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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held on 29 November 2000 at the P L Kapitza Institute for Physical Problems, RAS. The following reports were presented.

(1) **Vasil'ev P P** (P N Lebedev Physics Institute, Russian Academy of Sciences, Moscow) "Coherent effects in the generation of femtosecond pulses in semiconductor lasers";

(2) **Oraevskiĭ A N** (P N Lebedev Physics Institute, Russian Academy of Sciences, Moscow) "Bose condensate from the standpoint of laser physics".

Brief presentations of the reports presented are given below.

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Coherent effects in the generation of femtosecond pulses in semiconductor lasers

P P Vasil'ev

Coherence is one of the most basic physical concepts. The property of coherence may be inherent not only in the state of an electromagnetic field (an ensemble of photons), but also to groups of bosons or fermions residing in a condensed state. One glowing example is the coherent state of an ensemble of Cooper pairs in a superconductor. In addition, coherence is strongly manifested in the interaction of an electromagnetic field with a medium in quantum optical phenomena, like self-induced transparency, free induction decay, photon echo, superradiance, and some others [1]. In this case, the medium in the interaction with the field possesses a 'phase memory' and its state is determined not only by the current state of the electromagnetic field, but by its characteristics at preceding instants of time.

The phase relaxation time T_2 is the characteristic time scale in all the above dynamic processes. To make possible the observation of coherent electromagnetic field – medium interaction, the temporal characteristics of the electromagnetic field (for instance, the pulse durations or the delay between the pulses) should be shorter than this time. Semiconductor media exhibit extremely short times T_2 not exceeding 10^{-13} s (100 fs) at room temperature. The coherence of electromagnetic field–semiconductor interaction would therefore be expected to reveal itself only on the femtosecond time scale.

In this report the results of an experimental investigation of the coherent interaction of a light field with GaAs/AlGaAs-based semiconductor media are outlined. All measurements were conducted at room temperature. A detailed description of the samples was published elsewhere [2 – 4]. To prevent lasing and obtain a high ($> 2 \times 10^{18}$ cm^{-3}) density of electron – hole (e – h) pairs, a saturable absorber was produced in the semiconductor structures to which a blocking voltage was applied. By varying this voltage, it was possible to vary the initial e – h pair density and exert control on the characteristics of the cooperative (superradiant) e – h state.

Superradiance occurred in the samples when high-power nanosecond current pulses with an amplitude of 0.4 – 2.0 A were applied to the amplifying structure sections and when the blocking voltage imposed across the absorber lay in the range from -3 to -10 V. The superradiance pulses had a wavelength of about 885 nm (1.40 eV), a typical duration of 300 – 400 fs, and a peak power of over 20 W (a power density of about 10^9 W cm^{-2}). The radiation was linearly polarized, with the electric field vector lying in the plane of the heterostructure layers (the TE mode). Our attention was engaged by the instability of the pulse shapes and the large scatter in the instants of pulse origination which was many times larger than their duration. Strong coherent beats were observed in 90 – 100 μm long samples, which were caused by the coherent interaction of the optical field with the medium and by the existence of two spatial regions of cooperative state of electrons and holes. These two regions measured 20 – 30 μm by 5 μm by 0.2 μm each and were located near the sample faces. The coherent oscillations of the optical field lasted for over 10 ps, which was several times the double passage of light between the faces of the semiconductor [2]. Depending on the excitation conditions and the sample length, the frequency of coherent oscillations was 1 – 3 times the intermode frequency of the resonator formed by the crystal faces. The maximum oscillation frequency was 1.1 THz. In this case, the optical spectrum was a doublet, the separation of the components being equal to the reciprocal of the period of coherent oscillations. These temporal and spectral dynamics correspond to the situation in which the field amplitude changes its sign (the phase changes by π in a jumpwise manner), which is indicative of the coherence of field – medium interaction. The coherence in the semiconductor medium was retained throughout periods many times longer than the T_2 time. In our view, this is due to the cooperative properties of the ensemble of e – h pairs, which reside in a correlated state induced by the electromagnetic field.

