Quantum Electronics

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One may assume as generally accepted that quantum electronics started to exist at the end of 1954–beginning of 1955 (*1*, *2*). Just by that time theoretical grounds had been created, and the first device—a molecular oscillator—had been designed and constructed. A basis for quantum electronics as a whole is the phenomenon of stimulated emission, predicted by A. Einstein in 1917. However, quantum electronics was developed considerably later. And it is quite natural to ask the questions: why did it happen so? What reasons put obstacles for the creation of quantum devices considerably earlier, for instance, in the period of 1930–1940?

In order to try to answer these questions I should like to say some words about the principles on which quantum electronics is founded.

As I have already noted, the phenomenon of stimulated emission was predicted by Einstein. It is well known that an atom in an excited state may give off its energy in the form of emission of radiation (quantum) in two ways. The first way is a spontaneous emission of radiation, that is, when an atom emits energy without any external causation. All usual light sources (filament lamps, gas-discharge tubes, and so on) produce light by way of such spontaneous radiation. It means that scientists engaged in the field of optical spectroscopy were well acquainted with that type of emission many years ago.

The second way for an atom to give off its energy is through stimulated emission of radiation. That phenomenon was noted by Einstein to be necessary in order to describe thermodynamic equilibrium between an electromagnetic field and atoms. The phenomenon of stimulated emission occurs when an excited atom emits due to interaction with an external field (quantum). Then two quanta are involved: one is the external one, one is emitted by the atom itself. Those two quanta are indistinguishable; that is, their frequency and directivity coincide. This very significant characteristic of an induced radiation (which was, apparently, first pointed out by Dirac in 1927) made it possible to build quantum electronic devices.

In order to observe a stimulated emission, it is necessary, firstly, to have excited atoms and, secondly, that the probability of an induced radiation must be greater than that of a spontaneous emission. If atoms are in a thermal equilibrium, optical levels are not populated. If the atoms become excited they make a transition to the lower level due to spontaneous emission. This happens because the probability of a stimulated emission radiation is small at usual densities of the light energy. Therefore scientists engaged in the field of spectroscopy did not take into account the stimulated radiation and some of them, apparently, considered that phenomenon as a "Kunststück" of a theorist necessary only for the theory.

It is absolutely clear that if all atoms are in an excited state, such a system of atoms will amplify the radiation, and many scientists understood this already before 1940, but none of them pointed to the possibility of creating light oscillators in this way. It may seem strange because, in principle, optical quantum oscillators (lasers) could have been made even before 1940. But definite fundamental results were necessary. They appeared after the second world war, when radiospectroscopy started to develop rapidly. And just the scientists engaged in the field of radiospectroscopy laid down foundations for quantum electronics (*1*, *2*).

How should one explain this? There were some favorable circumstances which had not been available to the scientists working in the field of optical spectroscopy.

First of all, since for systems in a thermal equilibrium the excited levels in the radio range, contrary to the optical ones, may have a large population, and of course one should then take into account induced radiation. Indeed, if the concentration of particles on the lower level equals n_1, and on the excited level n_2, one may write down a net absorption coefficient for an electromagnetic wave in the form

$$\alpha = \frac{1}{v} h\nu(n_1 B_{12} - n_2 B_{21}). \qquad (1)$$

The value of B_{12} characterizes the probability of an absorption act, and B_{21} characterizes the probability of an induced radiation act. If the levels are not degenerated, $B_{12} = B_{21}$; they will take the form

$$\alpha = \frac{1}{v} h\nu(n_1 - n_2) B_{12}. \qquad (2)$$

For a frequency as in the optical range, under usual conditions of thermal equilibrium, one may put, with a high accuracy, n_2 equal to zero, and then the absorption coefficient will become

$$\alpha = \frac{1}{v} h\nu n_1 B_{12}. \qquad (3)$$

Therefore, for the optical range the absorption coefficient depends only on the population of the lower level. For as in the radio range, as a rule, $h\nu \ll kT$. In that case

$$n_2 = n_1 e^{-h\nu/kT} \approx n_1\left(1 - \frac{h\nu}{kT}\right).$$

Then the value of α will be

$$\alpha = \frac{1}{v} h\nu n_1 B_{12} \frac{h\nu}{kT}. \qquad (4)$$

As is seen from Eq. 4, due to stimulated emission, the value of the absorption coefficient becomes reduced by a factor $kT/h\nu$ compared to what it would be without the presence of induced emission. Therefore, all scientists engaged in radiospectroscopy have to take into account the effect of induced radiation. Moreover, for increasing an absorption coefficient one has to lower the temperature in order to decrease the population of the upper level and

