Physics – Uspekhi **54** (1) 3 – 7 (2011)

CELEBRATING 50 YEARS OF THE LASER

PACS numbers: **01.65.+g**, **42.25.–p**, **42.55.–f**

Laser: a source of coherent light

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DOI: 10.3367/UFNe.0181.201101a.0003

Abstract. The creation 50 years ago of a new source of coherent light waves, the laser, is briefly described from the historical and fundamental physics perspectives.

In 2010, fifty years elapsed after Theodore Maiman created the world's first laser at the Hughes Research Laboratory in the USA. This outstanding achievement of 20th-century science had a profound impact on technology in diverse fields of economics, social activity, and culture. The scientific community is celebrating this event in a number of countries. The Conference on Lasers and Electrooptics (CLEO) devoted to the 50th anniversary of the laser (Laser Fest) and organized by the Optical Society of America was already held in San Diego, USA, on 15–17 May 2010. The conference titled "50 Years of the Laser in the City of Light" was held in Paris on 22–23 June 2010. Conferences in Kazan and Moscow are also scheduled for the general meeting of the Russian Academy of Sciences in December 2010.

In his book of recollections *The Laser Odyssey* [1], published in 2000, Maiman described the history of the creation of the first laser that he successfully operated on 16 May 1960. It follows from Maiman's recollections, which were partially published in the *Priroda* [2], that this achievement was not accidental. Maiman moved to the Hughes Research Laboratory from Stanford University, where he was a graduate student of the outstanding theoretical physicist Professor Willis E Lamb, who discovered the splitting of the 2s and 2p levels in the hydrogen atom caused by vacuum polarization and made a seminal contribution to the foundations of quantum electrodynamics.

Under Lamb's supervision, Maiman was engaged in the development of a paramagnetic microwave amplifier based on a ruby crystal and defended his PhD thesis. Although Lamb did not want to part with his assistant, Maiman joined the Hughes Research Laboratory, where he plunged into his laser odyssey.[1]

[1] Translator's note: Maiman's doctoral thesis was devoted to experimental measurements of the Lamb shift of quantum levels in the helium atom. He defended his PhD thesis and then joined the Hughes Research Laboratory, where he was engaged for a few years in the refinement of a quantum microwave amplifier based on a ruby crystal. After the successful fulfillment of the ruby maser project, he plunged into his laser odyssey (see [1]).

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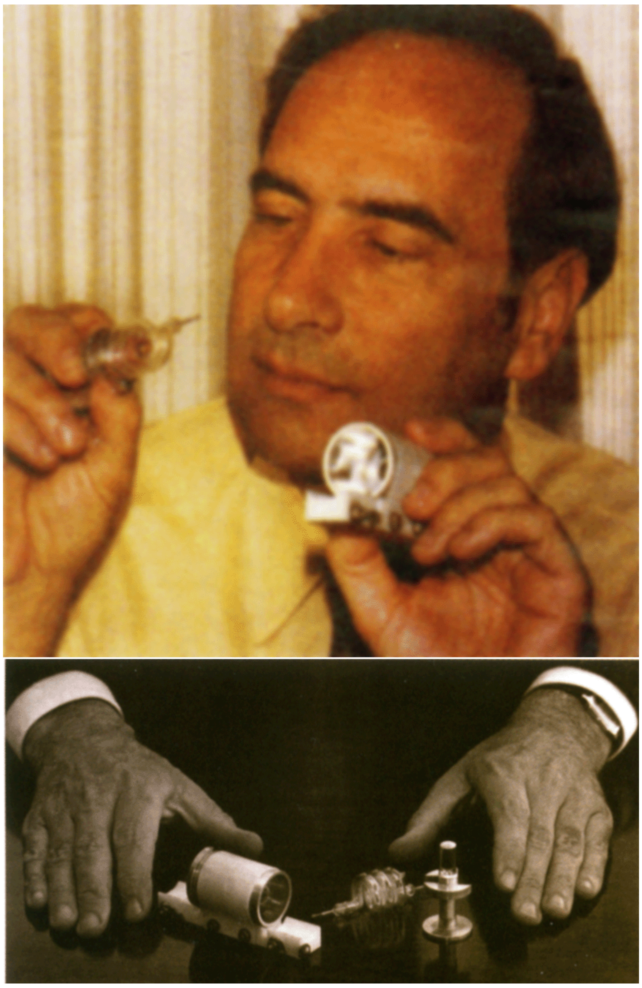
Received 23 July 2010
Uspekhi Fizicheskikh Nauk **181** (1) 3 – 7 (2011)
DOI: 10.3367/UFNr.0181.201101a.0003
Translated by M Sapozhnikov; edited by A M Semikhatov