As shown in Ref. [4], the superradiance in a semiconductor medium arises any time the optical gain coefficient

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(proportional to the density of e – h pairs) is high enough. The criterion for the magnitude of the gain coefficient α is the inequality

$$c\alpha T_2 > 1\,, \qquad (1)$$

where c is the velocity of light in the medium. For parameter values typical of a volume GaAs at room temperature, inequality (1) yields an α value greater than 1.3×10^3 cm^{-1}. This value far exceeds typical gain coefficients in lasers, which range from 50 to 300 cm^{-1}, depending on the losses in the resonator. That is why up to now superradiance has not been observed in semiconductor laser structures. To attain the needed gain coefficient to satisfy inequality (1), it is requisite, first, that currents with an amplitude many times the laser oscillation threshold are applied to the semiconductor structure and, second, that the development of laser oscillation in the sample is suppressed. These conditions are necessary to accumulate a sufficiently large number of e – h pairs required for their transition to the cooperative state prior to the onset of radiative recombination.

The properties of e – h pairs which reside in the cooperative state are indeed remarkable. We note some of them. It is known that electrons and holes in semiconductors can pair and, under specific conditions, make up condensates [5 – 7]. For low temperatures and low densities of electrons and holes, this is a Bose exciton condensate [6]. For high densities, the pairing of electrons and holes in the semiconductor may result in a collective state resembling the condensate of Cooper pairs in a superconductor [7]. In our experiments, an investigation was made of the recombination spectra of electrons and holes residing in a cooperative state in GaAs in relation to their density $(2-6) \times 10^{18}$ cm^{-3}. The average distance between electrons and holes for such densities is many times shorter than the exciton radius (the dimensionless parameter r_s lies in the range 0.27 – 0.47), which corresponds to the regime of high densities. It turned out that the cooperative e – h recombination line is 15 – 20 meV lower in energy than the conventional spontaneous recombination line and the laser line in the same structure. Figure 1 shows a typical e – h recombination spectrum in the cooperative state. One can see that the line center in this case is shifted to the red spectral domain by 20 meV relative to the edge of the unrenormalized forbidden band of GaAs for $T = 300$ K (1.424 eV). The line width is determined in effect by the lifetime of the cooperative e – h state. Also given in Fig. 1 is an approximation of the spectrum by the convolution of the density of states ($\sim \sqrt{E}$) and the Fermi function for the occupancy of electron and hole states in the bands, made by the formula

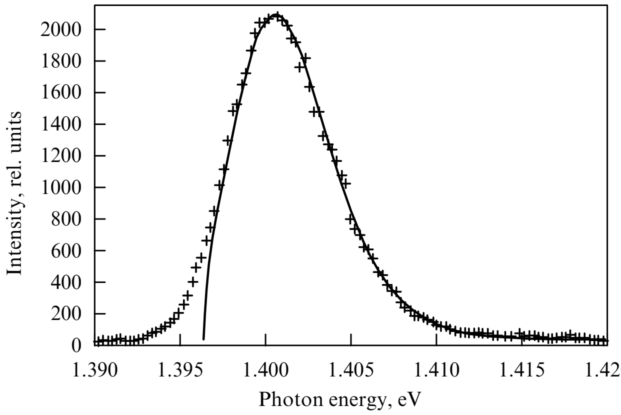

Figure 1. Recombination spectrum of the e – h cooperative state (+) and its approximation.

$$I(\hbar\omega) = I_0 \int_{E_{\rm g}}^{\hbar\omega} \rho_{\rm c}(E)\rho_{\rm v}(\hbar\omega - E_{\rm g} - E) \times f_{\rm e}(E) f_{\rm h}(\hbar\omega - E_{\rm g} - E)\,{\rm d}E\,.$$

This approximation provides a very good description of the recombination line everywhere over the region, with the exception of the long-wavelength tail, where the density of states is not described by a simple square-root dependence and needs to be modified [8]. By taking advantage of the approximation, it is possible to estimate the density of electron – hole pairs and their effective temperature, which is a conventional technique in the investigation of the e – h plasma radiation and the e – h condensate. The recombination spectra were studied experimentally for different e–h pair densities and the effective e – h temperature was plotted as a function of the density. This dependence is depicted in Fig. 2.

