Physics of lasers, laser physics, and optical physics

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Laser Spectroscopy IX: Proceedings of the Ninth International Conference, **Eds. M. Feld, J. Thomas, and A. Mooradian,** Academic Press, New York, 1990.

P. W. Milonni and J. H. Eberly, *Lasers*, John Wiley, New York, 1989.

Thirty years after the first laser has been put into operation the physics and technology of lasers has reached in a number of aspects parameters that are in fact at the limit both at the "macro" and at the "micro" levels.

We have come essentially to the end of the road to the shortest possible light pulses—pulses of $\sim 10^{-15}$ s duration have been obtained, pulses under the envelope of which only a few periods of light oscillations are accommodated. Compression of pulses, focusing in time has made it possible to achieve a sharp upward jump in the scale of power and intensity. "Table-top" terawatt (10^{12} W) lasers have been built achieving intensities of $\sim 10^{19}$–10^{20} W/cm^2. Pentawatt (10^{15} W) systems are on the verge of being constructed which would enable one to obtain intensities of 10^{24} W/cm^2. In entirely practical designs of solid-state lasers frequency instability $\sim 10^{-14}$ has been obtained which is close to the limit determined by spontaneous noise. The "natural" spatial coherence has been obtained in a single-mode laser which is also limited only by spontaneous noise. One has succeeded in nonlinear systems in controlling quantum indeterminancy of light fields—in generating macroscopic quantum squeezed states.

The use of nonlinear response of matter, which even quite recently was manifested only in specially designed experiments, has now become a routine spectroscopic method which has found widespread application in controlling light by light.

All this has radically altered the appearance of optical quantum electronics and physical optics. While in the sixties–seventies the physics of lasers was dominant in this field, now to a large extent a new field of physics has been formed, where optical methods are used for solving a wide range of physical problems which even quite recently were inaccessible to optical technology.

The new set of problems is now most frequently covered by the term "laser physics"; also the term "optical physics" is used fairly widely. (It should be stated that these terms have also been "officially" acknowledged. The specialty "laser physics" has been included by the Higher Certifying Commission of the USSR into the list of qualified physics specialties. The term "optical physics" is widely used in the English-language literature; in particular, one of the authoritative American journals has that name.)

The ideas, the conceptual approaches, the experimental methods of laser physics (optical physics) have demonstrated their effectiveness in atomic and molecular physics, solid-state physics, and plasma physics, and direct laser experiments in the field of high-energy physics and nonlinear quantum electrodynamics are entering the realm of real possibility. The area of applications in chemistry, biology, and biomedicine is rapidly expanding. These new tendencies are exerting a strong effect on education in physics.

The two books mentioned in the title of this review provide a good idea of the modern level of research work and of the directions in providing pedagogical literature in laser physics. The first of them—Proceedings of the IX International Conference on Laser Spectroscopy which took place in the summer of 1989 in Bretton Woods, New Hampshire, USA. The subject matter of regularly scheduled, beginning with 1973, international conference on laser spectroscopy has long ago gone beyond the bounds defined by its quite narrow name. In fact, the interests of the participants are concentrated primarily on the applications of lasers in fundamental physics. It should be stated that the years 1988–1989 were very fruitful, so that the collection of articles under review gives a good idea of the level of laser physics, and of new possibilities opening up for physics as a result of using modern laser methods.

In a brief review it is not possible, naturally, to give a to any degree detailed presentation of the materials of the collection of articles. Nevertheless the following list of problems examined at the conference (the sections of the collection of articles) accompanied by brief comments will, we hope, enable the reader to form an idea of the meaning assigned to the terms laser physics and optical physics, and to get a feeling of the tone of this dynamic field of physical science.

Atomic particles, localized in electromagnetic traps and cooled with the aid of laser light to ultralow temperatures. Experiments with such particles have brought in recent years many fundamental results in spectroscopy, in the physics of phase transitions, in chemical physics, and in physics and technology of optical frequency standards. Materials of three parts of the book are associated with this group of problems: "New Cooling Mechanisms," "Trapped Ion Spectroscopy," "Applications in Radiation Forces." Several research groups have reached temperatures of cooled ions of $T \approx 30\ \mu$K; at temperatures of $T \approx 10\ \mu$K the de Broglie wavelength is $\lambda \approx 250$ nm and, consequently, the description of the motion of the particles must be completely quantum. Brewer's group (IBM Laboratory, USA) reported elegant experiments in which the transition from order to chaos was observed in a system of two trapped ions. Work on direct observation of elementary quantum transitions of individual atoms or ions from one energy state to another—Bohr's quantum jumps—is being intensively developed.

