The experimental results of the investigation of coherent terahertz oscillations of the electromagnetic field from GaAs/AlGaAs heterostructures during the superradiant pulse generation have been presented. Optical doublets, which are typical for Rabi oscillations, with the splitting of 1.3–4.4 meV at 860–890 nm wavelengths have been discovered. The corresponding coherent oscillations in the time domain have been detected. The effect has been only observed in the strong coupling regime of the field with the electron–hole system. It has been demonstrated that it is the condensation of $e^{-}h$ pairs in phase space that makes the strong coupling possible in the present experimental conditions. The experimental result is yet another convincing evidence of the $e^{-}h$ condensation in bulk GaAs at room temperature, which has been discussed in our previous publications.

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The study of the interaction of resonant electromagnetic fields with quantum systems of different nature is an important part of contemporary quantum optics and quantum information technologies [1]. One of the fundamental effects of this interaction is Rabi oscillations which are the periodic energy exchange between the field and the quantum medium. In recent years, Rabi oscillations have been extensively investigated in a wide range of quantum systems, including ultracold gases, quantum dots, individual spins, superconducting qubits, exciton-polaritons in microcavities, etc. [2–5]. The emergence of Rabi flopping is a feature of the interaction of the electromagnetic field with both single quantum emitters and ensembles of oscillators, including collective spontaneous decay (superradiance) [6].

It has been generally accepted that Rabi oscillations require strong coupling between the electromagnetic field and the quantum emitter [1, 7, 8]. The figure of merit of this coupling is the parameter $g_0 = \mu \sqrt{\hbar \omega / 2 \varepsilon V}$ where $\mu$ is the transition matrix element, $\hbar \omega$ is the quantum energy, $\varepsilon$ is the dielectric constant of the medium, and $V$ is the volume of the optical mode. It is obvious that microcavities of different types with small values of $V$ should be used for increasing the coupling parameter. It has been shown both experimentally and theoretically that an increase in the number $N$ of emitters interacting with the field results in the rise of the coupling parameter according to the formula $g(N) = g_0 \sqrt{N}$ [6, 9, 10]. A necessary condition of the Rabi oscillations generation has the form

$$2g > (\kappa + \gamma)/2,$$

where $\kappa$ is the reciprocal of the photon lifetime in the cavity and $\gamma$ is the spontaneous recombination rate [1]. This relation demonstrates the advantages of exploiting high-$Q$ resonators with small values of $\kappa$ [5, 11–13].

Quantum dots and exciton-polaritons in quantum wells placed in microcavities are the main semiconductor objects for research in cavity quantum electrodynamics [14–16]. They allow for the observation of Bose–Einstein condensation of exciton-polaritons at appropriate conditions at cryogenic temperatures [17]. However, widespread laser heterostructures with typical cavity lengths of 100–500 $\mu$m have never been considered as candidates for the investigation of strong coupling and Rabi oscillations. Indeed, the value of the coupling strength $g_0/2\pi \sim 10^5$ Hz or 0.4 $\mu$eV at characteristic parameters of $\mu$, $\varepsilon$, and $V$. This value is smaller by a few orders of magnitude than typical values of $(\kappa + \gamma)$ [18], which makes impossible the observation of the effects under study in those devices.

However, as was noted above, the effective method of enhancing light–matter coupling is increasing the number of emitters interacting with the same optical mode. It has been experimentally found in our previous research the fact of establishing the superradiant
phase transition in laser heterostructures at room temperature [19–22]. It turned out that the electron–hole ensemble exhibited an off-diagonal long-range order [23], the coherence of superradiance exceeded that of lasing observed in the same samples, and the pulse propagation in the medium showed a superluminal nature [23, 24]. Furthermore, superradiance has super-Poisson statistics and its Wigner functions have broad areas of negative values. This implies that superradiant pulses have a quantum nature [25]. In this work, it is experimentally demonstrated that the condensation of electrons and holes towards the bottoms of the bands, which occurs with the mediation of resonant photons during the superradiant phase transition, enables the realization of strong coupling and the observation of Rabi flopping.