T Maiman and the first ruby laser.

Maiman decided to study the ruby crystal as a promising 'working' medium. The impurity Cr^{3+} ions in this crystal emit two closely spaced R_1 and R_2 luminescence lines in the red spectral region. Ruby itself is an Al_2O_3 single crystal (corundum) in which approximately 0.63% of the aluminum atoms are replaced by chromium.

The population inversion required to obtain lasing in ruby is difficult to achieve because the R-line transition terminates on the ground level of chromium ions, which is 100% populated under normal conditions. Therefore, to obtain inversion, it is necessary to excite more than 50% of the chromium to the upper level. Lasing can be achieved more simply in the so-called three-level scheme, where an intermediate level with a zero initial population is used as the lower level of the transition. This scheme was proposed by Basov and Prokhorov already during the maser era in 1955 [3].

The second problem concerning ruby was the absence of reliable data on the quantum efficiency of ruby's luminescence. The quantum efficiency was assumed low. However, accurate measurements specially performed by Maiman showed that it was no less than 20%.[2]

On 16 May 1960, using a high-power spiral xenon flashlamp for pumping, Maiman for the first time obtained the generation of optical coherent radiation.

Later, A Javan, W R Bennett, and D R Herriott made a helium–neon gas laser and then, as from the horn of plenty, reports on new variants of lasers followed. More than 50 different lasers were made during the first year. Now it is already impossible to accurately identify the number of different lasers, but my approximate calculations suggest that the number of crystal lasers alone exceeds 300.

To return to the 'prelaser' time, in 1958–1959, Townes and Schawlow [4], Basov, Vul, and Popov [5], and Prokhorov [6] published theoretical papers in which the fundamental concepts of the development of lasers were considered. It was proposed to use open resonators of the Fabry–Perot interferometer type to provide the positive feedback (Townes, Schawlow, Prokhorov). But the major problem in those years was to find a proper working medium and an efficient method for its excitation. Gases (Townes, Schawlow) and semiconductors (Basov, Vul, Popov) were proposed. The latter proposal appeared quite unusual because dielectric media were typically employed in optics, whereas in the case of semiconductors, we are dealing with a conducting quantum system, and this proposal was based on the attempt to use an electric current for obtaining the inverted population.

Later, the injection of charge carriers through a p–n junction was suggested for this purpose [7]. This method proved to be extremely fruitful and gave rise to a new direction, which can be called semiconductor quantum electronics. At present, semiconductor diode lasers dominate laser applications, accounting for more than 90% of all lasers sold. This direction gave an impetus to the synthesis of heterostructures and was distinguished by a Nobel Prize awarded in 2000 to Z I Alferov, who created the first continuous semiconductor laser [8].

I have especially emphasized this direction because the leading role in the development of the semiconductor, in particular, diode lasers, belongs to the studies performed in our country, at the Lebedev Physics Institute (FIAN) and the Ioffe Leningrad Physicotechnical Institute (LFTI).

It is an indisputable fact that the concept of lasers was advanced earlier, in 1954–1955. In 1964, N G Basov, A M Prokhorov, and C Townes shared a Nobel Prize for these studies. This well-known concept was based on the use of stimulated emission for amplification of an electromagnetic wave and the introduction of feedback to the system.

In some recent papers, the question was asked: "Why was the laser invented so late, six years after the creation of the maser?"

