Quantum Switching of Spatial Modes in the 2D-Exciton Resonance Spontaneous Emission

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The effect of quantum switching (QS) of spatial modes in the resonance spontaneous emission of 2D excitons, whose detection is reported here, is a result of spatial coherence of the 2D excitons. This coherence determines their ability to interfere and necessitates the use of nonclassical statistics for description of physical properties and for interpretation of observable quantities upon manipulations with many-particle ensembles.

The discovery of the QS was favored, first of all, by the highest quality of the studied GaAs/AlGaAs structure with a 10-nm quantum well, which showed the width of the heavy-hole exciton (hh-X) peak Γ_{FWHM}=(0.17±0.02) meV coincident, to within the experimental error, with the hh-X energy relaxation rate Γ_1=(0.16±0.03) meV, extracted from dynamics of the pump-probe photoreflectivity. The second important point is that we used the scheme of the resonance phase conjugation on the surface in the studies of the dynamics and spectra of the four-wave mixing. In this scheme, the nonlinear polarization in the QW plane ρ(x,y): $P_y^{(3)}(\boldsymbol{\rho}) \propto \chi_{yyyy}^{(3)} E_{2y}^2 E_{1y}$, is induced by two light pulses spaced in time $\{E_{1y}(t)\exp(i\mathbf{k}_1\mathbf{r})+E_{2y}(t+t_D)\exp(i k_z z)+\text{c.c.}\}$, with the second one incident strictly normal to the plane ρ(x,y). Under these conditions, the polarization $P_y^{(3)}(\boldsymbol{\rho})$, induced at positive time delay t_D between the pulses 2 and 1, serves as a source of the field propagating in the direction inversed with respect to that of the pulse 1 ($-\mathbf{k}_1$). At small values of the pulse areas ($\theta_1,\theta_2 \ll 1$, $\theta_{1(2)}=\int_{-\infty}^{\infty}\frac{\mu_{\mathbf{q}(\mathbf{0})}E_{1(2)}}{\hbar}dt$, where $\mu_{\mathbf{q}(\mathbf{0})}$ is the transition dipole moment of the 2D-exciton with the wave vector $\mathbf{q}=\mathbf{k}_1-k_z$), and for the pulse widths ($\delta t_1=\delta t_2 \ll T_1$, where $T_1=\hbar/\Gamma_1$), the expected dependence of the time-integrated signal $I_{FWM}(-\mathbf{k}_1)$ has the form:

$$I_{FWM}(-\mathbf{k}_1) \propto \theta_1^2\theta_2^4\,\Theta(t_D)\exp(-t_D/T_1), \text{ where } \Theta(t_D) \text{ is the theta-function} \quad (1)$$

It was found, however, in strong contradiction with Eq. (1) and with the results of similar studies on structures of poorer quality, that the signal in the reversed direction, up to the values of $\theta_1^2=\theta_2^2$ corresponding to the mean 2D-exciton density $n_X \approx 5\times10^9$ cm^{-2}, is described by the dependence:

$$I_{SCE} \propto \theta_1\theta_2\exp(-|t_D|/\tau_{coh}) \quad (2)$$

with $\tau_{coh} \approx T_1/2$.

Based on the facts (i) that the only mechanism of emission with bilinear dependence on θ_1 and θ_2 is the spontaneous emission of a spatially modulated ensemble of 2D excitons and (ii) that the direction ($-\mathbf{k}_1$) enters the four symmetric directions of emission of the phased grating with the period d=2π/q at the 2D-exciton resonance frequency ω_0 ($\omega_0=ck$, k=$|\mathbf{k}_1|$), we come to a definite conclusion that the detected photoresponse is related to the spontaneous coherent emission of the 2D-exciton ensemble with the wave function $\psi(\rho)$, which can be presented in the form of two-mode superposition of the Anderson-type multi-boson functions $\psi(\rho) = f_1(\rho)\exp(i\mathbf{q}\rho) + f_2(\rho)$, where $f^2_{1(2)} = n_{1(2)}(\rho) = \theta^2_{1(2)}$. In this case, the time τ_{coh} should be regarded as the time of decoherence of the multi-boson ensemble.

By combining the energy conservation law, which determines the module of the wave vector of the emitted (absorbed) photon ($\omega_0 = ck$), with the phase-matching conditions, formulated as equality of the 2D-exciton wave vector (**q**) and in-plane component of the wave vector of the emitted (absorbed) photon ($\mathbf{k}_\rho$), we conclude that the directions of the spontaneous coherent emission of the 2D excitons under single-mode excitation coincide with the directions of a classical optical beamsplitter. This is why, the appearance of the I_{SCE} signal in the additional direction ($-\mathbf{k}_1$) under the two-mode excitation may be considered as the effect of quantum switching of spatial modes in the 2D-exciton spontaneous emission.