Modified GaAs/AlGaAs laser heterostructures were used in the experiment. The active layer was 0.2-μm-thick intrinsic GaAs. The length of samples varied from 100 to 450 μm. The width of the emitting area was in the range of 6–7 μm. The reflection coefficient of the facets of the samples was 0.32. Three sections were formed along the cavity axis for the realization of the superradiant regime [20, 22]. The photograph of the two samples is presented in Fig. 1. Two areas at the facets of the structure were pumped by current pulses with an amplitude exceeding the lasing threshold by a few times.

A dc reverse bias in the range of −(1–10) V was applied to the central section of the samples for preventing laser generation. This ensured the achievement of the e–h pair concentration as high as 6 × 10^{18} cm^{-3}, fulfilled the quantum degeneracy criterion [26], and brought about the non-equilibrium condensation in phase space and superradiant phase transition [21]. All samples generated the standard laser radiation at small driving currents and without the reverse bias. The lasing spectrum consisted of a single longitudinal mode or a few modes of the cavity. The samples emitted femtosecond pulses with an energy of 10–30 pJ under superradiance. Here, the optical spectrum contained doublets at certain pumping ranges.

Figure 2 presents typical optical doublets of the superradiance generated from different samples. All spectra are shifted towards longer wavelengths by more than 10 nm as compared to the lasing spectra. The spectral splitting between the components was from 0.49 to 2.61 nm depending on the parameters of the structures and parameters of pumping.

The intensity autocorrelation functions during second-harmonic generation in a scanning Michelson interferometer were simultaneously recorded with the spectral measurements. This technique allows for the measurement of coherence and parameters of oscillations of the optical field with a femtosecond accuracy [18]. Figure 3 shows typical intensity autocorrelation functions of two 100 μm long samples. The functions were recorded with the resolution of individual fringes in a scanning Michelson interferometer. The round trip time of the cavity was 3.1–3.2 ps. It is clearly seen the oscillations of the field with a frequency of about 1 THz. The splitting between the spectral components of the doublets and the oscillation frequency depended on the pumping parameters. Figure 4 illustrates the measured spectral splitting for one of the samples as a function of the reverse bias.

Table 1 presents the parameters of six samples and corresponding experimental data. The experimental data shown in Figs. 2–4 and Table 1 can be explained within the frame of strong coupling and the Rabi oscillations approach. Indeed, the observation of Rabi flopping is impossible during lasing in the heterostructures under test. This is due to weak coupling between the electron–hole system and the electromagnetic field in the cavity. The typical bandwidth of the laser mode is less than 0.2 nm. Due to the Pauli principle, electrons and holes are strongly spread on energy. So, only a small part of the total number of the carriers injected in the active area interacts with the
laser mode. This part can be readily estimated by knowing the density of states within the bands, the threshold density of lasing, the radiation wavelength and the laser mode bandwidth. The estimation gives the value of $N$ for lasing in the range of $10^3$—$10^4$, which is not large enough for meeting the criterion (1). However, the non-equilibrium condensation of electrons and holes towards the bottoms of the bands takes place.

Fig. 2. Optical spectra of six samples under superradiance.
during the superradiant phase transition. This process has been previously described in detail [21, 27, 28]. As a result of the condensation, the number of oscillators, which interact with the field, grows rapidly and the coupling parameter $g(N) = g_0 \sqrt{N}$ increases by many orders of magnitude. When the number $N$ becomes so
large that the criterion (1) is met, then the regime of
strong coupling sets in and the observation of Rabi
oscillations becomes feasible. We have previously
found out that the number of \( e-h \) pairs, which were
condensed at the bottoms of the bands and taking part
in the superradiant process, grows with an increase in
the reverse bias [29]. This explains the observed
enhancement of the spectral splitting as a function of
voltage presented in Fig. 4.