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to weaken, in this way, the influence of stimulated radiation. It follows from Eq. 2 that for systems that are not in thermal equilibrium, but have $n_2 > n_1$, the net absorption coefficient becomes negative; that is, such a system will amplify radiation. In principle, such systems were known to physicists a long time ago for the radio range. If we pass molecular or atomic beams through inhomogeneous magnetic or electric fields, we can separate out molecules in definite state. In particular, one may obtain molecular beams containing molecules in the upper state only. Actually physicists engaged in the field of microwave radiospectroscopy started to think about application of molecular beams for increasing the resolving power of radio spectroscopes. In order to gain a maximum absorption in such beams, one must have molecules either in the lower state only or in the upper states only; that is, one must separate them using inhomogeneous electric or magnetic fields. If molecules are in the upper state, they will amplify a radiation.

As is well known from radio engineering, any system able to amplify can be made to oscillate. For this purpose a feedback coupling is necessary. A theory for ordinary tube oscillators is well developed in the radio range. For descriptions of those oscillators, the idea of a negative resistance or conductance is introduced—that is, an element in which so-called negative losses take place. In the case of a quantum oscillator the medium with a negative absorption factor is that "element." Therefore the condition of self-excitation for the quantum oscillator should be written in the similar way as for a tube oscillator. According to the analogy with usual tube oscillators, it is quite natural to expect that for a quantum oscillator the oscillations will also be quite monochromatic.

Finally, the resonator system is a very significant element of a quantum oscillator (maser or laser) as well as in any other oscillator with sinusoidal oscillations. However, resonator systems were well worked out for the radio range, and just those resonators operating in the radio range were used for masers. Thus, a very important element—a cavity—was also well known to the scientists engaged in radiospectroscopy. Therefore all elements of masers really existed separately but it was necessary to do a very important step of synthesis in order to construct the maser. First two papers—one of which was published in the U.S.S.R. and the other in the U.S.A.—appeared independently; and they both were connected directly with the construction of radio spectroscopes with a high resolving power, using molecular beams. As is easily seen from the aforesaid, this result is quite natural.

Those two papers initiated the development of quantum electronics, and the first successes in this new field of physics stimulated its further progress. Already in 1955, there was proposed a new method—the method of pumping for obtaining negative absorption (*3*). That method was further developed and applied for the construction of new types of quantum devices. In particular, the method of pumping was developed and applied for designing and building quantum amplifiers for the radio range on the basis of an electron paramagnetic resonance (*4, 5*). Quantum devices according to the suggestion of Townes were called masers. One might think that after the successful construction of masers in the radio range, there would soon be made quantum oscillators (lasers) in the optical range as well. However, this did not occur. Those oscillators were only constructed 5 or 6 years later. What caused such a delay?

There were two difficulties. One of them was as follows: at that time no resonators for the optical wavelength range were available. The second difficulty was that no methods were immediately available for gaining an inverse population in the optical wavelength range.

Let us consider firstly the question of resonators. It is well known that radio engineering started its development from the region of long waves where resonators were used in the form of self-inductance coils combined with capacitors. In that case the size of the resonator is much less than one wavelength. With development toward short waves the cavity resonators were used. The size of those cavities was comparable with a wavelength. It is quite clear that without the help of such cavities it is impossible to advance into the region of very short waves. In particular, it would be impossible to reach the optical range.

In 1958 there was proposed the so-called open type of cavities for masers and lasers in the region of very short waves (*6, 7*). Practically speaking this is Fabry-Perot's interferometer; however, a "radio engineering" approach made it possible to suggest using such a system as a resonator. Afterwards, spherical mirrors were used together with plane mirrors. The size of these resonators is much more than that wavelength.

At present open cavities are widely utilized for lasers.

