OPTICAL BISTABILITY IN TRANSMISSION OF THIN SEMICONDUCTOR FILM WITHOUT EXTERNAL FEEDBACK

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ABSTRACT: The optical bistability phenomenon in the steady-state light transmission by a thin semiconductor film is studied taking into account two-pulse two-photon excitation of biexcitons from the ground state of the crystal. It is shown that the transmission of one of the two pulses by the film is determined by the intensity of the second pulse. The criteria of existence of an optical bistability are established.

Keywords: *biexciton, pulse, bistability*

1. INTRODUCTION

It is known that a wide spectrum of nonlinear optical effects, including cavity-free optical bistability, can appear in the thin semiconductor films (TSF). The thin film approximation (the film thickness L is much less than the light wave length λ) allows us to convert the system of nonlinear partial differential equations for the field and medium to the simple system of the ordinary differential and algebraic equations. Below we present the main results of the investigation of the optical bistability in the light transmission by TSF, which brightly show the possibility of the transmission control of one beam by the second beam.

2. BASIC EQUATIONS. DISCUSSION OF RESULTS.

We assume that a TSF located in vacuum is exposed by two normally incident monochromatic laser pulses with the electric field envelopes $E_{i1}(t)$ and $E_{i2}(t)$ slowly varying in time and with the frequencies ω_1 and ω_2 respectively. Let the sum of the both photons coincides with the self-energy of the biexciton excitation from the ground state of the crystal. In this case if $\omega_1 \neq \omega_2$ only the process of two-pulse two-photon biexciton excitation takes place. The process of a single-pulse two-photon biexciton excitation is not possible because of a great resonance detuning. Such a situation can take place in the crystal like CuCl, in which the biexciton binding energy is of the order of 40 meV and the oscillator strength is giant. This property may favour the appearance of the optical nonlinearities even at moderate levels of excitation of a crystal. In following we shall ignore the interparticle interaction effects. The coherent photons of both pulses pair by pair excite the coherent biexcitons in the TSF, the radiative recombination of which is responsible for the formation of the secondary radiation generated by the film.

Using the threelinear Hamiltonian of the biexciton interaction with the fields of both pulses we can write the material equation for the amplitude $b(t)$ of biexciton polarization of the medium

$$i\dot{b} = -(\Delta + i\gamma)b - \mu E_1^+ E_2^+ , \tag{1}$$

where μ is the constant of two-photon biexciton excitation, $\Delta = \omega_1 + \omega_2 - \Omega_0$ is the resonance detuning, Ω_0 is the self-frequency and γ is the phenomenologically introduced damping constant of biexcitons. Following from the boundary conditions of the tangential field components conservation through the film-vacuum interface we obtain the system of electrodynamic equations for the transmitted fields E_1 and E_2 of pulses depending on the amplitudes E_{i1} and E_{i2} of the incident pulses

$$E_1^+ = E_{i1} + i\alpha\mu b E_2^-, \quad E_2^+ = E_{i2} + i\alpha\mu b E_1^- , \tag{2}$$

where $\alpha = 2\pi\hbar\Omega_0 L/c$, L is the film thickness. Further we consider the amplitudes E_{i1} and E_{i2} as the real quantities. The constant μ can be define by the expression $\mu E_c = g$, where g is the constant of the exciton-photon interaction. The characteristic field E_c we determine from the equation: $E_c^2/8\pi = \hbar\Omega_0 N_c/2$. For the crystal like CuCl, CdS the value of N_c is equal to 10^{15} cm^{-3}.

Next we shall introduce the dimensionless quantities

$$b = a\left(E_c/\alpha g\right),\ E^\pm = E_c f^\pm,\ E_{i1,2} = E_c f_{i1,2},\ \Delta = \delta/\tau_0,\ \gamma = \Gamma\tau_0,\ \tau_0^{-1} = \alpha g^2, \tag{3}$$

where τ_0 is the characteristic response time of the film on the external field. Then the system of equations (1)-(2) in the steady-state regime has the form:

$$\left(\delta + i\Gamma\right)a + f_1^+ f_2^+ = 0, \tag{4}$$

$$f_1^+ = f_{i1} + iaf_2^-,\ f_2^+ = f_{i2} + iaf_1^- . \tag{5}$$

For the normalized intensities $I_1 = f_1^+ f_1^-$, $I_2 = f_2^+ f_2^-$ transmitted through the film depending on the normalized intensities I_{i1} and I_{i2} of the incident pulses we obtain the following expressions

$$I_1 \frac{\delta^2 + \left(I_2 + \Gamma\right)^2}{\delta^2 + \Gamma^2} = I_{i1}, \tag{6}$$

$$I_2 \frac{\delta^2 + \left(I_1 + \Gamma\right)^2}{\delta^2 + \Gamma^2} = I_{i2}. \tag{7}$$

