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Coherence and lasers

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***Abstract*. Recollections are reported about the attitude of N.G. Basov to the problem of coherence of stimulated transitions at the very beginning of studies devoted the creation of masers and lasers. It is shown that the problem of coherence of stimulated transitions can be solved in a multiparticle system. The role of stimulated transitions in a variety of processes proceeding in the nature is discussed. The contribution of N.G. Basov and his school to the development of quantum electronics and laser physics is briefly discussed.**

Keywords: *lasers, coherence of stimulated transitions.*

Stimulated transitions in an active medium, which provide the basis for lasers, have the property of coherence. This means that the characteristics of electromagnetic waves emitted upon such transitions are completely similar to those of the stimulating field. By using a currently popular term, we can say that stimulated transitions *clone* a wave acting on the active medium. Now this fact is well known. However, in 1949 – 1950, when N.G. Basov began to reflect over the problem of generation of electromagnetic waves with the help of quantum systems, this was far from obvious.

In his reflections, N.G. Basov proceeded from the fact that, according to the Dirac theory [1, 2], the frequency, the direction of propagation, and the polarisation of a photon emitted upon the stimulated transition should be identical to the corresponding parameters of stimulating photons. However, according to the uncertainty relation

$$\tau_{st}\Delta\omega \geqslant 1, \qquad (1)$$

the width $\Delta\omega$ of the emission spectrum should be finite due to a finite time τ_{st} (probability) of the transition. It would seem that condition (1) excludes the possibility of emission of a narrow spectral line by an atom (and by a laser as a whole). It is this opinion that was hold by many physicists with whom N.G. Basov discussed this problem in 1949 – 1950. However, Basov felt intuitively that maser (laser) radiation generated in a continuous-wave regime should be monochromatic. This conviction was supported by his studies of microwave coherent sources, which were used in radiospectroscopy. Because of this, he proceeded steadily, together with A.M. Prokhorov, to the creation of the first maser.

N.G. Basov believed that the problem of coherence of stimulated radiation is fundamental. He discussed this problem with his co-workers many times even after the creation of masers.

N.G. Basov felt intuitively that the problem of monochromatism (coherence) could be solved for a multiparticle system. Let us see to what extent he proved to be right.

According to relation (1), each particle (atom, molecule, etc.) does emit a spectrum of a finite width because emission occurs during a finite time. However, the dipole moment of an atom is phased at the instant of its appearance in the excited state by the field in a resonator, so that the initial phase of the dipole moment of each new excited atom changes in phase with the field. Due to the phasing, only the spectral components of atomic emission having the frequency exactly coinciding with the frequency of the exciting field prove to be coherent. The amplitudes of these components are added, resulting in a coherent response of the active medium to the action of an external field (Fig. 1). The components corresponding to other frequencies are incoherent and cause noise within the bandwidth of the order of τ_{st}^{-1}. Let us demonstrate this by formal calculations [3, 4].

We assume for definiteness that atoms interact with the field when flying through a resonator, as in an atomic (molecular) beam maser. In this case, the polarisation p induced in a two-level atom by the electromagnetic field $E e^{-i\omega t}$ is described by the equation [4]

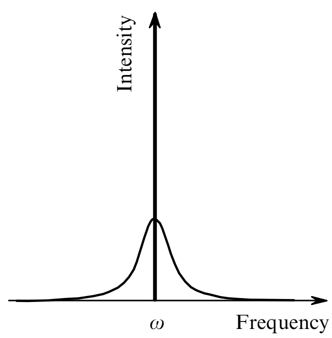

Figure 1. Creation of monochromatic emission in an ensemble of atoms, each of them interacting with a field during a finite time interval.

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$$\frac{d^2p}{dt^2} + \omega_a^2 p = -2\omega_a \frac{\mu^2}{\hbar} NEe^{-i\omega t}, \quad (2)$$

where ω_a is the resonance frequency; μ is the matrix element of the dipole moment of an atomic transition; and N is the difference of populations of the upper and lower atomic levels. We assume that the field is weak and neglect the change in the population difference. At the instant t_j, when the atom enters the resonator, the polarisation and its derivative are zero. The solution of equation (2) corresponding to these initial values is described by the expression

$$p(t, t_j) \approx \chi E(e^{-i\omega t} - e^{i(\omega_a - \omega)t_j} e^{-i\omega_a t}), \quad \chi = \frac{\mu^2}{\hbar(\omega - \omega_a)} N. \quad (3)$$