There were also systems suggested for the production of a negative absorption in the submillimeter (far infrared) wavelength range (*6*), the infrared and optical wave ranges (*7–10*). Those works stimulated a further advancement in the region of shorter waves and, in particular, into the optical range. However, the first quantum optical oscillator was made as late as 1960 (*11*). It was a ruby laser. After carrying out investigations in the optical range, many scientists started to think about further extension into the x-ray field. In that wavelength range the same difficulties arise as in the optical wavelength range. It was necessary to suggest new types of resonators and to find also the proper system that would produce negative absorption. As it is known, x-ray quantum oscillators have not yet been constructed. We have also considered this problem (*1*) and we have found that there are essential difficulties.

Indeed in the x-ray region the lifetime of an excited level state is small and one may assume that the line width is determined by that lifetime only. Then the absorption coefficient may be written in a very simple form

$$\alpha = \frac{\lambda^2}{4\pi}(n_1 - n_2) \qquad (5)$$

where λ is the wavelength and n_1 and n_2 are the densities of particles in the lower and upper level stated respectively. As it is seen from Eq. 5, the absorption coefficient decreases sharply as the wavelength becomes shorter. This is an extremely unpleasant circumstance. Indeed for the laser operation the value of α should be of the order of one inverse centimeter. If $\lambda = 1$ angstrom, the density of particles on the upper level must be not less than 10^{17} per cubic centimeter. The lifetime in the upper level τ is of the order of 10^{-16} second. Therefore, 10^{33} particles per cubic centimeter per second must be excited. In order to fulfill this condition one has to overcome essential experimental difficulties.

Nevertheless, the successes of quantum electronics are enormous even

without the construction of lasers in the x-ray region.

At present the range in which lasers and masers operate is extremely wide. Recently a far infrared range had not been available but now investigations in this region are carried out with a great success. In practice, with the help of masers and lasers one may produce emission from the lowest radio frequencies to the ultraviolet region.

Operation of all masers and lasers is based on the fact that in media with a negative absorption the processes of induced emission dominate due to a large field intensity over spontaneour or nonradiative transitions. Moreover, at present, for instance, one may produce with the help of a ruby laser such radiation energy densities at which the probability of multiquantum processes becomes comparable with the probability of one quantum process or even exceeds it. This is a new qualitative jump which leads to interesting results of several kinds.

First of all one may estimate (*12*) the maximum power which a ruby laser is able to give per square centimeter. That power equals 10^{11} watts per square centimeter; that is, 100 gigawatts per square centimeter. At that power the probability of a simultaneous absorption of three quanta of red light with transition of an electron to the conduction band is so great that a further growth of the field stops. For three-quantum processes the losses grow in proportion to the cube of the energy density; that is, a very strong dependence on the field takes place.

Large electric fields available in a laser beam may carry out ionization and dissociation of molecules and breakdown in a solid as well.

Multiquantum processes do not always have a bad effect (for instance, restriction of the maximum density given by laser) but they open up new possibilities for a further development of quantum electronics. This interesting and principally new direction is connected with the construction of lasers which utilize two-quantum transitions. It was pointed out in 1963 in the U.S.S.R. (*13*) and somewhat later but independently in the U.S.A. (*14, 15*) that construction of these oscillators should be possible. The idea of this laser is that if there is an inverse population between two levels with the energy difference $E_2-E_1 = h\nu$, generation of two frequencies ν_1 and ν_2 is possible in such a way that

$$\nu = \nu_1 + \nu_2 \qquad (6)$$

In particular, frequencies ν_1 and ν_2 may coincide. However, frequencies ν_1 and ν_2 may have any value as long as only the condition of Eq. 6 is fulfilled.

Operation of such an oscillator, as it was mentioned above, is connected with two-quantum transitions, the probability of which is rather great, if the field density is considerable. For self-excitation of these oscillators it is necessary to have another oscillator of a sufficiently large initial energy density with frequencies ν_1 or ν_2, and one may remove the external field only after self-excitation of the two-quantum oscillator. Such two-quantum oscillators have two possibilities:

1) Faster growth of the field density than in the case of usual lasers.

2) Possibility of producing any frequency within the framework of the relation shown in Eq. 6.

Construction of an oscillator for any given radiation frequency will greatly extend the region of application of lasers. It is clear that if we make a laser with a sweep frequency, we apparently shall be able to influence a molecule in such a way that definite bonds will be excited and, thus, chemical reactions will take place in certain directions.

However, this problem will not be simple even after design of the appropriate lasers. But one thing is clear: the problem is extremely interesting and perhaps its solution will be able to make a revolution in a series of branches of chemical industry.

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