AUTLER–TOWNES EFFECT ON THE EXCITONS AND BIEXCITONS IN SEMICONDUCTORS

P. I. Khadzhi[1], L. Yu. Nadkin[2], D. V. Tkachenko[2]

[1]Institute of Applied Physics, Academy of Sciences of Moldova, Kishinev, 2028, Moldova;

[2]Dniester State University, Tiraspol, MD 3300, Moldova. e–mail: tdsu4@idknet.com

Abstract: The behavior of the semiconductor dielectric susceptibility under the stationary action of a strong laser pulse in the range of M–band of luminescence and the test pulse in the exciton range of spectrum is investigated. The well pronounced Autler–Townes effect occurs at the exciton range. The position of the absorption peaks is determined by the amplitude and frequency of pump pulse.

1. INTRODUCTION

The optical Stark–effect in semiconductors in the exciton range of spectrum is one of the brightest nonlinear optical effects [1–3]. The interpretation of this effect, based on the idea of Bose–Einstein condensation of excitons induced by an external coherent laser radiation, was proposed in [2,3]. The absorption and gain of a weak test signal in the presence of Bose–condensed excitons due to the field of coherent laser radiation were investigated in [1,4,5]. In connection with the experimental investigations of the optical properties of semiconductors in the exciton range of spectrum at high level of excitation the pump–probe approach has acquired a special significance. This approach is based on the use of two beams of laser radiation, namely the strong pump and the weak test beams. The weak beam tests the changes of the optical properties of crystal, which occurred due to the action of the strong pump beam. This approach was used for the experimental investigation of the radiative recombination and nonlinear response of high density system of excitons and biexcitons [6–8], the red and blue shifts of the exciton resonance in the condition of picosecond pumping [9–12] and the analogy of the Autler–Townes effect on the biexcitons in CuCl [13]. The theory of this effect was proposed in [14, 15]. The well pronounced splitting of the biexciton absorption band in CuCl into two separated lines at high level of excitation was observed experimentally [13]. From the obtained value of the splitting the authors of [13] determined the value of the relevant dipole momentum in the range of M–band of luminescence due to the optical exciton–biexciton conversion. The idea about the observation of this splitting was firstly proposed in [16].

The different aspects of the pump–probe approach for the high density system of excitons and biexcitons were considered in [1, 4, 5, 14–18].

2. STATEMENT OF THE PROBLEM AND MAIN EQUATIONS

Let the strong monochromatic wave (pump pulse) of coherent laser radiation with the amplitude E_0 and frequency $\omega_l \approx \Omega_0 - \omega_0$ tuned to the transition between the exciton and biexciton states and the weak wave (test pulse) with the amplitude E and frequency $\omega \approx \omega_0$ incident on the semiconductor like CuCl. Here the Ω_0 and ω_0 are the self–frequencies of exciton and biexciton states respectively. As far as the pump pulse frequency is tuned to the transition between the exciton and biexciton states, the two excited states are mixed to create the dressed states. This corresponds to the Autler–Townes effect. The pump pulse is set below the exciton absorption band and we can observe the coherent effect in the steady state regime. The photons of pump pulse change the semiconductor energy spectrum

essentially and the photons of the weak pulse probe these changes in the exciton range of spectrum.

The Hamiltonian of interaction of excitons and biexcitons with light in the resonant approximation we can write in the form

$$H = -\hbar g(E^+ a^+ e^{-i\omega t} + E^- a e^{i\omega t}) - \hbar\sigma(E_0^- a^+ b e^{i\omega_l t} + E_0^+ a b^+ e^{-i\omega_l t}), \qquad (1)$$

where a and b are the exciton and biexciton polarization waves of the medium respetively, g is the constant of exciton–photon interaction, σ is the constant of optical exciton–biexciton conversion [20], $E_0^+\left(E^+\right)$ and $E_0^-\left(E^-\right)$ are the positive and negative frequency components of the fields of pump (probe) pulse.