Coherence and chaos, control of quantum fluctuations,

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"nonclassical" light. The interests of authors presenting their reports in the sections "Noise and Coherence" and "Cavity QED" have been focused on the above "hot spots" of modern optical physics. Without any doubt one of the most important events became the demonstration of the possibilities of observing in nonlinear-optical systems and in lasers of a complete hierarchy of phenomena of three-dimensional nonlinear wave dynamics, including effects of self-organization, the generation of space-time nonlinear wave structures, of four-dimensional dynamic chaos (optical turbulence)—phenomena that until the most recent times had been studied primarily in hydrodynamics and chemical physics.

The achievements of this field of optical physics (the terms "dry hydrodynamics," "optical synergetics" are more and more frequently becoming associated with this field) are due primarily to the development of effective methods of controlling *transverse interactions* of light waves in a nonlinear medium—we recall that traditional nonlinear-optical methods of transforming frequency and angular spectrum are based on the organization of effective *longitudinal interactions*.

As before the interest is high in papers aimed at the realization of the greatest possible coherence of laser radiation. In reports of a number of American groups new data were provided on solid-state lasers that have a temporal coherence close to the limit. M. Levenson (IBM Laboratory, USA) reported new experiments on determining the limiting spatial coherence of a single-mode laser. It should be stated that the first experiments of this kind were carried out in our country already in mid-seventies; Levenson's group confirmed these results utilizing a new methodology. Nonlinear optics presents very wide possibilities of controlling quantum fluctuations of radiation—generation of squeezed states. At present along with the parametric amplification circuits, which have by now become traditional, ever greater attention is being paid to squeezed states arising in optical solitons; apparently, here one can attain record-breaking squeezing.

Progress in the development of laser radiation sources. The materials assembled in the section under discussion reflect major achievements in this invariably topical field of laser physics. The purposeful work over many years of the group of Stanford University (USA) led by R. Byer culminated in the creation of a highly stable solid-state laser with diode pumping. An entirely practical Nd:YAG-laser with diode pumping stabilized by a high-Q cavity has a spectral line width of $\Delta\upsilon \approx 30$ Hz exceeding the natural width by only an order of magnitude. The breakthrough in the technique of stabilizing the frequency of compact solid-state lasers opens up quite new possibilities in spectroscopy, interferometry, and in fundamental experiments including laser experiments carried out in space. Tunable laser sources with frequency instability $\sim 10^{-13}$ are becoming within reach; for this purpose one can utilize the unique properties of a two-cavity parametric light generator. Great interest was evoked by the creation of sources of powerful picosecond and subpicosecond x-ray pulses. The group of R. Falcone (University of California at Berkeley) reported on an x-ray source generating pulses of duration less than 10^{-12} s in the wavelength range of $\sim$40–100 Å. X-rays arise in a dense "femtosecond" laser plasma excited in a solid-state target by short pulses of solid-state or excimer lasers developing a target intensity of 10^{16}–10^{18} W/cm^2. At the present time a number of groups in our country and in the USA are working on schemes for focusing such pulses into a spot of dimensions 200–1000 Å. The intensities of x-rays attained in this case of $\sim 10^9$–10^{12} W/cm^2 enable one to begin investigations in a new field of physics—nonlinear x-ray optics. The femtosecond plasma turns out to be a promising working medium for table-top x-ray lasers.

Surface spectroscopy. Nonlinear spectroscopy of surfaces produced in recent years many brilliant results. It has turned out that light reflected at the interface on harmonics and combination frequencies can be used for the diagnostics of properties of monomolecular layers, processes of adsorption and desorption on surfaces, etc.

In the latest investigations an ever greater emphasis is made on nonlinear-optical diagnostics of the dynamics of surfaces—chemical reactions, fast (including laser-induced) phase transitions of the surface, etc. In particular new data presented by the group from Moscow University on "cold melting"—destruction of long-range crystalline order in near-surface layers of semiconductors—were discussed.

Molecular spectroscopy and molecular dynamics. The combination of the technique of tunable lasers generating femtosecond pulses with the technique of molecular beams has made it possible to unify these two fields, and to carry out experiments aimed at direct recording in real time elementary chemical reactions, coherent excitation of states, etc.

