Nonlinear time-independent and time-dependent propagation of light in direct-gap semiconductors with paired excitons bound into biexcitons

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We study a new class of nonlinear cooperative phenomena that occur when light propagates in direct-gap semiconductors. The nonlinearity here is due to a process, first discussed by A. L. Ivanov, L. V. Keldysh, and V. V. Panashchenko, in which two excitons are bound into a biexciton by virtue of their Coulomb interaction. For the geometry of a ring cavity, we derive a system of nonlinear differential equations describing the dynamical evolution of coherent excitons, photons, and biexcitons. For the time-independent case we arrive at the equation of state of optical bistability theory, and this equation is found to differ considerably from the equations of state in the two-level atom model and in the exciton region of the spectrum. We examine the stability of the steady states and determine the switchover times between the optical bistability branches. We also show that in the unstable sections of the equation of state, nonlinear periodic and chaotic self-pulsations may arise, with limit cycles and strange attractors being created in the phase space of the system. The scenario for the transition to the dynamical chaos mode is found. A computer experiment is used to study the dynamic optical bistability. Finally, we discuss the possibility of detecting these phenomena in experiments.

1. INTRODUCTION

The paper written by Elesin and Kopaev,[1] on the optical hysteresis of excitons was followed by numerous theoretical and experimental investigations.[2–9]

The interest in optical bistability caused by excitons and biexcitons in condensed media is due the interest in the giant optical nonlinearities at the long-wave intrinsic absorption edge of the crystal spectrum, short relaxation times, and low switchover energies and short switchover times between the optical bistability branches.

More than that, in the unstable sections of the optical bistability curve, regular and chaotic self-pulsations may arise in the system of excitons, photons and biexcitons. All of this opens possibilities for studying essentially new optical phenomena that involve excitons and biexcitons and in using these phenomena for practical purposes, primarily for optical processing of data and for building new-generation computers with optical logical circuits.

In Refs. 10–22 we constructed a theory of optical bistability, optical switchover, and regular and stochastic oscillations accompanied by the formation of classical and strange attractors in the phase space of excitons, photons, and biexcitons.

The possibility of optical multistability in a system of coherent excitons and biexcitons being induced by noise was predicted in Refs. 23 and 24.

It must be noted, however, that in Refs. 5, 6, 18 and 19 optical bistability was studied only with allowance for the huge oscillator strength of the exciton–biexciton transition,[25–27] i.e., only the process of creation of a biexciton $\mathbf{p}$ through the absorption by an exciton $\mathbf{q}$ of a photon $\mathbf{p}-\mathbf{q}$ was taken into account. Ivanov *et al.*[28,29] were the first to show that there is also another process, determined by the term

$$\frac{1}{\sqrt{V}}M(p,q)b_p^\dagger a_\mathbf{q}a_{\mathbf{p}-\mathbf{q}},$$

which describes direct binding of two excitons, $\mathbf{p}-\mathbf{q}$ and $\mathbf{q}$, into a biexciton by virtue of the Coulomb attraction of the excitons. Actually, in Refs. 28 and 29 an essentially new mechanism of the exciton–biexciton transformation of the semiconductor spectrum was proposed, i.e., the formation of a biexciton through direct Coulomb binding of two excitons. In particular, it was found that this mechanism effectively shifts both exciton and biexciton levels toward the long-wave part of the spectrum.

The present paper studies time-independent and time-dependent optical bistability, the phenomena of optical self-oscillations and switchover when the exciton–photon interaction and the Coulomb binding of two excitons into a single biexciton introduced in Refs. 28 and 29 are taken into account. The Heisenberg equations of motion for excitons and biexcitons and a wave equation for the field are used to derive a system of nonlinear differential equations describing the dynamical evolution of the system. In the time-independent (stationary) case we derive an equation of state of the optical bistability theory. We also study the stability of time-independent solutions and predict the formation of regular and chaotic self-pulsations. The scenario of the transition to dynamic optical chaos is established, and we discuss