I think that the reason is that radiophysics as a science has its own methodology, which differs from that of optics. In optics, we typically deal with an object such as an electromagnetic wave with a very low coherence degree. This can be seen, in particular, in paper [9] by Fabrikant, who pointed out the possibility of light amplification by stimulated emission of radiation. However, he never said in his paper that stimulated

From left to right: A M Prokhorov, C Townes, and N G Basov (FIAN, 1967).

emission of radiation is a coherent process. Moreover, Albert Einstein, who was the first to show that stimulated radiation should exist, argued that it was a necessary condition for providing thermodynamic equilibrium between the atomic system described by the Boltzmann distribution and the radiation described by Planck's law. This argument is based on a purely energetic approach. The low coherence level in the optical range is explained by the fact that emitters (for example, atoms) are, as a rule, strongly coupled quantum systems that cannot produce a monochromatic signal during noticeable time intervals.

It is often claimed that P Dirac was the first to assert that stimulated radiation is coherent. However, for the transition probability with emission of Bose fields, quantum electrodynamics formally gives a term proportional to the number of quanta of this field already existing in the given state (i.e., inducing this transition). Therefore, it is unlikely that this statement can be directly attributed only to Dirac.

It is quite possible that these circumstances were the reason for some delay in the transfer of concepts of microwave quantum electronics to the optical range.

It is pertinent to note some features of coherent radiation in the optical range, i.e., the properties of laser radiation.

In my opinion, due to its small wavelength, laser radiation differs from radiation in the radiofrequency range by the more pronounced role of its spatial coherence.

Indeed, the spatial coherence of laser radiation is produced already in a resonator. As a rule, laser radiation consists of a few types of oscillations (modes), each of which has a high degree of spatial coherence. In an ideal laser with flat resonator mirrors, spatial modes are formed that are quite similar to the modes in a closed resonator. The simplest of these modes is symmetric with respect to the radiation propagation axis and is a wave having an amplitude maximum on the optical axis and a phase surface with a slightly spherical shape

This wave can be considered an ideal plane (absolutely spatially coherent) wave transmitted through an absorbing aperture with the transmission having a maximum at the center and decreasing to zero at a distance equal to the mirror radius. Such a wave emitted by a laser has no exact propagation direction, unlike the ideal plane wave (Fig. 1), because its transverse dimensions are finite. This is the phenomenon of diffraction.

[2] Translator's footnote: 75% (see [1]).

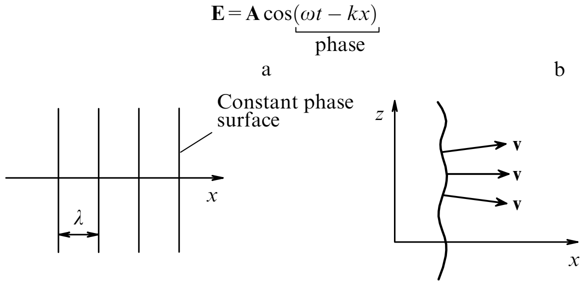


Figure 1. Spatial coherence. (a) Ideal plane wave. (b) Real constant-phase surface. $\mathbf{v}$ is the propagation direction of an element of the wave phase front. $\mathbf{v} \,||\, \mathbf{k}$, where $\mathbf{k}$ is the wave vector. Distortion of the wave phase front leads to the divergence of a beam with the angle $\alpha \sim v_{\perp}/v = k_z/k$ and the transverse coherence scale $z_c \sim 1/k_z$.

