

The future of lasers

A panel discussion: Nine specialists foresee an expanded frequency range, new kinds of lasers, and many novel applications.

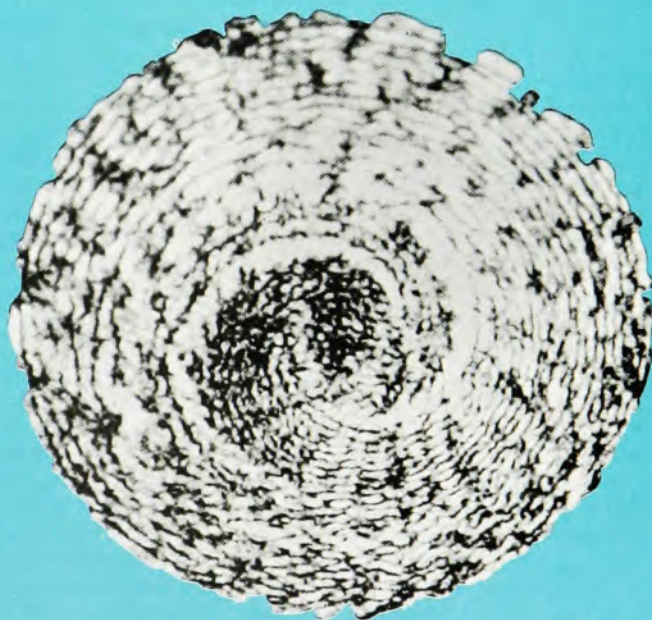
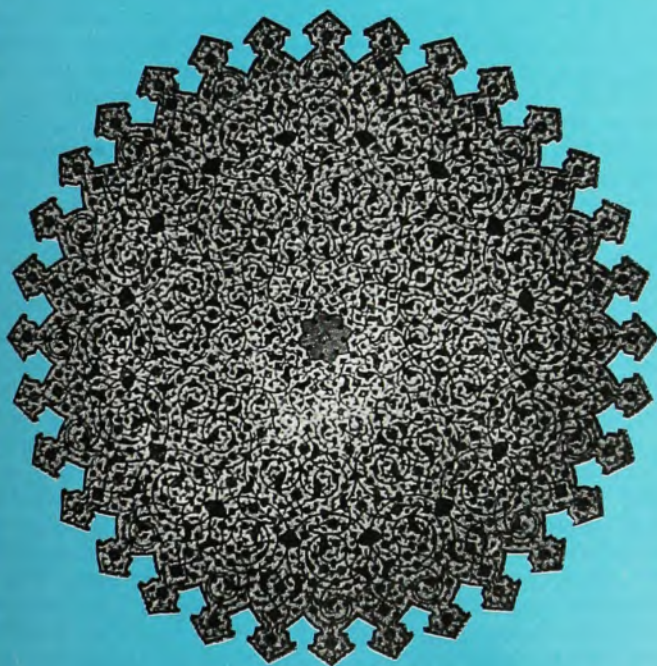
At the Esfahan Symposium on Fundamental and Applied Laser Physics, which took place 29 August–5 September 1971, the world's laser specialists gathered to exchange notes on the state of the field and its probable future. The symposium was held on the campus of Esfahan University in Esfahan, the second largest city of Iran, under the auspices of Arya-Mehr University of Technology and with the support and cooperation of Esfahan University and the Massachusetts Institute of Technology. Ali Javan (MIT) was director of

the symposium, which was sponsored by the International Union of Pure and Applied Physics.

The panel discussion reported here was moderated by Arthur Schawlow of Stanford University. In his introduction to the discussion, Schawlow invited each of the eight panelists to speak for a few minutes on some aspect of lasers or laser applications, scientific or otherwise. He particularly requested them to talk about the future and to be "as wild as possible!" After the contributions from the eight panelists, and a comment from

Schawlow himself, the discussion was thrown open to the floor; we report here the major contributions in full and excerpts from the discussion that followed.

Esfahan contrasts. These two photographs, which appeared in the symposium program booklet, show the dome of Lutfullah Mosque, Esfahan, on the left (photograph by A. Banani) and a gas-laser interference pattern on the right (photograph by J. R. Murray, MIT).