The solution (3) is written in the approximation $(\omega_a - \omega)/\omega \ll 1$. Because the atom is in the resonator during the time τ, its polarisation spectrum is described by the relation

$$p(\Omega, \tau, t_j) = \int_{t_j}^{t_j+\tau} p(t, t_j) e^{i\Omega t} dt. \quad (4)$$

It is clear that the polarisation spectrum of a single atom, which is determined by the integral over the interval , has the width of the order of τ^{-1}. The total polarisation spectrum of all the atoms is obtained by adding the spectra of individual atoms, which have appeared at different instants of time:

$$P(\Omega, \tau) = \sum_j p(\Omega, \tau, t_j)$$
$$= \frac{\chi E}{i} \sum_j e^{i(\Omega - \omega)t_j} \left(\frac{1 - e^{i(\Omega - \omega)\tau}}{\omega - \Omega} - \frac{1 - e^{i(\Omega - \omega_a)\tau}}{\omega_a - \Omega} \right). \quad (5)$$

In the limit of many particles, when summation can be replaced by the integration over t_j, we obtain

$$P(\Omega, \tau) \to \delta(\Omega - \omega). \quad (6)$$

Therefore, the polarisation spectrum of a very great number of particles becomes monochromatic although the polarisation spectrum of each individual particle is broad.

Note here that the saturation effect plays an important role in the formation of monochromatic radiation in a laser (maser). However, this problem is outside the scope of this paper.

The proof of a coincidence of the frequency of stimulated emission with the frequency of the external field presented above is based on the fact that the field and polarisation have a certain phase. However, the phase and the number of photons in a quantum state of the field cannot be determined exactly because fluctuations in the number of photons (Δn) and in phase ($\Delta\varphi$) satisfy the uncertainty relation

$$\Delta n \Delta\varphi \geqslant 1. \quad (7)$$

The amplitude and phase of a classical monochromatic field are strictly specified. This means that the wave energy (the number of photons) is also strictly defined. However, according to relation (7), in quantum mechanics this cannot take place. Consider how this problem was solved.

In the quantum theory of a laser, as in quantum electrodynamics, an electromagnetic field is described by a set of oscillators. In the case of a laser-generator, the field $\boldsymbol{E}(\boldsymbol{r}, t)$ can be naturally expanded in the resonator eigenmodes $\boldsymbol{U}_k(\boldsymbol{r})$:

$$\boldsymbol{E}(\boldsymbol{r}, t) = i \sum_k \left(4\pi \frac{\hbar\omega_k}{V} \right)^{1/2} \left[\hat{a}_k^+(t) \boldsymbol{U}_k^*(\boldsymbol{r}) - \hat{a}_k(t) \boldsymbol{U}_k(\boldsymbol{r}) \right], \quad (8)$$

where ω_k is the eigenfrequency of the mode $\boldsymbol{U}_k(\boldsymbol{r})$. The expansion coefficients $\hat{a}_k^+$, and $\hat{a}_k$ should be considered as the photon creation and annihilation operators for the corresponding resonator mode. These operators satisfy the permutation relations

$$\hat{a}_k \hat{a}_k^+ - \hat{a}_k^+ \hat{a}_k = 1, \quad (9)$$

which are valid for a mechanical oscillator. Here, $\hat{n}_k = \hat{a}_k^+ \hat{a}_k$ is the operator of the number of photons in the given mode of the resonator. However, a problem appears in the description of a coherent field. The average value of the coherent field is nonzero, but the field (8) averaged over a state with a specified number of photons is zero. This problem was eliminated by introducing the coherent states $|E_k\rangle$ of the field, which represent the eigenstates of the photon annihilation operator:

$$\hat{a}_k |E_k\rangle = E_k |E_k\rangle. \quad (10)$$

A quantum coherent state was considered by Schrödinger as early as 1927 [5]. The theory of this state applied to the problems of coherent optics was developed by Glauber [6], Sudarshan [7] and others.

The field [8] averaged over functions (10) is nonzero:

$$\langle \boldsymbol{E}(\boldsymbol{r}, t) \rangle$$
$$= i \sum_k \left(4\pi \frac{\hbar\omega_k}{V} \right)^{1/2} \left[E_k^*(t) \boldsymbol{U}_k^*(\boldsymbol{r}) - E_k(t) \boldsymbol{U}_k(\boldsymbol{r}) \right], \quad (11)$$

and, as shown below, is a quantum analogue of a classical coherent field.

