Quantum electronics and Einstein's theory of radiation

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The history of quantum electronics is considered in relation to Einstein's theory of radiation. It is shown that the papers of Albert Einstein on the quantum theory of radiation, published between 1905 and 1925, established the physical basis of quantum electronics. A discussion of quantum electronics devices and applications demonstrates, that irrespective of the wavelength (radio frequencies, microwaves, infrared, visible, ultraviolet, etc.), Einstein's theory of radiation is the cornerstone of quantum electronics as a whole.

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Quantum electronics is founded on three fundamental postulates. The first is that the energy of electromagnetic radiation consists of discrete portions of energy, known as optical quanta or photons. This discrete nature of radiation is manifested in its interactions with matter. According to the second postulate, photons are emitted both spontaneously and by stimulated processes. The stimulated emission predominates at sufficiently high intensities of an external field. The quanta of the stimulating and stimulated radiations are identical. The third postulate states that electromagnetic radiation quanta obey Bose-Einstein statistics. Therefore, the number of quanta per one field oscillator is unlimited. When one field oscillator is filled with a large number of undistinguishable quanta, a classical coherent electromagnetic wave is formed.

Albert Einstein carried out investigations which became the foundation of quantum electronics. In fact, in 1905 he published the first paper on the quantum theory.[1] He used a statistical analysis of fluctuations of the energy of equilibrium radiation and applied the hypothesis of light quanta to conclude that the interaction of radiation with matter is discrete, a fact which he used also in analyzing the photoeffect and photofluorescence. An explanation of the red edge of the photoeffect and of the Stokes frequency shift in the florescence spectrum provided an immediate proof of the fruitfulness of this approach.

Seventy-five years later there is no need to prove the correctness of viewing optical radiation as a photon flux. However, it is worthwhile to recall that the quantum nature of the interaction of electromagnetic radiation with matter was established by Einstein 50 years before the foundation of quantum electronics.

In 1916, Einstein published[2] a derivation of the Planck formula in accordance with the then well-known Bohr postulates. These later papers of Einstein played an important role in elucidating the nature of equilibrium radiation emitted by quantum systems, i.e., by systems with discrete energy levels. For us these papers are remarkable by the introduction of the concept of stimulated radiation, hypothesis of its existence, and determination of its properties from very general thermodynamic considerations. Einstein's conclusion can be formulated briefly as follows.

Stimulated radiation is postulated as the effect in which the probability of a single event is proportional to the density of the radiation energy acting on an excited particle. The frequency of radiation emitted by this particle is exactly equal to the frequency of the radiation acting on it, and the spatial directionality of the stimulated radiation is the same as the directionality of the stimulating radiation. The processes of stimulated emission and absorption are equiprobable to within the degree of degeneracy of the energy levels involved.

Somewhat later, in a paper published together with P. Ehrenfest,[3] Einstein considered polarization of radiation and applying thermodynamic ideas once again he came very close to the formulation of complete identity of the quanta of the stimulated (induced) and stimulating (inducing) radiations.

It follows that, having established the quantum nature of the interaction of electromagnetic radiation with matter, Einstein proved also the existence of the process essential for the generation of identical photons.

One should note that this theory of radiation represented a corpuscular approach which was then in unresolved conflict with the wave representation.

In 1924 Einstein in extending Bose's method for derivation of the Planck formula, based on successive application of the hypothesis of optical quanta, developed a theory of a degenerate monatomic ideal gas,[4] and demonstrated a far-reaching analogy between radiation and gas. This established a generalized thermodynamic description of a system of particles with symmetric eigenfunctions, i.e., the Bose-Einstein statistics. The fundamental property of the identical particles obeying the Bose-Einstein statistics of their indistinguishability. This statistics is obeyed by electromagnetic radiation quanta. Quanta of stimulated radiation, having identical frequencies, polarizations, directions of propagation, and phases are indistinguishable. The state of the whole radiation field is determined by the number of quanta per one field oscillator. This number is unlimited. This is why in describing a radiation field in quantum electronics we can go over from the corpuscular to the wave representation, which is characterized by the principle of superposition of oscillations, including coherent ones.