Nicolaas Bloembergen

Harvard University

A reasonably safe prediction on future progress in a branch of physics consists always of pushing the values of important physical parameters to new limits. In the case of laser physics one can think of pushing the frequency to the ultraviolet and perhaps to the x-ray region. There are no known obstacles to obtaining laser light beams in the vacuum ultraviolet down to about 1200-Å wavelength by extension of familiar techniques of nonlinear optics. Clearly a lot of materials research and development is required. One may reasonably expect that, within a decade, high-resolution spectroscopy with tunable laser sources may be done anywhere between 100-micron and 0.1-micron wavelength.

The push toward the x-ray region will be more difficult. Perhaps the pulsed x-ray emission from laser-induced high-Z plasmas may be used to pump an x-ray laser. A big pay-off would be x-ray holography, making visible the electronic structure of matter, in particular the structure of biochemical molecules.

Other physical parameters that may be pushed are the time duration and peak power level of ultrashort light pulses. There appears to be no fundamental limitation why light pulses as short as 10^{-14} sec could not be obtained. For flux densities exceeding 10^{12} watts/cm², corresponding to light-field amplitudes of about 3×10^7 volts/cm, all materials will ionize rapidly in very short times, of the order of a picosecond or less. In a completely ionized plasma the peak flux could be raised further. Short, powerful, tunable pulses from picosecond dye lasers will clearly be important in analyzing excited states and intermediate products in photochemical reactions.

Turning to shorter-range predictions and more immediate developments, I wish to point out that nonlinear spectroscopy is likely to grow enormously. The exploration of this field has only just begun, and it is potentially much richer than linear spectroscopy. One has frequency and spatial dispersion in multidimensional spaces. Instead of the second-rank linear dielectric tensor, one must worry about the symmetry properties of third- and fourth-rank tensors. One could probe the band structure at points in highly absorbing regions, by observation of nonlinear processes in the transparent regions.

High-resolution absorption-dip spectroscopy is another example of nonlinear spectroscopy. Talks at this symposium have shown that one can now do in the near and far infrared all the tricks that were done in magnetic resonance at microwave and radiofrequencies a few decades ago. One can fore-

see important analytical and chemical applications of these techniques with infrared lasers.

Alexandr M. Prokhorov

P.N. Lebedev Physical Institute, Moscow

There are many things to speak about, but one of the fields, the far-infrared and submillimeter region, will be developed during the next few years because this region is still not very popular; there are no available sources and no available materials. I think it will be developed because, for solid-state physics, this is a rather important region. The other field I want to mention is stimulated Raman scattering; we can use Raman components to have a mode-locked laser with pulse duration about 10^{-14} sec. And this would be very interesting and important because, at such short pulses, all electronic nonlinearities will be involved. On the other hand, if you investigate the interaction of this high-power radiation with matter, you should not bother about multiphoton absorption. There will be only a tunneling effect because the power will be very high and the tunneling time will be short comparable with the period of the light. This is not the only application. For chemical applications it will also be important. But it is difficult to predict what will happen before actual experiments are made. One thing we can now foresee is the electronic nonlinearity—especially when we discuss the self-focusing process for picosecond and subpicosecond pulses. What is important is the nonlinearity at 10^{-15} sec, and this is rather exciting. Subpicosecond pulses will be developed in the coming years.

Sergio P. Porto

University of Southern California

I would like to mention three fields, three things that we are going to do ourselves and that we think are quite interesting. One is the question of the application of lasers to crystal structure. Natural crystal structure is now studied through x-ray diffraction. It's very simple, when one knows the structure, to calculate precisely how many phonons will be available and what the polarizability tensor is, and so on. One can go this way, or one can go backwards by finding the phonons that exist by finding the polarizability tensor, and then go back and find the crystal structure. But where Raman spectroscopy has an advantage over x-ray analysis is that x-ray crystallography measures the average configuration, whereas in Raman spectroscopy you are making the analysis in a much shorter time domain; so you can see variations in that average structure. For instance, if you have a crystal that