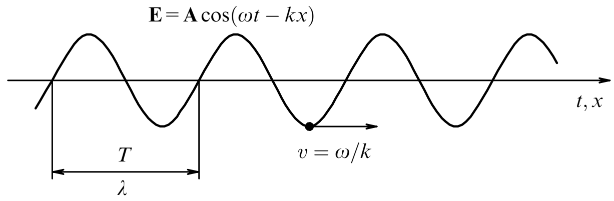


Figure 2. Time coherence. $\mathbf{A}$ and ω being integers implies monochromaticity; $\mathbf{A}$ and ω randomly deviating in time from their mean values implies nonmonochromaticity and partial coherence. The interval t_c within which the field can be considered monochromatic is determined by the relations $1/t_c = 1/t_A + 1/t_\omega$ and $t_c \gg T$, where T is the oscillation period, $t_A \sim A/(\partial A/\partial t)$ is the characteristic time of the wave amplitude variation, and $t_\omega \sim \omega/(\partial\omega/\partial t)$ is the characteristic time,.

On the other hand, the phase front of the wave can also be distorted due to statistical fluctuations of the optical properties of the medium or optical elements, i.e., optical inhomogeneities. This impairs the spatial coherence and eventually leads to an increase in the radiation divergence. If the wave phase is $\psi(x, y, z, t)$, then the wave vector of the wave is

$$\mathbf{k} = \nabla\psi \,. \tag{1}$$

In an ideal plane wave, $\psi \equiv \psi(x, t)$ (x is the wave propagation axis) and the wave vector $\mathbf{k} = \mathbf{n}_x \, \mathrm{d}\psi/\mathrm{d}x \equiv \mathbf{n}_x \, k_x$ is constant.

If ψ depends on the transverse coordinates z and y, then $\mathbf{k}$ is not parallel to the x axis and, depending on a point chosen on the phase surface, the wave vector has different slopes to the x axis. Therefore, the restricted aperture of the wave increases as a whole, i.e., the wave diverges. The divergence angle α is $k_{\perp}/k$. The characteristic value of $k_{\perp}$ is determined by the properties of optical elements of the laser.

In such cases described by statistical (random) quantities, a correlation function η is usually introduced that describes the correlation of the quantity under study at a specified point r_0 and at another point:

$$\eta(r_0) = \frac{\int_0^{\infty} E(r)\, E(r_0 + r)\, \mathrm{d}r}{\int E^2(r)\, \mathrm{d}r} \,, \tag{2}$$

where r_0 is a point in a plane perpendicular to the x axis and r is an arbitrary point in the same plane. The ideal spatial coherence corresponds to $\eta = 1$; in a diffraction diverging beam, $\eta \approx 1$ up to $r_0 = R_0$, where $2R_0$ is the beam diameter. The high spatial coherence allows the maximum focusing of radiation. This is illustrated in Fig. 1.

A similar statement can be made about the time (longitudinal) coherence of laser radiation (Fig. 2). Masers and lasers are known to generate highly monochromatic radiation. In this connection, it is interesting to mention a story at the dawn of quantum electronics, which Basov told us at that time. On the one hand, scientists in the field of radiophysics stated with assurance that generators should emit ideal monochromatic radiation if noises and uncontrollable technical fluctuations were neglected. Basov asked the opinion of our outstanding physicist L D Landau. Landau said that radiation cannot be ideally monochromatic because the width of any emission line is limited by its natural width in quantum physics. It is interesting that a similar story was told by Townes at the conference "50 Years of the Laser in the City of Light" in Paris, 22–23 June 2010. Townes had asked Niels Bohr the same question and received the same answer. True, Bohr called him later and said that maser radiation can be monochromatic. Now this question does not lead to debate. This radiation can be ideally monochromatic because a particle that has emitted energy in such devices is immediately replaced by another identical particle that in a way continues to maintain the emission process in time.

Nevertheless, the time coherence, i.e., the phase of a signal in these devices fluctuates for reasons mentioned above, and the value of this fluctuation is described, similarly to (2), by the correlation function

$$\eta(t_c) = \frac{\int E(t)\, E(t + t_c)\, \mathrm{d}t}{\int E^2(t)\, \mathrm{d}t} \,.$$

The time t_c up to which the field can still be considered coherent in this interval corresponds to $\eta \approx 1$, and a continuously emitted wave can be represented by a sequence of intervals of length t_c, with somewhat different frequencies in each of these intervals such that $\omega t_c \sim \pi$ (Fig. 3).