Fundamental measurements. Among the papers presented in this section are: the laser spectroscopy of positronium (group from Stanford University, USA), investigation of parity violation in atomic cesium (Institute of High-energy Physics, Zurich), new measurements of the Rydberg constant by the method of two-photon spectroscopy of Rydberg states of hydrogen (Ecole Normale Superieure, France) observation of sub-Doppler orientation of rubidium nuclei (Spectroscopic Laboratory of the Massachusetts Institute of Technology, USA), investigation of the diffraction of atoms and the ponderomotive action of light on atoms (Massachusetts Institute of Technology, USA) and others.

Laser spectroscopy in biomedicine. Discussions that took place at the conference on this topic were stimulated to a great extent by the invited papers of V. S. Letokhov (Institute of Spectroscopy, Troitsk), "Prospects of Laser Spectroscopy of Biomolecules with Nanometer Spatial Resolution" and of S. Svanberg *et al.* (Lund Institute of Technology, Sweden) "Medical Applications of Laser Spectroscopy."

Much new material is contained in the section "Laser Spectroscopy" which contains papers devoted to the improvement and application of more or less traditional methods.

A radical change in the place, significance, evaluation of optical methods in pure and applied sciences exerts a strong influence on education. We are speaking here not only concerning the special training of optical physicists and engineers for optical industry. The place and role played by physical optics in the general physics education, and in the university course on physics have also changed. The generally recognized principle of structuring a university course on general physics is the selection from among a multitude of facts of graphic physical phenomena sufficiently transparent and clear for discussion and at the same time suitable for a precise formulation of fundamental physical ideas and principles.

Modern laser physics and optical physics has to an enormous extent broadened the list of such phenomena. What we have just said refers first of all to the foundations of quantum physics; here it is unlikely that anybody would deny that the student should become acquainted with the basic ideas of quantum physics already in a general course on physics. And now their presentation can be accompanied by discussion of graphical experiments demonstrating the quantum behavior of individual atoms and molecules, characterizing the dynamics of quantum transitions, of optical macroscopic quantum phenomena (including the generation of squeezed states; cf., also the first part of this review), of different effects in excited atoms and molecules illustrating the essence of the quasiclassical approximation, which restructures the bridge between quantum and classical phenomena (from this point of view of special interest are laser experiments on the excitation of wave packets in Rydberg states.) The presentation of the foundations of nonlinear physics, and of nonlinear wave dynamics becomes truly exciting in the language of optics. Here we are speaking not only of clarifying the picture of simplest nonlinear interactions, but also about graphic models, closely associated with experiment, of dynamic chaos and the phenomena of self-organization. There are numerous classical and quantum statistical problems forming the basis of modern statistical optics. At present in a number of universities in our country and abroad lecture courses have been established reflecting the new achievements, which make wide use of the new possibilities of their didactic utilization.

The book under review by the well-known American theoretical physicists Milonni and Eberly can be recommended as one of the textbooks for courses of such a kind. The authors have adopted the title "Lasers"; but the book is more nearly an introduction to laser physics, and not simply a more or less standard presentation of the basic ideas of the physics of lasers. Its first ten chapters (approximately one third of the book) are devoted to the fundamentals of classical and quantum physics of radiation of light and of its interaction with matter. Here the authors have succeeded in preserving a sensible length to discuss the main concepts, the necessary mathematical apparatus (one should separately note the successful presentation of the fundamentals of the theory of interaction of a two-level quantum system with radiation), and what is particularly important, to carry out a specific and clear comparison of classical and quantum approaches in the theory of radiation and absorption of light.

The second third of the book is devoted to the physics of lasers.

The concluding part contains a presentation of the fundamentals of statistical and nonlinear optics.

Within such a structure, of course, there is a definite tribute to tradition; many relatively new topics appear as "additive" material. At present it would appear more logical to include concepts concerning the physics of nonlinearity, nonlinear response of matter to a light field among the basic concepts, on which the entire course of optical physics is structured. With such an approach one can, in particular, tie together, as is well known, the quantum and the classical pictures of stimulated radiation. A number of suggestions could be made also concerning a more organic presentation of the basic concepts of statistics. Although these comments are based on the experience of teaching physical optics at the University of Moscow the reviewer clearly recognizes that the best way of arguing about pedagogical ideas is the writing of textbooks. Therefore in concluding this review we make special note of the positive features of the book by Milonni and Eberly.

Without doubt the pedagogical merits of the book include: the choice of material is successful, the problems and examples are well selected, the ratio between the excellently presented theoretical material, qualitative models, and physical discussion is well balanced.

A Russian translation of the book by Milonni and Eberly would certainly be very useful.

Translated by G. M. Volkoff