is ferroelectric at one temperature or pyroelectric for some other temperature, there will be domains existing after the transition has taken place that are inaccessible to the x-ray spectroscopist but that we can see. If those domains are of the order of a wavelength of light in size we can even get $K = 0$ phonons, and we can analyze these very precisely and know the nature of the distortion of the crystal structure. If the distortions are very small—much smaller than the wavelengths of light—we have essentially a breakdown of K conservation, and broad features appear that will probably not be as important. The other aspect of this that I think is very important is the study of the phase transition itself. As the crystal is heated or cooled, a phase transition occurs. The following picture is the best way to visualize what causes the phase transition. Imagine there is a phonon which becomes soft and decreases in frequency as the phase transition approaches. As the frequency decreases it crosses the frequency of another phonon. A coupled-oscillator problem then occurs; the phase transition then becomes a reality. Looking for the microscopic mechanism of phase transitions is right now, in my opinion, the hottest subject for which one can find an application of the laser.

Charles H. Townes

University of California

Any review of the past development of quantum electronics is likely to make one enthusiastically optimistic about the future. Every two or three years there has been another revolution in what appears practical; over ten or fifteen years this characteristic has opened up the field to wide applications and a great range of fruitful developments. One can reasonably expect striking progress to continue for some time, for there is yet a considerable way to go before we reach any natural or physical limits in the useful characteristics and performance of lasers. Acceptance of this conclusion, and recognition that both optics and electronics have been remarkably useful as separate fields, makes the marriage between the two, which is quantum electronics, seem indeed a powerful combination. There appears every reason to expect that laser techniques will permeate much of our science and technology, and in time even get into the home. One cannot do justice to such a large and diffuse field in a few minutes. Hence I shall make only a few additional comments on very specific areas in which I myself am working. These also tempt me to reminisce a bit.

I first became interested in trying to make a molecular oscillator in order to



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produce submillimeter and far-infrared oscillators for spectroscopic purposes. This original goal has not yet been fully achieved, although many other striking successes have occurred. While the prospect for convenient scientific techniques in the far infrared still looks good, this region is in fact one of the last to which quantum electronics is contributing, and much remains to be achieved. Further development of the infrared and particularly of the far infrared is of great scientific importance, and probably will occur rapidly over the next few years. One field for which it is especially important is astronomy. A very large fraction of the total radiation from astronomical objects is in the infrared and far infrared; yet these spectral regions have scarcely been tapped for astronomical purposes, and they badly need development. Unfortunately, the atmosphere absorbs much of the infrared spectral region rather severely, and has prevented anything more than very rudimentary astronomy in the submillimeter region. But with high-flying planes, balloons and spacecraft we can work above the atmosphere. Furthermore, there is much good work to be

done in the atmospheric windows where infrared is transmitted. Quantum electronics, including coherent techniques and good amplifiers, is a key to further development of infrared techniques, and it should have an enormous impact on astronomy. At the University of California, Berkeley, we are accordingly attempting several technical developments.

One example of our efforts to utilize quantum electronics properly in the infrared region is a long-baseline stellar interferometer for 10 microns wavelength. By "long," I mean in the realm of kilometers, and with angular resolution far beyond any previously obtainable in the infrared. We are also trying to develop techniques for infrared pictures by using up-conversion. Sensitive detectors, which use Josephson effects and maser-type amplifiers, represent other goals. Heterodyne techniques are being applied in the infrared for very high spectral resolution of line emission from astronomical objects. Most of these goals will, I feel sure, be achieved in some way. A few will be remarkably successful, others will be replaced by better ideas. Regardless of what may be the success of these particular efforts, the rapid development of quantum electronics resulting from the work of many laboratories will undoubtedly help open up an important and as yet very meagerly explored branch of astronomy.

Ali Javan

Massachusetts Institute of Technology

I address my comments mainly to the applications of the nonlinearities of atomic and molecular resonances in laser spectroscopy. The importance of this field of study became evident in the early years following the advent of gas lasers, when a variety of nonlinear effects were applied to obtain enormous reductions of the spectral-line profiles in a host of atomic systems, enabling measurements of their line structures. The potential impacts of this field have now been enhanced dramatically with the recent realization of the necessary technology to mix and compare widely different frequencies of electromagnetic waves over a range extending from the microwave into the far and the near infrared—and soon, with the aid of the already known methods, into the visible portion of the spectrum. We can now look forward to the exploitation of these methods in the next decade of spectroscopic application, and obtain improvements in precision and accuracy of many orders of magnitude. In addition to the molecular spectra in the infrared and optical region, we must now go back to our simple elements and re-examine their spectra. Atomic hydrogen and

ionized and neutral helium must be examined again. These will surely lead to a redetermination of the Rydberg constant with much improved accuracy. Other fundamental constants and processes will be determined with better precision. And very soon, we will also know an ultimate value for the speed of light.