We can thus see that the work of Einstein on the quantum theory of radiation, carried out between 1905 and 1925, provided the physical foundation for the later emergence of quantum electronics. One should point

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out that the importance of these cursorily discussed Einstein's papers is far from being limited to the formulation of the fundamentals of quantum electronics. It is difficult to overestimate the importance of this work of Einstein for physics as a whole. The paper by Pauli, published in 1965 in a memorial issue of the present journal,[5] gave convincing proof of the importance of Einstein's contribution to quantum theory.

A self-consistent quantum theory of the emission and absorption of light was formulated in 1927 by Dirac[6] who justified the statistical laws of radiation formulated by Einstein, and— having calculated the probability of emission of radiation—found a relationship between the phenomenological Einstein coefficients and the characteristics of a radiating atom. The most important result of the quantum theory of radiation propounded by Dirac is a rigorous justification of the existence of stimulated radiation postulated by Einstein and of its coherence, guessed intuitively by Einstein.

We can thus see that 1927 saw completion of the foundations of quantum electronics. However, it was at the end of 1954 and beginning of 1955 that direct theoretical principles of quantum electronics were formulated and the first device—a molecular oscillator—was built. This indicated that the physical ideas of Einstein's theory of radiation could not have been used immediately and directly in constructing new sources of radiation.

The problem was that, to observe stimulated radiation, one requires excited atoms and, moreover, the probability of the stimulated emission must be higher than the probability of the spontaneous process. These requirements cannot be satisfied under the experimental conditions usual in classical optical spectroscopy. Radiofrequency spectroscopy is characterized by much lower frequencies: the situation is then fundamentally different and favorable for the realization of the ideas of Einstein's theory of radiation in quantum electronics.[7] In the rf range an excited level may have a high population under thermal equilibrium conditions, so that the spontaneous emission is much weaker and the stimulated emission determines directly the experimentally observed effect reducing the value of the absorption coefficient. Therefore, rf spectroscopy cannot be regarded simply as a quantitative extension of optical spectral investigations toward lower frequencies. One should also bear in mind the existence of rf monochromatic radiation sources, ways of channeling and reception of such radiation, availability of cavity resonators, and high degree of development of the theory of self-oscillatory systems with feedback. These were the circumstances why rf spectroscopy became the starting point of quantum electronics and why scientists working in rf spectroscopy were the founders of the new science.

The stimulated emission was first observed on earth in its pure form in a molecular oscillator (maser) at the wavelength of 1.25 cm. This was of great fundamental importance. A detailed analysis of the history of the early stages and growth of quantum electronics[8-10] shows that the microwave origin is not accidental. The fundamental principles of quantum electronics, established by Albert Einstein in the development of the theory of radiation, could be realized only as a result of development of the theory of oscillations, microwave electronics, and rf spectroscopy.[1)]

Modern quantum electronics, defined as the branch of physics concerned with the methods of amplification and generation of electromagnetic oscillations on the basis of stimulated emission, and as the technology of the corresponding amplifiers and oscillators together with their applications—briefly the science and technology of masers, lasers, and their applications—now covers a colossal range. Quantum electronics occupies a prominent place in the scientific and technological revolution now taking place (see, for example, our reviews[11,12]). Although quantum electronics originated in the microwave range, the most revolutionary changes resulting from it have been in optics. This has happened because, although the principle of operation of masers and lasers is the same, there is an important difference between them. In the rf range the appearance of lasers has provided devices which are basically new in respect of the operating principle but have properties usual in classical electronics. Undoubtedly, the use of masers has resulted in a great improvement in the parameters of rf devices. The sensitivity of amplifiers has been improved by two or three orders of magnitude, and the stability of the oscillator frequencies has increased by three or four orders. The importance of these achievements of quantum electronics in the rf range is very great but—in principle—these are quantitative changes of the known qualitative properties since coherent rf amplifiers and oscillators generating monochromatic oscillations have been available before the establishment of quantum electronics.