We now consider the question of the coherence of stimulated radiation. According to the quantum theory of radiation, as mentioned above, the probability of the transition of a quantum system from the upper to the lower state formally contains a part proportional to the number of quanta already existing in the radiation field in the same state. Therefore, the mathematical apparatus gives the answer to this question. But it is desirable to find a more illustrative explanation of this statement. In my opinion, this can be done by following the evolution of the dipole moment in the transition of an atom from one state to another.

The dipole moment, which is zero in a stationary state, becomes nonzero only when the atom undergoes transition from one state to another, i.e., occurs in a mixed state. The amplitude of this dipole moment increases, reaches its maximum, and again decreases to zero when the transition is completed. The dipole moment has the high-frequency

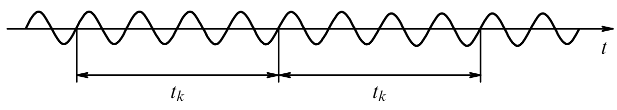


Figure 3. Illustrative representation of laser radiation with a duration t exceeding the coherence time t_k. The radiation field of a continuous-wave laser can be represented as a continuous sequence of length-t_c 'segments' of a harmonic function $\mathbf{A}\cos(\omega t - kx)$ in which the field is monochromatic. It follows that the frequency uncertainty is $\Delta\omega \sim 1/t_c$.

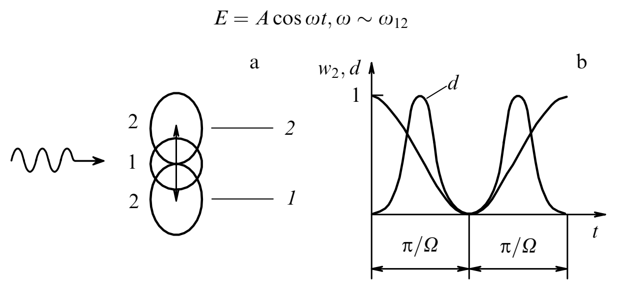


Figure 4. A quantum two-level system (quantum oscillator), $E = A\cos\omega t$, $\omega \sim \omega_{12}$. The dipole moment is zero at levels 1 and 2, and therefore the transition direction in the atom is uniquely determined by its initial state. If the atom is at level 1, it undergoes a transition to level 2 (absorption); if vice versa, the atom emits stimulated radiation. (b) Time evolution of the probability w_2 of finding the atom at the upper level and the time dependence of the dipole moment amplitude d reaching the maximum at $w_1 = w_2 = 1/2$; $\Omega = d_{12}A/\hbar$ is the Rabi frequency.

component at the frequency of the incident wave, which should be close to the transition frequency $\omega_{21} = (E_2 - E_1)/\hbar$. For a two-level system, an exact solution exists [10]. In particular, when the signal frequency coincides with the transition frequency, the system undergoes successive transitions from one level to the other and back, as shown in Fig. 4. The high-frequency oscillations of the dipole moment always exactly coincide with the external signal frequency. It is important here that in the stationary state, irrespective of which of these levels the atom resides in, the dipole moment is zero, i.e., it has no the initial phase (!). In this sense, the atom always 'adjusts' to the external field, unlike the classical dipole, which can both absorb and emit stimulated radiation for a certain phase relation between its intrinsic oscillations and the incident external field. This is illustrated in Figs 4 and 5.

Returning to the topic, we recall that in the 'prelaser' time, the possibility of creating coherent light sources raised doubts because the light emitted by any optical sources initially has very low time coherence.

Finally, in my opinion, it is pertinent to mention here the paper by Paul and Fischer [11], clearly illustrating the picture of absorption or stimulated emission of an electromagnetic wave by an atomic dipole (Fig. 6).