A recent development has opened the way to observe the nonlinear resonances under extremely dilute gas conditions where pressure effects are at a minimum. An inspection shows that in special cases it may be possible to find the center frequencies of these resonances reproducibly to within accuracies better than one part in 10^{14} . This, together with our ability to determine the absolute frequencies in the optical and infrared region, will enable the realization of much improved atomic clocks, capable of better testing some fundamental laws of nature—possibly predictions of some general relativistic effects.

There have been vague speculations on the possibility of laser emission in the x-ray region. Let us remind ourselves that a practical way to achieve this has not yet been discussed, but I forecast that this is within the realm of possibility and will be discovered in the decades to come.

Boris P. Stoicheff

University of Toronto

Only ten years ago very few scientists were involved in Raman spectroscopy and only a handful had heard of Brillouin scattering. With the development of the laser, this situation has rapidly changed, so much so that it is difficult to keep up with the literature. Last year alone 30 ion lasers were sold specifically for experiments in Raman and Brillouin scattering. Clearly, there has been a revolution in the field of light scattering in the past five or six years—and it seems to me it is about time that many of us left it!

I can foresee that in a few years a similar revolution will occur in infrared spectroscopy and probably in the visible region—and I do feel sorry for the old timers, those spectroscopists working in these regions who have not kept up with the new techniques, because there is no doubt that they will be swamped.

One of the most difficult regions for work in spectroscopy is the vacuum ultraviolet. Materials that transmit such radiation are almost nonexistent, and those with even 50% reflectance are few. This is also a region where we need new ideas for laser sources. Some advance has already been made, but this is just a beginning; new lasers in the vacuum ultraviolet will eventually lead to improved optical compo-



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nents, new materials and much more spectroscopic research in this region.

One of the states of matter that we know very little about is the liquid phase. Many beautiful experiments have been carried out in light scattering with lasers, particularly in the critical region. With further work we should be able to make some headway to a better understanding of liquids.

And one final remark. Of course, it would be one of the greatest discoveries to find another population somewhere in the universe. I believe that contact can probably only happen through the use of lasers and masers. This is not a new idea; some searches have already been made, and I think we should continue to explore.

Pierre Jacquinot

Centre National de la Recherche Scientifique, Orsay

I would like to give here the point of view of a laboratory that is essentially interested in atomic spectroscopy and atomic structure. In such a laboratory there are some limitations in the use of lasers, because many problems can be solved only by means of emission spectroscopy with conventional sources and spectrometers (including the recently developed Fourier spectrometers): for example the study of spectra of the various neutral and ionized atomic species is still a major problem, because only about 20% of these spectra are known and correctly analyzed. And of course the spectra emitted by celestial objects have to be observed with spectrometers. However, even in emission spectroscopy, lasers can be

helpful—especially in the infrared region, because some lines of interest for the understanding of spectra are too faint to be observed otherwise than in a laser. In our laboratory we have succeeded in obtaining about 100 lasing lines of eight metallic elements, which have brought useful information in atomic spectroscopy.

But of course all the lines that can be observed in absorption could be studied much better with lasers than with conventional techniques. So far we have studied only specific cases where there is a coincidence of the line to be studied with the line emitted by a laser, and very high resolution has been obtained in isotope shifts and hyperfine structures of rare gases even by limiting ourselves to linear absorption. But of course this can become of more general use when tunable lasers are available. In addition the use of saturated absorption is highly recommended in many cases.

But there are also different methods of using lasers as sources, essentially resting upon the optical pumping produced by laser light, this pumping being detected by nonoptical means. For instance, in a Rabi experiment with an atomic beam the magnetic moment of paramagnetic states can be reversed by the pumping in the C region, and this can be used as a sensitive means to detect optical absorption transitions. This experiment is being developed for measurements of isotope shifts of radioactive elements. Another method, which could be simpler and of more general use, rests upon the recoil suffered by atoms of an atomic beam when they absorb photons of a laser beam: Here preliminary experiments are just beginning.