On the other hand, in contrast to classical electronics, all the light sources in optics are of quantum nature. The very idea of quanta has originated from an analysis of the properties of optical radiation. However, before the appearance of quantum electronics all the optical light sources have been emitting nonmonochromatic and noncoherent oscillations. Coherent and monochromatic generators of electromagnetic oscillations have not been available in optics. In contrast to these conventional light sources, lasers emit light waves of high spatial directionality, spectrally monochromatic, and temporally coherent. The appearance of lasers has made it possible to concentrate radiation energy in space, time, and in frequency intervals to an extent previously impossible. This has raised optics to a basically new level with applications in regions traditionally outside the optical range. These new applications have become possible because stimulated emission of radiation is used directly for the generation of light in modern optics. The main property of lasers—the extreme concentration of the radiation energy—follows directly from Einstein's theory of radiation.

[1)] The fact that a system of excited atoms is capable of amplifying optical radiation was understood by 1940 by scientists working in optics.[18] However, it was not realized at the time that the effect can be used to generate coherent oscillations.

Thus, the place occupied by quantum electronics in modern scientific and technological revolution is determined by new potentialities of laser optics and not by modifications of the earlier basic possibilities. Moreover, quantum electronics is based on the underlying principles of twentieth-century optics. Its appearance and further growth have confirmed these principles and extended the range of their practical applications.

Lasers are now being used in an extremely wide range from submillimeter wavelengths to the vacuum ultraviolet, both in the continuous-wave and pulsed regimes. There is a very great variety of many types of lasers. A detailed description or even a simple list is impossible within the confines of our paper. We shall mention simply two important recent achievements of quantum electronics, which are the construction of lasers emitting radiation of high power and high monochromaticity which is tunable in respect of the wavelength, and excimer lasers for the ultraviolet range.

Quantum electronics is characterized by a multiplicity of active media used in lasers and of the physical phenomena employed as the means of excitation. However, the main and common requirement is the need to provide energy in creating a thermodynamically nonequilibrium state in which the stimulated emission predominates over the absorption process. In this process of creation of laser radiation there are energy losses and the efficiency of most lasers is low, but the properties of laser radiation—which are the direct consequence of stimulated emission—have many applications that more than compensate the energy losses.

In many of these applications the useful effect of the interaction of laser radiation with matter is primarily due to the concentration of energy in the interaction region and (usually) in a very short time interval. The number of possible applications of such high-power interactions is very large. One of the most important is the possibility of using laser radiation in solving the problem of controlled thermonuclear fusion (see, for example, Ref. 13). At present the temperatures achieved in laser-produced plasmas amount to a few million degrees and the interaction of laser pulses with solid targets has produced neutron radiation. There is no doubt about the urgency and importance of continuing research on controlled thermonuclear fusion, particularly as a long-term project. Therefore, considerable attention is being given at present to the choice of further directions in research on such fusion and interpretation of the results obtained so far. The main property of laser radiation, which is directly usable in solving problems of this type, is its high spatial coherence and, consequently, its high directionality.

The monochromaticity of laser radiation opens up basically new possibilities in strong resonance interaction with matter. The high spectral intensity of laser radiation makes it possible to ensure selective interaction of resonance radiation with matter. At high intensities of such laser radiation these selective processes may be irreversible. This makes it possible to achieve laser isotope separation and laser purification of materials, and to use laser radiation in photochemistry and photobiology. Some of these possibilities have already been realized, at least under laboratory conditions. The most convincing results have been obtained in laser isotope separation (see, for example, Ref. 14). Fine and highly selective effects of resonance interaction of intense laser radiation with matter are becoming more and more promising. In such interactions one uses fully and directly all the properties of laser radiation.

We can see that in the development of masers and lasers, and in their applications, i.e., throughout quantum electronics, the fundamental and main features are the effects and properties of stimulated radiation.

