students, some at the graduate level. In work with Professor Robert Buhrman, Hallen fabricated submicron tunnel junctions and was put in charge of overseeing the installation of a $100,000 high-vacuum evaporation system. Offered financial aid for graduate study at four leading universities, he has chosen to stay at Cornell.

Lu, an electrical engineering major and a participant in the Engineering Cooperative Program, accumulated a grade-point average of 3.99 while carrying out a full program of extracurricular activities. He was secretary of Eta Kappa Nu, the honorary society in electrical engineering, and served as chairman of the society's tutoring committee funded by the Summers memorial endowment. Lu was also a member of the Cornell wrestling team.

McCone has achieved a number of distinctions in addition to graduating with a grade-point average of 3.71 as a major in mechanical and aerospace engineering. She was named the Society of Women Engineers Outstanding Sophomore Engineer, received a Bell Laboratories Achievement Award, and was elected to the engineering honorary society Tau Beta Pi. She held a Navy ROTC scholarship and was cited as a Distinguished Midshipman. She was active in sports and belonged to the student chapter of the American Society of Mechanical Engineers, the Engineering Ambassadors (which works with high school students interested in Cornell), and the Society of Women Engineers.

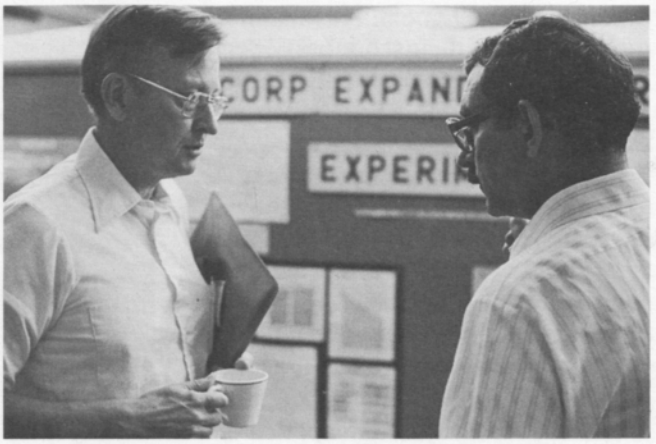
Hans Hallen, one of the six engineering seniors honored as Presidential Scholars, receives his award from Cornell President Frank H. T. Rhodes.

Rosenkopf was a National Merit Western Electric Scholar, won an Eastman Kodak grant for excellence in operations research and industrial engineering, was elected to the honorary Tau Beta Pi, and received the Byron Saunders Award as the most outstanding student in the 1984 class in OR&IE. On the side, she worked as a stockroom attendant for the Department of Chemistry, served as editor of the *Cornell Desk Book*, and was active in intramural athletics and in the Society of Women Engineers and the student chapter of the Institute of Industrial Engineers. During her senior year she was a teaching assistant in the course Applications of Operations Research and Industrial Engineering—a responsibility seldom given to an undergraduate.

Scrivanich was consistently on the Dean's List and was the ranking student in chemical engineering throughout his upperclass years. His honors include the annual chapter award of the American Institute of Chemical Engineers and election to Tau Beta Pi. He served as a tutor in chemistry and chemical engineering for all four years and was active in athletics, playing freshman football and various intramural sports.

Skinner, an outstanding scholar with a cumulative average of 4.01, majored in electrical engineering and was elected to the honoraries Tau Beta Pi and Eta Kappa Nu. She served as a tutor in the Summers tutoring program. In extracurricular activity she held several offices, including that of president, in Alpha Chi Sigma, and was a member of the Sage Chapel Choir.

VANTAGE



Top: Informal discussions during coffee breaks augmented the formal proceedings at the geology symposium. Shown here are James Dorman of Exxon and Muawia Barazangi, the symposium coordinator.

Below: A large hall of exhibits attracted delegates during the breaks.

■ Geologists and geophysicists from around the world met at Cornell June 26–28 for the first International Symposium on Deep Structures of the Continental Crust. Organized by Cornell's Institute for the Study of the Continents (INSTOC), the event attracted about three hundred delegates from government agencies, academic institutions, and industry.

The symposium emphasized recent applications of the seismic reflection profiling technique, which is used to explore the deep structure of the earth's crust. In research conducted by the Cornell-based Consortium for Continental Reflection Profiling (COCORP), previously unknown structures as deep as 40 kilometers have been discovered and mapped in the United States, and six other countries now have similar programs.