The coherent state $|E_k\rangle$ can be represented as an infinite sum of the states $|n_k\rangle$ with a certain number of photons:

$$|E_k\rangle = \sum_n \exp\left(-\frac{|E_k|^2}{2} \right) \frac{E_k^n}{\sqrt{n!}} |n_k\rangle. \quad (12)$$

It follows from (12) that the number of photons in the coherent state is uncertain, and the probability of detecting in the state $|E_k\rangle$ the number of photons equal to $|n_k\rangle$ is

$$w(n_k, E_k) = \exp(-|E_k|^2) \frac{|E_k|^{2n_k}}{n_k!}. \quad (13)$$

Expression (13) is the well-known Poisson distribution. Arecchi [8] studied the statistic of photons emitted by a helium-neon laser and showed that it is very well described by expression (13).

One of the important properties of the quantum coherent state is that the uncertainty in the number of photons and the phase in this state is minimal:

$$\Delta n_k \Delta\varphi_k = 1. \quad (14)$$

The average number of photons in the coherent state $|E_k\rangle$ is

$$\langle n_k\rangle = |E_k|^2, \quad \Delta n_k = \left\langle \left(\langle n_k\rangle - n_k\right)^2 \right\rangle^{1/2} = \langle n_k\rangle^{1/2}, \quad (15)$$

so that

$$\Delta\varphi_k = \langle n_k\rangle^{-1/2}. \quad (16)$$

Therefore, the phase uncertainty decreases with increasing an average number of photons in an electromagnetic wave. In the classical limit, when $\langle n_k\rangle \to \infty$, the phase uncertainty $\Delta\varphi_k \to 0$. This fact can be clearly interpreted by introducing the operators of the so-called quadrature components

$$\hat{X}_k = \frac{1}{\sqrt{2}}(\hat{a}_k + \hat{a}_k^+), \quad \hat{Y}_k = \frac{1}{\sqrt{2}}(\hat{a}_k^+ - \hat{a}_k). \quad (17)$$

In the general case, the uncertainty relation for the components $\hat{X}, \hat{Y}$ has the form

$$\Delta\hat{X}_k\,\Delta\hat{Y}_k \geqslant 1. \quad (18)$$

In the vacuum state of the electromagnetic field, as well as in the coherent state, we have

$$\Delta\hat{X}_k = \Delta\hat{Y}_k = 1. \quad (19)$$

Let us represent the vacuum state in the phase plane $\hat{X}_k, \hat{Y}_k$ as a circle with the unit radius (Fig. 2). Then, the coherent state can be represented by a similar circle, only displaced from the centre by the distance $\langle n_k\rangle^{1/2}$ and rotating around the centre with the frequency ω_k. The angle $\Delta\varphi_k$ is the phase uncertainty in the coherent state, which decreases with increasing $\langle n_k\rangle$.

Let us elucidate the question about the relation between the phases of exciting and emitted fields. Because the phase of the emitted field is determined by the polarisation phase of an active substance, we will construct a state of the active medium similarly to the coherent state of the field. We can introduce the creation ($\hat{A}^+$) and annihilation ($\hat{A}$) operators for active particles in the excited state and construct the function $|P\rangle$, of the coherent state of the substance satisfying the relation

$$\hat{A}|P\rangle = P|P\rangle. \quad (20)$$

The parameter P describes the average polarisation of the active medium related to the dipole moment of a two-level atom. As for the coherent state of the field, we have

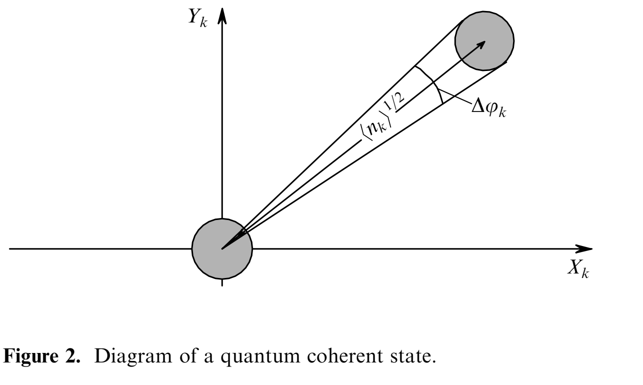

Figure 2. Diagram of a quantum coherent state.

$$|P\rangle = \exp\left(-\frac{1}{2}|P|^2\right)\sum_N \frac{P^N}{\sqrt{N!}}|N\rangle, \quad (21)$$

where $|N\rangle$ is the eigenfunction corresponding to a certain number of active particles.