Substitution of (7) into (6), for example, gives the possibility to obtain the complete equation for the transmitted intensity of the first pulse depending on the intensities I_{i1} and I_{i2} of incident pulses:

$$I_1\left[\delta^2+\left(\Gamma+\frac{I_{i2}\left(\delta^2+\Gamma^2\right)}{\delta^2+\left(I_1+\Gamma\right)^2}\right)^2\right]=I_{i1}\left(\delta^2+\Gamma^2\right). \qquad (8)$$

By the substitution $1 \leftrightarrow 2$ in (8) we can obtain the analogous expression for the intensity I_2.

For the crystal like CuCl $\tau_0 \sim 10^{-13}s$. Taking the damping constant γ of the biexcitons in the limits from 10^{10} s^{-1} to 10^{12} s^{-1} we obtain that the normalized constant Γ changes in the limits from 10^{-3} to 10^{-1}. That is why further we take $\Gamma=0$. The steady-state regime in the system is settled during the time of order of τ_0. This is explained by the fact that the radiation rapidly leaves the film. In this case the formula (8) takes the form

$$I_1\left[1+\frac{\delta^2 I_{i2}^2}{\left(\delta^2+I_1^2\right)^2}\right]=I_{i1}. \qquad (9)$$

The dependence $I_1\left(I_{i1}\right)$ is the transmission function of the first pulse, where the pump intensity I_{i2} of the second pulse and the detuning δ are the parameters. From (9) we can see that it is possible to scale all quantities by δ. If we introduce new variables $J_{i1,2}=I_{i1,2}/\delta$, $J_{1,2}=I_{1,2}/\delta$, then the formula (9) may be presented in a simple form

$$J_1\left[1+\frac{J_{i2}^2}{\left(1+J_1^2\right)^2}\right]=J_{i1}, \qquad (10)$$

which does not contain the detuning δ. The normalized pumping J_{i2} we can consider as the bistability parameter. If $J_{i2}<2$ the transmission function $J_1\left(J_{i1}\right)$ is the nonlinear but single-valued function of J_{i1}. If the bistability parameter $J_{i2}>2$ the transmission function appears to be three-valued depending on J_{i1}. For $J_{i2}=2$ the function $J_1\left(J_{i1}\right)$ has a region of a steep change, namely the region of the differential gain. The transmission function $J_1\left(J_{i1}\right)$ exists in the fold between the straight lines $J_1=J_{i1}$ and $J_1=J_{i1}\left(1+J_{i2}^2\right)^{-1}$. When the intensity J_{i1} of the incident pulse increases, the representative point moves at first along the lower branch of the hysteretic curve $J_1\left(J_{i1}\right)$, where the transmission is very small, then in the point, where the tangent becomes vertical line to the hysteretic curve it takes place the jump to the upper branch of the curve, which leads to the steep bleaching of the film in transmission. The more the value of J_{i2}, the more the jump intensity of the transmitted radiation at the critical point. If the intensity of incident radiation J_{i1} decreases, the representative point firstly moves down along the upper branch of the hysteretic curve, then the jump to the lower branch appears, which leads to the steep darkening in the film transmission. The appearance of the bistable behavior of the transmission function $J_1\left(J_{i1}\right)$ means that it takes place the bistability in the dependence on the intensity J_{i1} at fixed δ or on the detuning δ (chirping of the incident pulse) at fixed J_{i1}.

If we study the dependence $J_2\left(J_{i1}\right)$ (the transmission of the second pulse) at the fixed values of J_{i2}, we obtain the hysteretic transmission too. But in this case the representative point moves firstly along the upper branch of the hysteretic curve, then the jump occurs to the lower branch, which leads to the abrupt darkening of the film in the transmission. The jumps from one branch to the other one take place at the same values of the incident intensity J_{i1}.

It is seen from (8) that the parameter Γ influences on the behavior of the transmission function so as the increase of this parameter makes worse the condition of the existence of bistable transmission.

We point out that the transmission function $J_2\left(J_{i2}\right)$ at the fixed values of J_{i1} is characterized by the same peculiarities, as the function $J_1\left(J_{i1}\right)$ at the fixed J_{i2}.

3. CONCLUSION

It follows from the presented results that the light transmission of one of pulses depending on the incident intensity of the second pulse is determined by the incident intensity of this pulse, which gives the favourable possibility for the controlling of light transmission by the light of the other beam. The bistability parameter for the first pulse is the incident intensity of the second pulse.