Members of the Cornell Department of Geological Sciences who were active in the symposium events include Jack E. Oliver, Larry Brown, Sidney Kaufman, and Muawia Barazangi, the symposium coordinator. Sponsors included the Cornell Program for the Study of the Continents (COPSTOC), an industrial affiliates' program closely related to COCORP, and five United States and international organizations in the geological sciences.

■ Almost a year to the day after groundbreaking ceremonies, the DeFrees Hydraulics Laboratory, an addition to Hollister Hall, was dedicated on June 4.

The first use of the new room was as a gathering place for celebrants attending the dedication ceremony. The huge (5,000 square feet) sunken room, with high windows looking out on Central Avenue, still had no equipment in place, but it was well filled with faculty and staff members, students, and family members and friends of the late

Joseph H. DeFrees. Within a few months, professors and graduate students from the School of Civil and Environmental Engineering and from a number of other disciplines will be carrying out an extensive program of research involving hydraulics.

The new laboratory is named for the Warren, Pennsylvania, inventor, manufacturer, and philanthropist, who once studied hydraulics at Cornell in the first facility—the long-unused structure built by the Beebe Lake Dam in 1898 and still a familiar campus feature. The new $700,000 laboratory was made possible by gifts from DeFrees and his wife, Barbara Baldwin DeFrees, with additional funds from the Allegheny Coupling Company, the Allegheny Valve Company, and the DeFrees Foundation. These two companies, which specialize in equipment for the petroleum and tank transportation industries, were founded by DeFrees, who served as president of both until 1978.

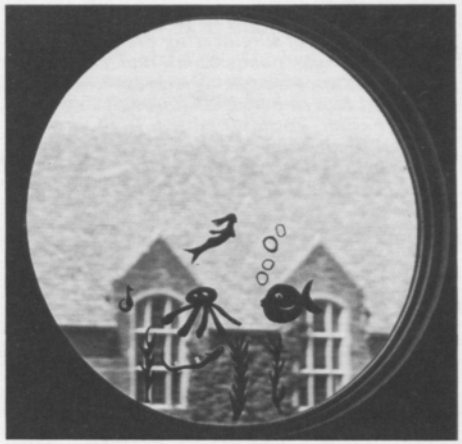
Presiding at the dedication program was Thomas E. Everhart, dean of the College of Engineering. Speakers were Cornell President Frank H. T. Rhodes; Richard N. White, director of the School of Civil and Environmental Engineering; Gerhard H. Jirka, associate professor of environmental engineering, one of the faculty members who will use the facility; and Mrs. DeFrees.

DeFrees, who died in 1982 at the age of seventy-six, was graduated from Cornell in 1929 with a degree in civil engineering. In addition to directing his businesses, he was an inventor, the holder of more than seventy patents. His interest in developing and encouraging craftsmanship and inventiveness among today's engineering students was reflected in the earlier gift to Cornell of a collection of antique scientific instruments, now on permanent display in Hollister Hall. A plaque in the new laboratory cites DeFrees as "Inventor, engineer, businessman, citizen of Warren, Pa., humanitarian, benefactor and a loyal and dedicated Cornellian. His vision and his generosity have provided this hydraulics laboratory."

Left: Participating in the dedication program were Cornell President Frank H. T. Rhodes and Barbara DeFrees.

Below left: Mementos of the occasion are displayed by Richard N. White, director of the School of Civil and Environmental Engineering.

Below: A feature of the new laboratory is this large "porthole" (the Law School is opposite on Central Avenue). The unplanned decorations were contributed by anonymous students.



Equipment to be installed includes three major facilities: a 105-foot wave tank capable of generating any type of wave; an 80-foot hydraulic tilting flume for studies of turbulence and sediment transport; and an 80-foot wind-water tunnel for studies of the interaction of air and water. The laboratory will also have analytical facilities for water-quality testing, and an electronic data-acquisition system. Funding for the equipment is provided by the National Science Foundation, Barbara DeFrees and the DeFrees family, and industrial sources.

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the period November, 1983, through February, 1984. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

■ AGRICULTURAL ENGINEERING

Cooke, J. R. 1984. Microcomputer software selection. In *Dairy farming in the 1980's*, pp. 58–62. Proceedings, 1984 Dairy Days (10–11 January 1984, in Ithaca, NY); Animal Science Mimeograph Series. Ithaca, NY: Cooperative Extension, Cornell University.

