On the twenty-fifth anniversary of the laser

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In connection with the twenty-fifth anniversary of the laser in 1985 I would like in this brief article to mention some fundamental ideas which led to the construction of lasers.

The physical bases of quantum electronics were laid in the papers of A. Einstein long before its creation. I shall dwell here only on two fundamental papers of A. Einstein which have a direct relationship to quantum electronics. The first paper appeared in 1905 and was devoted to the quantum theory of light.[1] In this paper he formulated the hypothesis of light quanta and applied it to analyze the photoeffect and photofluorescence. When the photoeffect was discovered it turned out that there exists a "red" boundary beyond which the photoeffect disappears as the wavelength of the light is made longer, and this is independent of the intensity of light. The quantum nature of light gives a good explanation of the "red" limit, and it might seem that such an explanation could have been easily thought of since Newton already advanced the hypothesis of the corpuscular nature of light. However, at that time the wave hypothesis of light was victorious. After the tremendous successes of the wave theory of light, when many optical devices made wide use of interference and diffraction of light and the Maxwell equations gave a complete explanation of all the phenomena of propagation of light in different media, in particular in crystals, a return to the quantum hypothesis of light appeared to be impossible. However, the wave theory of light could not explain such a fundamental fact as the spectral distribution of light radiated by a black body. This was the so-called ultraviolet catastrophe, when, according to the wave theory, the intensity of radiation in the short wavelength region does not fall off, but increases, in complete contradiction with the experimental facts. Planck succeeded in obtaining a formula which completely describes the experimentally observed spectral distribution of the radiation from a black body. In deriving this formula he postulated that bodies emit light in the form of quanta. The coefficient of proportionality has been named the Planck constant. But Planck considered that the quantization property is associated with the properties of the radiating bodies themselves, and not with the radiation field. Einstein was the first to understand clearly that the wave theory of light cannot explain all the facts and that in order to explain them it is necessary to introduce the concept of light quanta also. Essentially, this was the first step towards the recognition of the fact that light can have both wave and quantum properties. The second paper of A. Einstein,[2] which I wish to discuss, was published in 1916 and is devoted to a derivation of Planck's formula. In this paper the concept of stimulated emission by excited atoms under the influence of an external field was introduced for the first time. This concept is the cornerstone of quantum electronics. The probability of stimulated emission is proportional to the density of the radiation incident on an atom, and the frequency of radiation from the atom in such an event is equal to the frequency of the quantum incident on it; the spatial direction properties on the acting and emitted quanta also coincide, i.e., these quanta are identical.

From what has been said above it follows that if radiation acts upon a system of excited atoms then, after the passage of light through this system, the intensity of the light increases, i.e., amplification of light takes place. For the amplification of light it is not necessary that all the atoms should be in the upper state. It is sufficient that there should be more of them than of atoms in the lower state taking degeneracy into account.

The stimulated emission predicted by Einstein aroused great interest, and physicists began to seek experimental verification of this phenomenon. At that time only optical spectroscopy was developed, but for optical transitions, the upper levels were practically not populated at all, and, consequently, stimulated emission did not play any role. It was necessary to create such conditions that the population of the upper levels would be considerable and would exceed the number of atoms in the lower state. Then it would be possible to observe amplification of light or a change in the sign of the dispersion curve of the index of refraction, which is considerably simpler. Just such an attempt was made in a gas discharge. For that period of time this likely was the only possibility of realizing such an experiment.

As the development of quantum electronics has shown, such a situation can actually arise in a gas discharge under quite definite conditions and for definite atomic transitions.