Another principal aspect is that direct use of stimulated emission has made it possible to cover an enormous range of wavelengths in quantum electronics: these extend from the classical rf range to the vacuum ultraviolet. It is important to stress two aspects. First of all, the problem of construction of x-ray and γ-ray lasers has not yet been solved. This is a major task now facing quantum electronics. Secondly, in the rf range the effect of stimulated emission may be observed in the generation of oscillations in systems where population inversion takes place in energy levels involved in NMR or ESR, i.e., in systems which are essentially of quantum nature, as well as in the interaction of electron fluxes with periodic inhomogeneous structures, i.e. in classical systems.

The question of stimulated emission of radiation from classical (nonquantum) objects is of great interest. The coherent radiation emitted by electrons in a synchrotron in the centimeter wavelength range[15] has been investigated from 1948–1950. It has been found that a synchrotron generates coherent radiation in this wavelength range, acting essentially as a multiplier of the frequency of the hf accelerating field. Harmonic generation is due to the formation of electron bunches. This is in agreement with the modern view (see, for example, Ref. 16) of the need to ensure phase matching of particles in emitting stimulated radiation from systems with a continuous spectrum. This idea was first formulated clearly soon after the birth of quantum electronics.[17] Phase and spatial bunching of excited oscillators under the action of a field, including a fluctuation field, gives rise to a finite correction to the polarization current and, consequently, it produces additional coherent radiation so that we have stimulated emission. The radiative instability of a system of excited oscillators is not related to the basic quantum features and can be explained fully also from the classical point of view. The necessary requirement is the nonlinearity (anharmonicity) of the oscillators. An example of an anharmonic oscillator is a relativistic electron in a magnetic field. Classical microwave masers based on cyclotron resonance have been constructed in this way.

In recent years optical radiation has been generated in systems with a continuous spectrum (free electrons). It is worth noting that the stimulated emission from systems with a continuous spectrum was first achieved in the microwave range and then at the optical frequencies. This happened also in the case of systems with discrete spectra. Such a sequence of events confirms once again that the rf range is objectively suitable for the generation and realization of properties of stimulated radiation. One should also add that practically all nonlinear and coherent effects in quantum electronics, apart from those associated directly with the propagation of radiation in free space, have been observed first in the rf range. Nonlinear effects in the propagation of high-intensity monochromatic electromagnetic radiation in free-space plasma have again been found first in the rf range (Luxembourg-Gor'kov effect).

We are now faced with an interesting question whether frequency multiplication or generally nonlinear frequency conversion, considered from the most general point of view, is a stimulated process. We must bear in mind that in harmonic generation the phase relationships have to be maintained and the emissivity of macroscopic nonlinear oscillators is governed by the intensity of the initial radiation.

Thus, one of the fundamental postulates of Einstein's theory of radiation—that of stimulated emission and coherence—goes beyond the quantum theory framework. The validity of this postulate in classical systems stresses its general physical importance.

We can go even further. As pointed out above, stimulated emission from a quantum system under terrestrial conditions was first observed in a molecular oscillator (maser). In outer space one frequently encounters conditions for population inversion in extended regions of strongly rarefied interstellar gas of some particular chemical composition. The result is maser and sometimes laser cosmic radiation. Astronomical (or radioastronomical) investigations of such radiations, the very idea of which has arisen only after the birth of quantum electronics, are important in modern astrophysics. This example is evidence of the fruitfulness of the application of the concepts of quantum electronics in branches of science far from the traditional applications.

We can see from above that the extension of the idea of stimulated emission to, on the one hand, the classical range and, on the other, directly to phenomena of cosmic scale is evidence of the high degree of universality of this idea. It is also clear that, on the whole, the main range of development and applications of the idea of stimulated coherent processes is in the quantum domain and this applies particularly to lasers and interaction of laser radiation with matter, which are topics of current interest in quantum electronics.

The above discussion seems to us to provide convincing evidence that Einstein's theory of radiation is the cornerstone of quantum electronics as a whole.

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