My conclusion is that although a great part of atomic spectroscopy will still use spectrometers for the analysis of emission spectra, lasers should become very important when tunable ones are available with the following qualities: wide range, high stability, sharp lines, high power, and in some cases, continuous output.

Raymond E. Kidder

Lawrence Radiation Laboratory

The area I am most concerned with and interested in is possibly the farthest-off application that has been discussed so far. However, I think it is an exceedingly important one: The production of useful power from thermonuclear fusion.

In this context the laser has already provided us with a new approach to fusion that differs markedly from previous approaches by eliminating the troublesome "magnetic bottle." This doesn't necessarily mean that this particular approach will ultimately turn out to be the best one, but I think it

indicates that already the laser is widening the scope of possibilities for controlled fusion. More generally, the laser beam's precise controllability in space and time may well play an essential role in the exceedingly difficult task of controlled fusion in ways that are now unforeseen.

One other application that I'd like to mention is the use of lasers in chemical processing, and particularly in isotope separation. For this one needs favorable spectroscopy and chemistry, both of which should be available for separating such isotopes as those of carbon, nitrogen and oxygen. The separation of deuterium from hydrogen has already been demonstrated in the laboratory experiments of Mayer, Kwok, Gross and Spencer. (We didn't attempt this at Livermore on grounds of insufficient challenge, Edward Teller saying that one should be able to separate deuterium "with your bare hands.") At the other end of the periodic table is uranium, where the chemistry is more severely limited and the spectroscopy is not yet known with sufficient resolution. However, here too one may expect that eventually a laser scheme for isotope separation will be discovered.

So these are two applications, controlled fusion and isotope separation, that I think I can add to the list compiled by the other panelists, and I predict that lasers are likely to make a very big difference in both.

Arthur L. Schawlow

Stanford University

We didn't mention x-ray generation, which sounds as if someone here may be very close to it, or somebody else may be, by the brute-force method of pumping in lots of laser power. This, I believe, will happen fairly soon, and I think the applications will be quite surprising ones—just as the applications of lasers were not confined to communication. I think also that it is a very exciting time now because we really are getting tunable lasers; some of them are even cw, but they all have the properties that Professor Jacquinot asks for. And they are now extending into the visible and ultraviolet regions, which is right for doing photochemistry, although clever people have ways of doing it in the infrared.

I think also that a laser is very useful for spectroscopic analysis of complex spectra, because you excite just particular states; thus, when we excite an iodine molecule with a broad-band lamp the fluorescence is extremely rich and complex. With a laser you get only two lines, $\Delta J = +1$ and $\Delta J = -1$, for each value of v . It's a very much simpler spectrum—perhaps a hundred times simpler—and similar simplifications may be obtained elsewhere.

Comments and discussion from the floor

Benjamin Lax (*National Magnet Laboratory, MIT*): I would like to comment on a remark made by Professor Prokhorov. Submillimeter spectroscopy is already here, and far-infrared lasers are now being used in conjunction with high magnetic fields to do resonant spectroscopy. The 337-micron HCN laser is a good example. With a pulsed magnet available at any laboratory, it can be used to extend resonant spectroscopic studies of the microwave type into the infrared.

Another important advance is in the field of atomic spectroscopy—two-photon studies using high-power lasers. So we can now study transitions that are forbidden for single photons. I believe such studies will lead to a revolution in atomic spectroscopy, from the far infrared all the way to the ultraviolet.

Willie Low (*Hebrew University of Jerusalem*): I would like to illustrate a remark made by Professor Bloembergen by an example. Not very much is known today about the band structure of various systems, particularly three-dimensional systems. Two-photon laser spectroscopy can now be used, in principle, to study the structure of such bands in the same way as is done in atomic systems. I think that this field is just opening up.

The next thing I have to say relates to comments made by Dr Stoicheff. I think that Brillouin scattering will be important in the study of chemical reactions in the time domain of 10^{-7} to 10^{-10} seconds. I also think it is important to utilize Brillouin scattering to generate acoustic waves in the region beyond 40 KMHz. For example, the 100- to 200-KMHz region would fall within the dispersion region of some important cases, enabling the determination of their band structure.