We investigate the response of the system in all orders of the perturbation theory for the pump amplitude E_0 and the first order for the test amplitude E in the steady state. From (2) and (3) we can obtain the expression for the stationary amplitudes a and b, and then for the polarization of medium and finally we derive the following expression for the susceptibility χ of medium:

$$\chi = -\hbar g^2\left(\Delta + i\gamma_1 - \sigma^2 E_0^2(\Delta + \Delta_l + i\gamma_2)^{-1}\right)^{-1}, \qquad (4)$$

where $\Delta = \omega - \omega_0$, $\Delta_l = \omega_l - \Omega_0 + \omega_0$ are the detunings. Introducing the normalized variables $\delta = \Delta/\gamma_1$, $\delta_l = \Delta_l/\gamma_1$, $s = \gamma_2/\gamma_1$, $f_0 = \sigma E_0/\gamma_1$ and $\chi_0 = \hbar g^2/\gamma_1$ we obtain from (4) the following expressions for the dispersive (real) χ' and absorptive (imaginary) χ'' components of the susceptibility

$$\frac{\chi'}{\chi_0} = -\left(\delta - (\delta+\delta_l)\frac{f_0^2}{(\delta+\delta_l)^2+s^2}\right)\left(\left(\delta - (\delta+\delta_l)\frac{f_0^2}{(\delta+\delta_l)^2+s^2}\right)^2 + \left(1 + s\frac{f_0^2}{(\delta+\delta_l)^2+s^2}\right)^2\right)^{-1}, \qquad (5)$$

$$\frac{\chi''}{\chi_0} = \left(1 + s\frac{f_0^2}{(\delta+\delta_l)^2+s^2}\right)\left(\left(\delta - (\delta+\delta_l)\frac{f_0^2}{(\delta+\delta_l)^2+s^2}\right)^2 + \left(1 + s\frac{f_0^2}{(\delta+\delta_l)^2+s^2}\right)^2\right)^{-1}. \qquad (6)$$

3. DISCUSSION

Now we will discuss the behavior of the absorptive component of susceptibility (absorption band of the weak pulse in the exciton range of spectrum) depending on the resonance detuning δ in the conditions, when the photons of the pump pulse are in the exact resonance at the frequency of M–band ($\delta_l = 0$, $\omega_l = \Omega_0 - \omega_0$). At low level of excitation the absorption band has the Lorentz–like shape $\chi''/\chi_0 = (1+\delta^2)^{-1}$ with the maximum at $\delta = 0$.

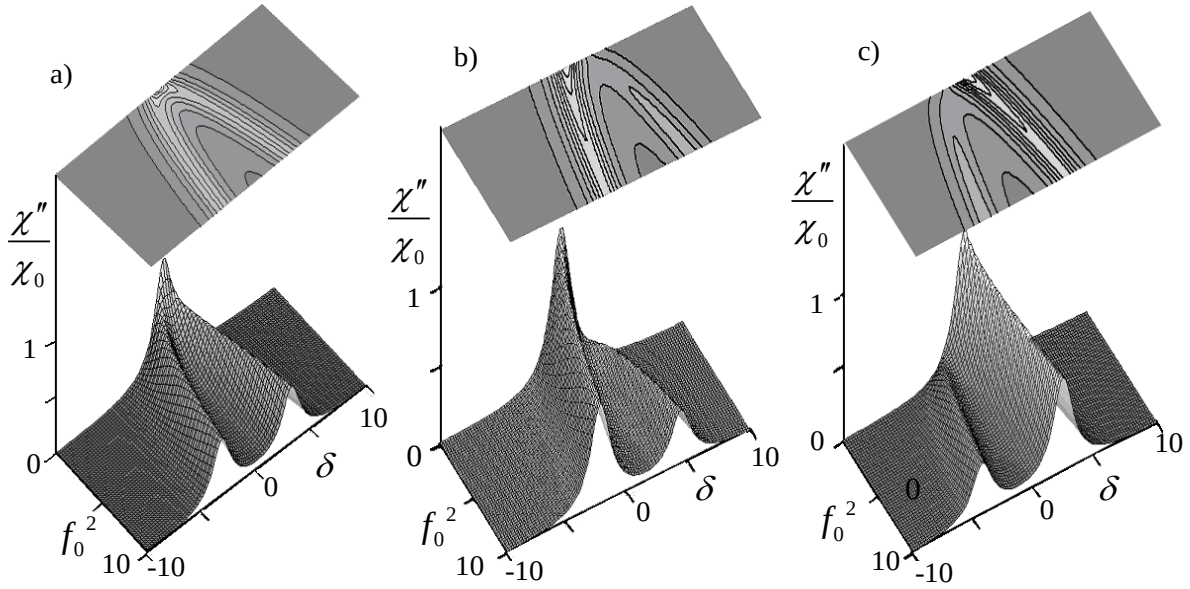

Fig. 1. The absorptive component of the susceptibility χ'' depending on the resonance detuning δ and pump field intensity f_0^2 for the different fixed pump detuning δ_l, which equals to a) 0, b)–2 and c) 2.