It follows from (21) that the number of particles contributing to polarisation is uncertain, and the distribution (21) provides a minimal uncertainty in the number of particles and in the polarisation phase of the active medium. As for an electromagnetic wave, the uncertainty in the polarisation phase disappears when $N \to \infty$: the exciting and emitted waves prove to be in phase or their phase shift is constant. For this reason, the use of a constant phase shift between the field and polarisation in the derivation of expression (6) for a multiparticle system is justified.

Therefore, the problem of coherence and monochromatism of stimulated emission indeed can be solved for a multiparticle system, as N.G. Basov assumed.

N.G. Basov and A.M. Prokhorov have always emphasised that a quantum generator (the general term for masers and lasers) is a self-oscillation system, with all the properties inherent in it. Thus, N.G. Basov and A.M. Prokhorov wrote in their report presented at the session of the A.S. Popov Society in 1954: 'We call a self-oscillation system, which uses the energy related to the transitions between different molecular levels, a molecular generator. A contour of the molecular generator is a volume resonator. A molecular beam containing a positive number of excited molecules propagates through the volume resonator. The negative feedback in the generator is performed via the electromagnetic field of the resonator, whose action on the dipole electric moments of molecules causes stimulated emission of molecules in the beam' [9]. Therefore, a laser is a complicated system, whose operation is determined by all its components. The general theory of a laser should also include the properties of the resonator. Being a self-oscillation system, a laser represents inevitably a nonlinear system as well. The laser cavity and nonlinearity play an important role in the development of lasing regimes. Therefore, it should be emphasised here that all the above discussion concerns only the properties of stimulated transitions, independently of whether they occur in the cavity or in a free space.

Let us call the attention to one circumstance in the general theory of lasers, which is directly related to the problem of coherence of stimulated transitions. The fluctuations of the phase and the number of photons in the quantum coherent state are random stationary processes. However, the quantum fluctuations of the electromagnetic vacuum and the dipole moment of active atoms in a real laser cause diffusion of the phase of the generated field making it nonstationary. Its average value varies as [10]

$$\langle\Delta\varphi^2\rangle = Dt, \quad D = \frac{\Delta\omega_c}{\langle n\rangle}\frac{N_{up}}{N_{up} - N_{la}}, \quad (22)$$

where $\Delta\omega_c$ is the half-width of the laser cavity line; $\langle n\rangle$ is the average number of photons in the cavity; N_{up} is the number of particles (atoms) at the upper energy level; and N_{la} is the number of atoms at the lower energy level. The spectral width $\Delta\omega$ of the laser line is determined by the diffusion coefficient D of the phase:

$$\Delta\omega = D. \quad (23)$$

Formula (22) in the theory of lasers is usually attributed to Ch. Townes and A. Shawlow [10]. It is similar to the formula obtained by Bernshtein for a radio-frequency generator [11]. It follows from expression (22) that the phase diffusion slows down with increasing the average number of photons in the cavity. In this case, the coherence of emission increases with increasing the number of photons in the cavity and the number of excited particles involved in lasing.

The following circumstance is of interest. The cross section for the stimulated resonance transition between atomic levels calculated in the dipole approximation is

$$\sigma_{\text{ind}} = \frac{8\pi^2}{\lambda}\frac{|\mu|^2}{\hbar\gamma}. \tag{24}$$

If the linewidth is caused only by spontaneous radiative transitions, then

$$\sigma_{\text{ind}} = \lambda^2/2\pi. \tag{25}$$

In the optical wavelength range (and at longer wavelengths), the cross section (24) greatly exceeds the effective geometric cross section of an atom. At first glance, this seems paradoxical; however, consistent calculations solve this paradox. The structure of a field interacting with an atom was calculated in paper [12]. The field was assumed classical, representing a plane wave away from the atom. The calculation showed that the field is distorted near the atom. Fig. 3 shows the lines of equal wave-energy fluxes neat the atom. One can see that the atom 'collects' the energy from the area that greatly exceeds its geometrical cross section.