Cooke, J. R., and D. C. Davis. 1983. Microcomputer-based instruction in finite element analysis. II. Applications. ASAE paper no. 83-5539, read at meeting of American Society of Agricultural Engineers, December 1983, in Chicago, IL.

Davis, D. C., and *J. R. Cooke*. 1983. Microcomputer-based instruction in finite element analysis. I. Implementation. ASAE paper no. 83-5538, read at meeting of American Society of Agricultural Engineers, December 1983, in Chicago, IL.

MacVicar, T. K., and *M. F. Walter*. 1984. An electronic transducer for continuous water level monitoring. In *Transactions of the ASAE* 27(1):105–09.

McLaughlin, N. B., and *R. E. Pitt*. 1984. Failure characteristics of apple tissue under cyclic loading. *Transactions of the ASAE* 27(1):311–20.

Millier, W. F., R. A. Pellerin, J. A. Throop, J.u.d. Werken, *A. N. Lakso,* and *S. G. Carpenter*. 1984. The role of impact shaking in the harvest of apples. In *Proceedings of International Symposium on Fruit, Nut, and Vegetable Harvesting Mechanization*, pp. 89–96. St. Joseph, MI: American Society of Agricultural Engineers.

Naylor, L. M. 1983. Looking ahead to sludge spreading in New York. *Biocycle* 24:47–48.

———. 1983. Septage, a resource: Problems and potential. 1983. In *Proceedings of Hamilton Conference on Land Application of Septage*, ed. J. Cox, pp. 9–18. Hamilton, MA: Massachusetts Society for Promoting Agriculture.

Naylor, L. M., and H. L. Brumback. 1983. *Cheese production wastewater treatment residuals as a fertilizer*. Report no. 83-4. Ithaca, NY: Department of Agricultural Engineering, Cornell University.

Naylor, L. M., and *R. C. Loehr*. 1984. Priority pollutants in municipal sewage sludge. In *Managing sludge by composting*, ed. J. Goldstein et al., pp. 185–205. Emmaus, PA: J. G. Press.

———. 1984. Transfer of synthetic organics from sludge to soil. Paper read at Municipal Wastewater Sludge Organic Chemicals Health Effects Workshop, 10–12 January 1984, at USEPA Health Effects Research Laboratory, Cincinnati, OH.

Rehkugler, G. E., and *J. A. Throop*. 1983. *Apple bruise detection using a microcomputer*. Research report on processed apples. Ithaca, NY: Institute of Food Science, Cornell University, and Processed Apple Institute.

Richards, B. K., M. F. Walter, and R. E. Muck. 1984. Variation in line transect measurements of crop residue cover. *Journal of Soil and Water Conservation* 39(1):60–61.

Taylor, R. W., G. E. Rehkugler, and *J. A. Throop*. 1983. Apple bruise detection using a digital line scan camera system. Paper read at National Conference on Agricultural Electronics Applications, 11–13 December 1983, in Chicago, IL.

■ APPLIED AND ENGINEERING PHYSICS

Bloom, J. A., and *W. W. Webb*. 1984. Photodamage to intact erythrocyte membranes at high laser intensities: Methods of assay and suppression. *Journal of Histochemistry and Cytochemistry* 32:608–16.

Carley, W. W., and *W. W. Webb*. 1983. F-actin aggregates may activate transformed cell surfaces. *Cell Motility* 3:383–90.

Sakisaka, Y., T. N. Rhodin, B. Egert, and H. Grabke. 1984. Resonance effects in photoemission from Si- and P-covered Fe(100) surfaces at the 3p and 3s-thresholds. *Solid State Communications* 49(6):579–85.

Schneider, M. B., J. T. Jenkins, and *W. W. Webb*. 1984. Thermal fluctuations of large cylindrical phospholipid vesicles. *Biophysical Journal* 45:891–99.

Schneider, M. B., and *W. W. Webb*. 1984. Undulating paired disclinations (oil streaks) in lyotropic liquid crystals. *Journal de Physique* 45:273–81.

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Opposite: The old hydraulics laboratory by Beebe Lake Dam, a familiar campus feature, was the subject of reminiscence at the recent dedication of the DeFrees Hydraulics Laboratory (see page 31). The old building has been unused for many years.