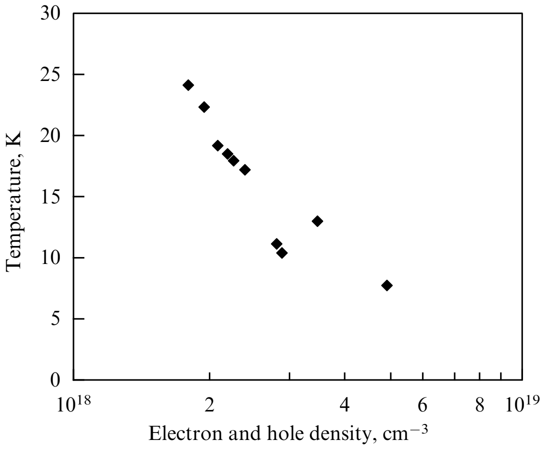

Figure 2. Density dependence of the effective temperature of electrons and holes in the cooperative state.

Our attention was engaged by the very low magnitude of the effective temperature of 7 – 25 K, which corresponds to an energy gap in the e – h spectrum of 1.5 – 2.5 meV. Moreover, the temperature decrease with density is typical for an electron – hole condensate [9, 10], unlike the temperature increase characteristic of an e – h plasma. The experiments lent support to the view that the cooperative e – h state is characterized by a very low temperature. It turned out that the electrons and holes that persisted in the crystal after the superradiance pulse and had not directly participated in it are characterized by an elevated temperature exceeding the lattice temperature. The center of spontaneous recombination line of this overheated part of the e – h subsystem (1.451 eV) is shifted towards the short-wavelength spectral region by 15 – 18 meV relative to the center of conventional spontaneous emission line.

The pairing of electrons and holes in the cooperative state is favored not only by the existence of a common electromagnetic field and exchange of photons, which produce and cancel in pairs the electrons and holes possessing oppositely directed momenta of equal amplitude, but also by the existence of an electric field in the p – n junction of the laser structure, which is responsible for electron and hole currents whereby electrons and holes have oppositely sensed momenta.

Therefore, for the first time observations were made of the superradiance of electrons and holes in a bulk semiconductor at room temperature. The coherent interaction of the optical field with an e – h system was attended with oscillations at a frequency of over 1 THz with a change of sign of the field amplitude. The superradiance mode in the semiconductor was accompanied by the formation of a cooperative e – h state (the domains of macroscopic polarization). The lifetime of this cooperative state is shorter than 1 ps. In this case, the coherence of interaction of the electromagnetic field with the e – h system is retained throughout periods much longer than the T_2 time. This may be caused by the pairing of electrons and holes residing in the cooperative state, their condensation, and the formation of a state similar to the BCS state of Cooper pairs in superconductors. In this case, the scattering of the pairs by each other does not result in a loss of coherence.

References

1. Allen A, Eberly J H *Optical Resonance and Two-Level Atoms* (New York: Wiley, 1975) [Translated into Russian (Moscow: Mir, 1978)]
2. Vasil'ev P P *Kvantovaya Elektron.* (Moscow) **21** 585 (1994) [*Quantum Electron.* **24** 540 (1994)]
3. Vasil'ev P P *Kvantovaya Elektron.* (Moscow) **24** 885 (1997) [*Quantum Electron.* **27** 860 (1997)]
4. Vasil'ev P P *Kvantovaya Elektron.* (Moscow) **29** 4 (1999) [*Quantum Electron.* **29** 842 (1999)]
5. Keldysh L V, Kozlov A N *Zh. Eksp. Teor. Fiz.* **54** 978 (1968) [*Sov. Phys. JETP* **27** 521 (1968)]
6. Griffin A, Snoke D W, Stringari S (Eds) *Bose – Einstein Condensation* (Cambridge: Cambridge Univ. Press, 1995)
7. Iida T, Hasegawa Y, Higashimura H, Aihara M *Phys. Rev. B* **47** 9328 (1993)
8. Smith L M, Wolfe J P *Phys. Rev. B* **51** 7521 (1995)
9. Jeffries C D, Keldysh L V (Eds) *Electron – Hole Droplets in Semiconductors* (Amsterdam: North-Holland, 1983)
10. Kalt H et al. *Phys. Rev. B* **42** 7058 (1990)