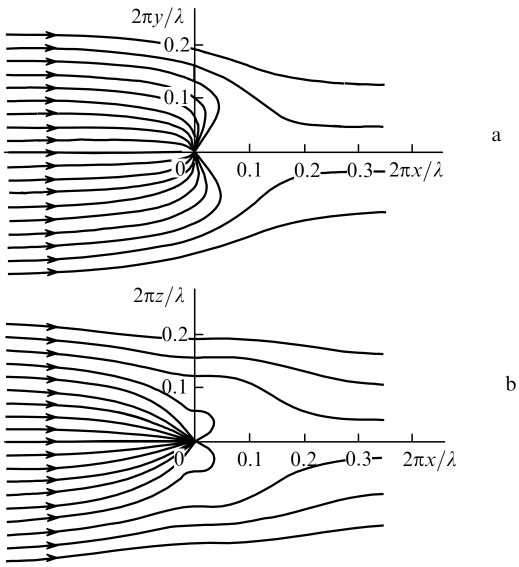

Figure 3. Diagrams of absorption of light by an atomic dipole; (a) the projection of the energy flux in the xy plane and (b) the projection of the energy flux in the xz plane for a dipole oscillating along the z axis. The distance along the axes is normalised to the wavelength λ.

A coherent electromagnetic wave is not the only manifestation of the coherent state of the matter. There exist coherent states of different types, such as a Bose–Einstein condensate of atoms in traps and a superconducting condensate of Cooper pairs. The coherent (ordered) distribution of atoms can be observed in crystals, etc. Studies in the field of laser physics suggest that stimulated transitions should play a key role in the formation of a coherent state of any nature. We believe that these transitions underlie a universal mechanism responsible for a spontaneous violation of symmetry in nature [13]. This violation can occur when the stimulated process of creation of some object with a characteristic feature dominates over the decay process. This condition is equivalent to the lasing condition. It seems that stimulated processes have played a decisive role in the formation of our Universe, when the symmetry of matter was violated in favour of electrons and protons. A similar assumption concerns the appearance of living organisms, whose proteins have the left chirality.

Let us return again to N.G. Basov as a person. His scientific activity has played a decisive role in the statement of many problems related to the development of quantum electronics (Fig. 4). All those who discussed with N.G. Basov scientific problems emphasise his unusual physical intuition and the ability to see the future problems through the mist of current days. One of the examples – a deep

Figure 4. N.G. Basov and first molecular generators (mid-1950s).

penetration to the problem of coherence of stimulated transitions – was discussed above. Another example is semiconductor lasers.

About 1957, when euphoria caused by the creation of masers and paramagnetic amplifiers gave way to a regular development of these devices, the possibility appeared to reflect about the further development of quantum electronics. It is at this time that N.G. Basov became interested in the optical wavelength range.

One of the most important problems to be solved became an appropriate choice of an active medium for a laser and of the method for its pumping. It was assumed that materials having narrow luminescence lines are most suitable for the creation of a laser. For this reason, a search for active media was performed among gases and luminescent crystals. N.G. Basov began, however, to think about the use of semiconductors as laser media. Nobody could exclude the possibility of creation of such a laser. But everybody 'understood' that it was unlikely that a semiconductor, which has broad luminescence bands, could be an appropriate laser material. Everybody, except N.G. Basov. He predicted intuitively that semiconductors are very promising for creation of lasers [14] and developed extensive studies in this field. Within the framework of these investigations, injection lasers were proposed and their modifications representing structures with the bands of different widths [15], which were later called heterostructures. The result is known: injection semiconductor lasers are now the most widely used type of lasers.

It should be noted that N.G. Basov initiated in 1959 a wide research program devoted to the development of lasers, which was called 'Photon'. N.G. Basov was a scientific supervisor of this program. In this program were engaged, along with the Laboratory (now Department) of Quantum Radiophysics, all optical laboratories (now the Department of Optics) at the Lebedev Physics Institute. These studies have led to the creation of lasers of different types, some of them having been developed for the first time [16].

The main feature of the scientific creative power of N.G. Basov was his anticipation of new ideas. It seems that for this reason, he and his disciples have performed a great deal of pioneering studies. A brief summary of the main scientific achievements of N.G. Basov and his school is presented below.