How can we explain the fact that no attempts were made to construct lasers in the 1930's? Experiments which were mounted at the time had only a single aim—to prove the existence of stimulated emission. But no one expressed the idea of the possibility of constructing monochromatic generators of light on the basis of stimulated emission, and this is the fundamental step in the production of quantum light generators. This idea appeared only after work had begun on quantum generators in the radio frequency range—the masers. Masers themselves were constructed in 1954–1955[3,4] on the basis of work in the field of gas radio spectroscopy, which underwent rapid development after the second World War, in connection with the industrial production of

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smoothly tunable generators of ultrahigh frequencies. Gas spectroscopy investigated resonance transitions in the UHF range. In contrast to the case of optical spectroscopy, the population of the upper levels in this case was considerable and absorption was determined by the difference between the numbers of molecules in the lower and upper levels. This difference in the number of molecules amounted to only a small fraction of the number of molecules in the lower level, and, consequently, the effect of stimulated emission must necessarily be taken into account in order to determine correctly the magnitude of absorption. Since generators of monochromatic oscillations in the radio frequency range already existed, the theory of self-oscillatory systems was highly developed. If one has an amplifying element, feedback and a resonator, such a system can generate monochromatic oscillations. All this aided the construction of a quantum generator where the effect of stimulated emission is used as the amplifying element.

After the construction of masers, radio astronomers discovered cosmic sources of monochromatic radiation, i.e., in certain regions of cosmic space conditions for maser action are produced. Of course it could have happened that at first monochromatic sources in the cosmic space would have been discovered, and later masers would have been created under laboratory conditions. But this is not the way it happened. After the construction of masers, work began on the construction of lasers, i.e., of optical generators of light. This was extremely important since in the optical frequency range there were no monochromatic sources of light, while in the radio frequency range there existed radio generators long before the birth of quantum electronics.

A number of difficulties had to be overcome for the construction of lasers. One of the essential difficulties consisted of the fact that at that time the problem of resonators had not yet been solved. This problem also existed for classical generators in the radio-frequency range. In order to understand the complexity of this problem we must return to the history of the development of generators in the radio-frequency range. At first success was achieved in the long wavelength radio-frequency range where oscillatory circuits consisting of an inductance and a capacity were used as resonating systems. Gradually success was achieved with ever shorter wavelengths. In the transition to ultra-high frequencies the dimensions of the oscillating circuits were becoming comparable with the wavelength and the concept of a pure inductance and capacity began to lose meaning. Then for this frequency range volume resonators had begun to be used whose dimensions were comparable with the wavelength. In penetrating into the millimeter and submillimeter wavelengths the dimensions of the resonator became so small that they also began to lose meaning. But if the volume resonators are made much greater than a wavelength then they lose in selectivity, since such a resonator possesses a large number of characteristic oscillations which overlap. It might seem that there is no solution. Only after open resonators were proposed in 1958[5,6] whose dimensions were much greater than a wavelength was the fundamental problem concerning resonators solved; at the present time they are widely used for lasers.

Another important problem is the production of population inversion. In 1955[7] a method of obtaining population inversion in a three-level scheme under the action of an external pumping source was proposed. A significant contribution to the development of this method was made in Ref. 8. This idea made possible the construction in 1957–1958 of UHF quantum amplifiers using paramagnetic crystals having an extremely low noise level.[9,10] The same idea also made an important contribution to the construction of lasers. The first laser, constructed in 1960,[11] worked on the basis of a three-level scheme. It was constructed using open resonators, and flash lamps were used as a pumping source.

After the construction of the first laser rapid development of laser technology began. Other methods of obtaining population inversion were developed, and open resonators underwent further development.

At the present time lasers operate over a wide range of wavelengths, with smoothly tunable dye lasers having become highly developed, and in more recent time also solid state lasers. At present it is possible to obtain very short light pulses (femtoseconds) wherein a small number of optical oscillations is contained. Powerful laser radiation allows the observation of different kinds of nonlinear phenomena. Therefore, nonlinear optics has been greatly developed. As regards practical applications of lasers, they are widely used in many fields of science, technology and medicine. At the present time further development of lasers and their applications is taking place. One can assert with confidence that we are now on the linear sector of laser development and so far there are no signs of a saturation effect.

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