The incident plane wave excites the oscillations of the atomic dipole, which in turn produces an electromagnetic field around itself; this field is added to the incident plane wave field. As a result, the energy flux density near the atom

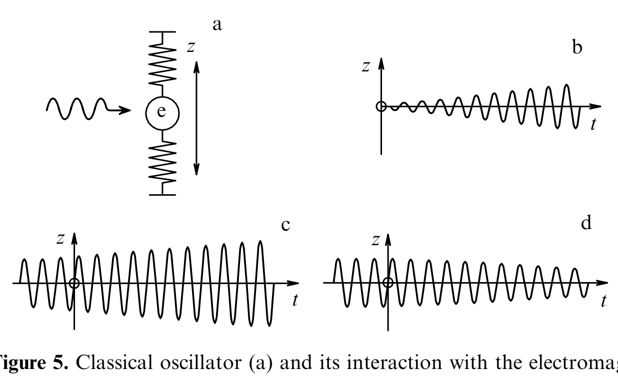


Figure 5. Classical oscillator (a) and its interaction with the electromagnetic field $E = A\cos\omega t$; $\omega \sim \omega_0$ is the eigenfrequency. (b) The initial state is the state of rest; the result: radiation is always absorbed; the excited initial state; the result is (b) absorption and (c) stimulated radiation.

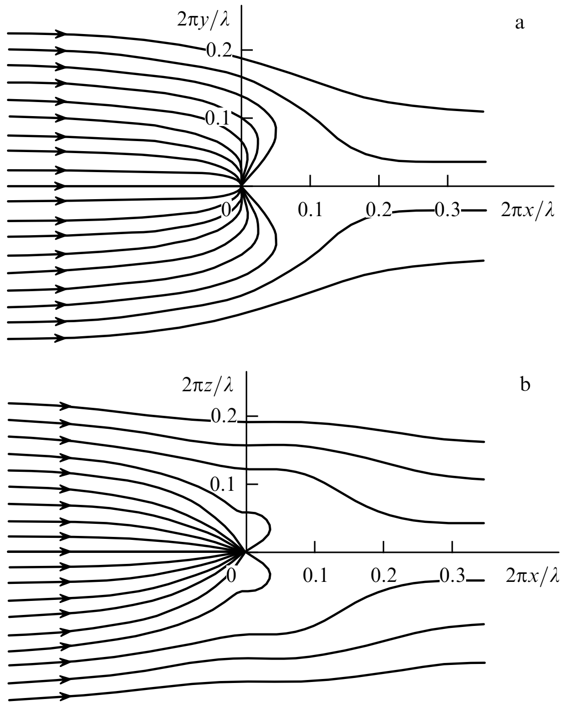


Figure 6. Diagrams illustrating the absorption of light (plane wave) by an atom. The maximum effective absorption area is $\lambda^2/2\pi$, where λ is the wavelength. The characteristic size of the atomic dipole is $a_0 \sim 0.1$ nm $\ll \lambda$.

considerably changes, as shown in Fig. 6, and the atom 'draws in' the field energy to itself from a spatial region much greater in size than the geometric size of the atom. Asymptotically, at a large distance from the atom, the electromagnetic wave field restores the initial properties of the plane wave.

At present, the properties of laser radiation are well understood, and the same concerns lasers. Lasers play a considerable role in the creative activity of humankind.

As regards laser radiation, I believe that four main factors can be distinguished (somewhat conventionally, of course): the high time coherence ($\Delta\omega/\omega \sim 10^{-16} - 10^{-17}$), ultrashort laser pulses ($\sim 10^{-15}$ s), the high power (and power density) (up to 10^{15} W), and the high electric–light energy conversion efficiency ($\sim 70\%$), which became possible after the development of diode lasers.

The reports presented at the joint meeting of the scientific session of the Department of Physical Sciences, RAS and scientific councils of the Lebedev Physics Institute, RAS and the Prokhorov General Physics Institute, RAS devoted to the 50th anniversary of the laser (see this issue, p. 93) concern a particular area of laser physics, and it is therefore unnecessary to speak about them here. I emphasize separately that applications of lasers are extremely broad, and we can only wonder that the laser has so many faces that numerous applications of lasers often have no common qualitative foundations.

But this subject, which has remained unexhausted so far, is beyond the scope of this article.

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