Finally, I would like to challenge the panel to comment on the use of lasers in nuclear physics.

Townes: One application in nuclear and particle physics is the generation of coherent polarized gamma rays by scattering a laser beam off a high-energy beam of electrons. This is now a standard technique.

Prokhorov: I would like to comment on the application of lasers to isotope separation. We have recently performed an interesting experiment in our laboratories on boron trichloride, which has two isotopic forms. Using a CO_2 laser we can selectively excite one isotopic species into a highly excited vibrational state from which the mole-

cules dissociate. The vibrational quantum number of this state is about 30. To remove the dissociated isotope, we added hydrogen, but it reacted violently with the free radicals that were formed and produced enormous shockwaves.

Schawlow: I think that one of the important things needed is an efficient visible laser. The need for such a laser was mentioned in connection with thermonuclear fusion, but I think it would find all sorts of everyday uses also, like cutting metals, communications, photography and, if the cost was low, perhaps even typewriter erasers! How does one get such a laser? I don't know. My guess is that a high-density gas is a more likely candidate for the active medium of such a device than is a liquid. The gas atoms would have large oscillator strengths and would be pumped by a broad-band source, something like the gaseous analogue of a semiconductor laser.

C.O. Alley (*University of Maryland*): I would like to mention another application to nuclear physics of lasers with high power densities. I think one is now on the verge of being able to observe short pulses with power sufficiently high to observe photon-photon interactions due to virtual pair production. With fast time resolution, such experiments might just be feasible in the next few years.

Another application that has not been mentioned so far is precision ranging over large distances with very short laser pulses. We are currently measuring the point-to-point distances of the Earth-Moon system to an accuracy of 30 cm, and we think that by utilizing mode-locked lasers and taking atmospheric corrections into account, accuracies better than 3 cm will be achieved within the next year or so.

Javan: I think this business of photon-photon scattering due to the vacuum polarization effect will probably be more difficult than it appears because of the nonlinear properties of matter, which could dominate the scattering process even at very low pressures.

Schawlow: If we ever do get the elusive x-ray laser, one possible application would be the coherent excitation of nuclear states. Then maybe we could do wave-echo (photon-echo) experiments in the nuclear region.

R.V. Khokhlov (*Moscow University*): I would like to attract attention to possible applications of ideas in laser physics to other fields, such as neutrons, protons and nuclei. It may be possible to get coherent emission of neutrons, protons and other particles.

It may also be possible to observe Raman-type interactions between particles. The idea of light scattering may be applicable in interactions between particles. I cannot comment on a possible source of pumping—this is clearly a problem. One possibility may be the application of high-intensity light of the order of 10^{21} watts/cm², but there may also be other possibilities.

Javan: Actually I had been thinking of making a comment on some far-out ideas, and I see that Professor Khokhlov has been thinking along similar lines. In fact, I was about to propose that instead of "masers" and "lasers" we should think of "basers" to describe boson amplification by the stimulated-emission effect.

Schawlow: But Professor Khokhlov suggests that fermions could also be used.

Javan: I don't think anything can be done with fermions, but if we stick to bosons we might have a chance.

Pierre Giacomo (*Bureau International des Poids et Mesures, Sèvres*): Some people have suggested using lasers as primary standards of time and length measurement. I would like to insist that it is essential that primary standards in different laboratories or different countries agree among each other, at least within one part in 10^{11} or 10^{12} .

Javan: Methods for such frequency or wavelength reproducibility have already been demonstrated with the recent extension of absolute frequency-measuring techniques into the near infrared. For instance, if the frequency of a laser is compared with that of a cesium clock, which already offers one part in 10^{12} accuracy, one would automatically have at hand a length standard of the same accuracy. In that case, one would wish to define the speed of light as a dimensionless parameter and define the length standard by means of frequency measurements, utilizing an existing atomic clock.

John Hall (*Joint Institute for Laboratory Astrophysics, Boulder, Colo.*): In considering the length as a standard one would probably want to use length metrology, and for us that means observations by means of interferometric techniques. The limitations in that case are due to physical imperfections of the optical components, which seem to limit the accuracy to one part in 10^8 or 10^9 . In principle, at least, one can perhaps improve this limit by one or two orders of magnitude using laser tricks and interferometers with long arms—30 meters, for example. □