The amplitude of the absorption peak rapidly decreases and the half-width of the absorption band increases, when the pump amplitude f_0 increases. The radical transformation of the spectral shape of the absorption band takes place when intensity of pump pulse approaches the value $f_0^2 = s^3/(1+2s)$ (Fig. 1a). The central peak at $\delta = 0$ in this case converts into the minimum and two new symmetrical absorptive peaks appear at the detunings $\delta_{\pm} = \pm\left[(1+s) f_0 \sqrt{f_0^2 + s} - s(f_0^2 + s)\right]^{1/2}$. The new absorptive peaks move apart and their amplitudes decrease monotonously, when the pump amplitude f_0 increases (Fig. 1a). The exciton level splits into two quasilevels, which more and more move apart from the former position of the exciton level with the increasing of f_0.

If the photons of the pump pulse have the nonzero resonance detuning ($\delta_l \neq 0$), then it takes place the appreciable nonsymmetrical (relatively to $\delta = 0$) renormalization of the absorptive component of the susceptibility χ'' (Fig. 1b, c) due to the peculiarities of the dispersion law. In the

absence of the pump field ($f_0 = 0$) the absorptive band as before has the symmetrical Lorenz–like shape.

4. REFERENCES

[1] Moskalenko S.A., Snoke D.W. *Bose–Einstein condensation of excitons and biexcitons and coherent nonlinear optics with excitons.* (Cambridge University Press, 2000).

[2] Schmitt–Rink S., Chemla D.S., Haug H. *Phys. Rev. Lett* **52**, 2752 (1986).

[3] Schmitt–Rink S., Chemla D.S., Haug H. *Phys. Rev. B,* **37**, 941 (1988).

[4] Moskalenko S.A., V.G. Pavlov. JETP, **112,** 167 (1997).

[5] Moskalenko S.A., Pavlov V.G., Misko V. R. *FTT*, **40,** 924 (1998).

[6] Leonelli R., Manar A., Grun J. B., Hönerlage B. *Phys. Rev. B,* **45**, 4141 (1992).

[7] Smith G. O., Mayer E.J., Kuhl J., Ploog K. *Solid State Commun.* **92**, 325 (1994).

[8] Finkelstein G., Bar-Ad S., Carmel O., Bar-Joseph I., Levinson Y. *Phys. Rev. B,* **47**, 12964 (1993).

[9] Hulin D., Joffre M. *Phys. Rev. Lett*. **65**, 3425 (1990).

[10] Fröhlich, Nöthe A., Reimann K. *Phys. Rev. Lett.* **55**, 1335 (1985).

[11] Peyghambarian N., Gibbs H.M., Jewell J. L., Antonetti A., Migus A., Hulin D., Mysyrowicz A. *Phys. Rev. Lett.* **53**, 2433 (1984).

[12] von Lehmen A. Chemla D.S., Zucker J. E., Heritage J. P. *Opt. Lett.* **11**, 609 (1985).

[13] Shimano R., Kuwata-Gonokami M. *Phys. Rev. Lett*. **72**, 530 (1994).

[14] Khadzhi P.I., P.I. Corovai P.I., P.I. Tkachenko P.I. *FTT*, **44**, 744 (2002).

[15] Khadzhi P.I., Corovai A.V., Korovai O.V., Tkachenko D. V. *Moldavian J. Phys. Sci.* **1**, 152 (2002).

[16] Hanamura E., *Phys. Rev. B,* **44**, 8514 (1991).

[17] Agarwal G.S.. *Phys. Rev. A*, **51**, R2711 (1995).

[18] Khadzhi P.I., Tkachenko D.V.. *FTT* **40**, 934 (1998).

[19] Khadzhi P.I. *Nonlinear optical processes in the system of excitons and biexcitons in semiconductors.* (Kishinev, Shtiintsa, 1985).