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Bose condensate from the standpoint of laser physics

A N Oraevskiĭ

1. Coherence of Bose condensates and the inversion condition

Bose condensate has long been the object of keen interest of researchers. It has drawn their attention primarily in the context of the problems of superconductivity and superfluidity [1, 2]. The coherent state of a laser-generated electromagnetic field with a specific frequency and spatial configuration can also be considered as a Bose condensate of photons. Relatively recently, a new wave of interest in Bose condensate research was generated in connection with the pursuance of successful experiments to cool atoms to record breaking low temperatures of the order of 10^{-7} K [3 – 5]. For so low a temperature it has been possible to obtain a Bose condensate of atoms captured in a trap [6]. A Bose condensate of atoms is primarily of general physical interest. In the state of a Bose condensate, the wave nature of matter is much pronounced and an ensemble of particles large enough in number behaves like a classical field which possesses an amplitude and a phase.

The Bose condensate of particles has always *a priori* been assumed to be a coherent state of matter. In this case, the Bose condensation of particles was silently implied to form this coherent state automatically. But for a researcher with the mentality of a laser physicist this statement is hard to accept without proof. To take one example, the accumulation of photons in a single resonator mode in an 'underexcited' laser is possible due to spontaneous transitions, but this state of the electromagnetic field will not be coherent. The coherent state of the electromagnetic field (photons) in a laser is formed by *induced* transitions when the *self-excitation* condition is fulfilled.

Laser. According to the self-excitation condition, the emission of electromagnetic energy by the active medium of a laser should exceed the losses arising from possible absorption and dissipation inside the laser and the emergence of radiation from the laser for subsequent use. In the context of a two-level model of the laser active medium, this condition is of the form

$$\frac{N_2}{g_2} - \frac{N_1}{g_1} > \Delta N_{\rm th}\,, \tag{1}$$

where $\Delta N_{\rm th}$ is the threshold value of the population difference, which depends on the total loss of electromagnetic radiation inside the laser and the transparency of the output mirror. Clearly the fulfillment of similar conditions is also necessary to obtain the *coherent* state of any Bose particles. Condition (1) is sufficient for laser excitation. The necessary condition is the inequality

$$\frac{N_2}{g_2} > \frac{N_1}{g_1}\,, \tag{2}$$

which is referred to as the 'inverse population condition.'

For interband transitions in a semiconductor laser, the condition equivalent to inequality (2) is of the form [9]

$$\mu_{\rm e} - \mu_{\rm h} > \hbar\omega\,, \tag{3}$$

where $\mu_{\rm e,\,h}$ are the respective chemical potentials of electrons and holes, and $\hbar\omega$ is the energy of emitted photons. Inequality (3) testifies to the fact that the electron and hole states should be degenerate, i.e., their densities should be substantial.

Bose condensate of atoms. Let us consider the process of Bose condensation from the viewpoint of formation of a coherent state. The relationship equivalent to the inversion condition in a laser should follow from the requirement that the formation of a Bose condensate under the action of the condensate itself (induced production of coherent particles) should exceed the condensate decay rate. The result is the relationship

$$n(\varepsilon) > \left[\exp\left(\frac{\varepsilon}{kT}\right) - 1\right]^{-1}. \tag{4}$$

The right-hand side of inequality (4) is nothing but the equilibrium distribution function of the particles outside of