The measured Rabi oscillations \( \Omega \) in Table 1 are
well described by [1]

\[
\Omega = 2 \sqrt{g_0^2 N \frac{(\kappa - \gamma)^2}{4}}
\]

Strictly speaking, this expression has restricted appli-
cability in the case of highly excited semiconductors
where many-body effects can play an important role
[30]. However, this formula provides a qualitatively
correct estimation of Rabi frequency in our case.
Indeed, the number of \( e-h \) pairs can be estimated by
the value \( N = (0.58-1.2) \times 10^8 \) based on the measure-
ment of energies of superradiant pulses. The values of
the interband dipole matrix element \( \mu \) in GaAs are in
the range of 20–29 D according to the data published
elsewhere [31]. Using the values of \( \kappa \) and \( V \) from
Table 1, Eq. (2) gives Rabi frequencies \( \Omega/2\pi = 0.6–
1.7 \) THz. This corresponds well to the experimental
data.

It is worth paying attention to an important feature.
Two bottom spectra in Fig. 2 exhibit a fine structure of
the doublets consisting of two subharmonics. The
existence of the fine structure can be explained by the
interaction of quantum emitters. Indeed, as demon-
strated in [8, 32, 33], the inclusion of this interaction
leads to a more complicated spectrum as compared to
to the doublet spectrum described by Eq. (2). Subhar-
monics emerge due to the interaction of dipoles with
each other and the spectrum becomes asymmetric.
The author used Eq. (5.14) from [8] and Eq. (10) from
[32] and calculated the spectrum of Rabi oscillations
for the parameters of the sample H11 from Table 1.

The comparison of the calculated and experimental
spectra is presented in Fig. 5.

The shape of the spectra is qualitatively similar
despite the opposite position of the subharmonics.
The other reason for the appearance of the fine struc-
ture of the spectrum of Rabi oscillations can be a non-
uniform spatial distribution of the coherent \( e-h \) state
within the cavity and its division into two symmetric
parts. This issue requires an additional study.

To summarize, doublet optical spectra and corre-
sponding coherent oscillations of the electromagnetic
field generated by bulk GaAs/AlGaAs heterostruc-
tures during superradiance have been studied. It has
been demonstrated that superradiance exhibits strong
coupling of the field and medium in contrast to lasing
in the same samples when weak coupling exists. It has
been shown that strong coupling occurs under condi-
tions of the present experiment when only a large
enough number of \( e-h \) pairs condenses in phase
space. Rabi oscillations have been observed with a
spectral splitting in the range of 1.3–4.4 meV at
860–890 nm wavelengths. The corresponding coher-
ent oscillations of the electromagnetic field with fre-
quencies of up to 1.1 THz have been detected. The
experimental results are yet another convincing evi-

Table 1. Experimental data

| Sample | H11 | S03 | H16 | C13 | D07 | B08 |
|--------|-----|-----|-----|-----|-----|-----|
| Emission wavelength (nm) | 861 | 856 | 864 | 885 | 879 | 881 |
| Cavity length (micron) | 100 | 100 | 100 | 150 | 150 | 350 |
| Mode separation (nm) | 0.81 | 0.84 | 0.83 | 0.68 | 0.67 | 0.26 |
| \( Q \) | 1.35 \times 10^4 | 1.35 \times 10^4 | 1.35 \times 10^4 | 1.98 \times 10^4 | 1.97 \times 10^4 | 4.63 \times 10^4 |
| \( V (\text{cm}^{-3}) \) | 1.2 \times 10^{-10} | 1.2 \times 10^{-10} | 1.2 \times 10^{-10} | 1.8 \times 10^{-10} | 1.8 \times 10^{-10} | 4.2 \times 10^{-10} |
| \( k/2\pi \) (THz) | 0.74 | 0.74 | 0.74 | 0.50 | 0.50 | 0.21 |
| Spectral splitting (nm) | 1.79 | 2.72 | 2.52 | 0.84 | 2.49 | 2.37 |
| \( \Omega/2\pi \) (THz) | 0.72 | 1.09 | 1.01 | 0.32 | 0.97 | 0.91 |
| \( \Omega \) (meV) | 2.91 | 4.41 | 4.09 | 1.29 | 3.92 | 3.65 |

Fig. 4. Splitting between the doublet components versus
the reverse bias.
dence of $e\sim h$ condensation in bulk GaAs at room temperature discussed in our publications previously.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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