Problem	The contribution of N.G. Basov and his school	Comment
1. The proposal of masers (generators and low-noise amplifiers)	The proposal and creation of the first masers [17]. The proposal of low-noise quantum amplifiers [18] and electromagnetic pumping in a three-level system [19]	The Lenin (1959) and Nobel (1964) prizes
2. The proposal and study of lasers at the first stage of their development	Inventor's certificate for semiconductor lasers [14]. 'Photon' program [16]	
3. Semiconductor lasers	The proposal of an injection laser and its modification in the form of a structure with different widths of the energy gap [14]	The Lenin prize (1964)
	The proposal and creation of lasers with electron [20] and optical [21] excitation	
	The creation of the first heterolaser based on InGaAsP/InP and other ternary heterostructures (lasers for communication) [22]	The State prize (1990)
4. Frequency standards	Series of studies on microwave (masers) and optical frequency standards [22–24]	The Lenin Komsomol prize (1972), the State prizes (1983, 1988)
5. Laser dynamics	A model is formulated for the description of the dynamics of masers and lasers, which takes into account the field, the polarisation of an active medium and populations of working levels as dynamic variables [25]. This model is known in the literature as the Maxwell–Bloch model The numerical discovery of the regime of irregular (non-periodic) pulsations in a single-mode laser, which was called later the dynamic chaos [26, 27]. The experimental observation of periodic pulsations in a semiconductor laser at liquid helium temperature [28]	
6. Gas-dynamic and chemical lasers	The proposal of thermally-pumped molecular lasers [29] and the development of their theory [30] The proposal [31] and creation of chain-reaction chemical lasers [32]. The proposal of a purely chemical cw laser [33] The proposal of a new type of a chemical laser based on the photon branching of a chemical reaction [34–36]. The creation of highly efficient singlet-oxygen generators and a high-power oxygen-iodine laser based on them [37]	The Lenin prize (1984)
7. Excimer lasers	The creation of the first xenon excimer laser [38, 39, 40]	The State prize (1978)
8. High-pressure gas lasers	The proposal and experimental implementation of electroionisation pumping, which allowed the creation of high-pressure molecular gas lasers [41]	
9. Optically pumped gas lasers and high-power UV pump sources	The proposal of lasers based on photodissociation of molecules [42]. The development and creation of explosion-pumped lasers [43]. The development of high-power radiation sources. The proposal and creation of optically pumped gas lasers [44]	The State prize (1980)

Problem	The contribution of N.G. Basov and his school	Comment
10. X-ray lasers and X-ray optics	Various pumping schemes for X-ray lasers are proposed and analysed [45–47]. A method is proposed for manufacturing of mirrors for the soft X-ray range [48, 49]	State prize (for studies of X-ray optics, 1991)
11. Laser fusion	The proposal of the idea of laser fusion [50]. The first observation of thermonuclear neutrons excited by laser irradiation [51]. Pioneering papers on the design and compression of targets [52]	
12. Laser-induced chemical reactions	The first experiments on the IR laser-induced chemical reactions [34] and the mechanism of laser-induced chemical reactions based on the Fermi resonance in molecules [53]. The observation of the vibrationally selective dissociation of molecules upon simultaneous excitation by IR and UV lasers [54]. Biochemical reactions [55, 56]	
13. Laser isotope separation	The discovery of the isotopic selectivity of collisonless dissociation of molecules [57]. A series of studies on isotope separation [58]	
14. Phase conjugation	The discovery of phase self-conjugation if high-power laser radiation based on the Brillouin scattering [59]	The State prize (1983)
15. Laser spectroscopy	Sub-Doppler laser spectroscopy [60] The proposal and development of a highly sensitive method of intracavity laser spectroscopy [61, 62]	The Lenin prize (1978). The D.S. Rozhdestvensky prize (1983)
16. High-power light amplifiers	The discovery of the superlight propagation of a light pulse in amplifying media [63]	
17. Projection television	The proposal and study of a projection TV device based on an electron-beam excited semiconductor laser [64]	
18. Laser plasma and laser technology	The proposal and various applications of lasers in technology processes [65]	The State prize (1982)
19. Laser ranging	A setup is developed and the distance to the Moon is measured with high accuracy [66, 67]	
20. Optical communication	The limiting capacity of an optical communication channel is analysed [68]	
21. Electroionisation chemistry	Unique nitrogen-containing compounds are synthesised in an electroionisation-discharge plasma [69]	The State prize (1989)
22. Helical structures of optical beams	The prediction, discovery, and study of helical structures of optical beams [70, 71]	
23. Laser cooling of atoms	The laser cooling and trapping of atoms is theoretically studied and experimentally implemented [72]	The D.S. Rozhdestvensky prize (2001)

N.G. Basov was a person of a world rank. It is difficult to reflect his versatile scientific, scientific management, instructive, and pedagogical activity in a small paper, and we recommend to the reader other papers and books devoted to N.G. Basov [9, 73–77].

More than sixty scientists from a large scientific community created and supervised by N.G. Basov were awarded prestigious premiums such as the Lenin, State, Lenin Komsomol Prizes, and the nominal prizes of the Academy of Sciences.

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