Ultrafast acoustic switching of an optically pumped cavity polariton system in the bistable regime

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Abstract. Nonequilibrium transitions are investigated in a plane exciton-polariton system with complex acousto-optical excitation: stationary resonant optical excitation of polaritons along the normal to the surface of the resonator and picosecond strain pulses causing reversible exciton energy perturbations. It is shown that acoustic pulses can be used for ultrafast switching of the optical response of a bistable polariton system. Switching is experimentally implemented in a high-Q GaAs microcavity.

1. Introduction

Excitonic polaritons in semiconductor microcavities (MCs) are half-light-half-matter boson quasiparticles. They are formed due to the strong coupling of the cavity and exciton modes in the active MC layer, inherit a very small effective mass and macroscopic coherence length from the cavity photons and a high interaction rate from excitons, and exhibit collective properties characteristic of both matter and light waves [1,2].

Due to the small effective mass, polaritons exhibit quantum coherent properties at relatively low densities, when the polariton system is a weakly nonideal Bose gas with repulsive pair interaction. [2] In the case of resonant coherent excitation, slightly exceeding the low polariton (LP) energy, the nonlinearity of the LP system arising due to the repulsive interparticle interaction can lead to its optical bi- or multistability at critical points with changing number and/or stability of the possible stationary solutions, small field fluctuations can lead to fast nonequilibrium transitions between the stability branches[3-6].

An important difference between the resonantly excited LP fluids in high-Q MCs from widely investigated nonlinear optical systems is that the renormalization of the LP level, $E_{LP}$, may exceed its spectral width even at relatively low excitation densities $P$. As a result, the blue shift of the polariton resonance energy turns out to be the main cause of the nonlinearity of the LP systems.
Recently, the possibility of switching between the stability branches at a fixed P with a short-term detuning perturbation $D=i\hbar \omega - E_{LP}$ was theoretically considered in Ref. 7. It was predicted that reversible picosecond disturbances of $E_{LP}$ can lead to ultra-fast switching between the stability branches of a bistable LP system. In this paper, we experimentally investigate the possibility of switching a resonantly excited LP system from the lower to the upper stability branch in GaAs-based planar MCs by picosecond strain pulses, which cause reversible change of exciton energy $E_X$ in a time scale of several picoseconds. To generate picosecond strain pulses, we used a 200-fs violet laser pulses [8,9]. The experiment shows that the strain pulses can be used for controlled switching of the transmitted signal in high-Q MCs by more than an order of magnitude in a hundred ps time scale.

2. Theoretical model

The LP condensate is described by the wave function $\psi$, whose amplitude is proportional to the electric field density in the active MC layer. For simplicity, consider the model of a spinless LP system. Such an approximation is justified in the case of circularly polarized pumping, when the LPs inherit and retain the circular polarization of the pumping. In the case of a strictly constant pumping system. Such an approximation is justified in the case of circularly polarized pumping, when the LPs sets of four 10-nm-thick In$_{0.05}$Ga$_{0.95}$As quantum wells (QWs) separated by 10-nm-thick GaAs barriers. 25 and 29 AlAs and GaAs pairs in the top and bottom Bragg mirrors ensured the high Q factor of the MC resulting in the LP decay rate $\gamma \sim 15 \mu$ eV. The Rabi splitting $R \approx 7.5$ meV.

In planar MCs the dependence of $|\psi|^2$ on $|f|^2$ gets more complicated because the driven $k=0$ mode can scatter into states with $k \neq 0$. This scattering leads to the gradual accumulation of LP energy in $k \neq 0$ states resulting in an additional blue shift of the LP resonance and lowering the critical value of $|f|^2$ for the LP system transition to the upper stability branch at the cost of extending the transition latency period. The minimum $|f|^2$ for the upper transition is decreased to $|f|^2 = \frac{1}{\gamma^2} \frac{(D_D)^2 \gamma^2}{|V|}$.

The intermode scattering into states with nonzero $\vec{k}$ can be neglected only at the times much shorter than the latency period at the used $|f|^2$. Thereby in the experiment we have to use $|f|^2 < |f|^2$.
LP emission was registered using a streak camera in transmission geometry to avoid any contribution from the scattered laser beam. The experiments were performed at $T=4$ K.

The subTHz frequency modulation of the LP resonance was achieved using strain pulses generated in a 0.35-mm-thick GaAs substrate by 200-fs light pulses from a frequency doubled Ti-sapphire laser ($\lambda=400$ nm, repetition rate 5 kHz) focused to a spot with a diameter $\sim 0.15$ mm. The violet pulse is absorbed in the near-surface region of the GaAs and generates a bipolar picosecond strain pulse. [9]

The strain pulse propagates through the GaAs substrate and bottom Bragg mirror with the sound velocity $s=4.8\times10^3$ m/s, reaches the MC active layer in $\sim 73$ ns and shakes the QWs, then reaches the boundary MC-air, reflects and in $\sim 1.5$ ns again shakes QWs. The calculated time dependence of the strain pulse amplitude $v(t)$ in the middle of active layer of the MC at $W=1.6$ mJ/cm$^2$ is shown in the insert in Fig. 1. Details of the calculations can be found elsewhere [9]. The strain pulse arriving at In$_{0.05}$Ga$_{0.95}$As QW causes a change in the exciton and, hence, polariton energy.

4. Experimental results and discussion

Figure 1 shows the dependence $I_{LP}(t)$-|$\psi|^2(t)$ in a range of times when the strain pulse created by the fs laser pulse with $W=1.6$ mJ/cm$^2$ perturbs $E_x$. It shows that the incident strain pulse causes a weak short-term increase in $I_{LP}$, whereas the reflected pulse realizes an irreversible switching of the signal to the upper branch of stability with an $I_{LP}$ increase of about 13 times in less than 250 ps.

To answer the question why the reflected rather than incident strain pulse leads to the irreversible signal switching let us consider the structure of these pulses in more detail. Insert in Fig. 1 shows that the strain pulse generated by a violet femtosecond laser pulse is bipolar and highly asymmetric: the amplitude of its earlier (compressive) peak is markedly smaller than that of the final (tensile) peak [9]. The transition of LP system to the upper stability branch is initiated by the blue shift of $E_{LP}$, i.e. by the compressive peak. The tensile peak following the compressive one in the incident pulse causes the red shift of $E_{LP}$ and, therefore, prevents the switching. The subsequence of peaks in the reflected strain pulse is opposite, it ends with a compressive peak with an amplitude almost twice the amplitude of the compressive peak in the direct pulse, which explains the much higher efficiency of the reflected pulse.

The duration of the perturbation of $E_{LP}$ by the strain pulse ($\sim 50-100$ ps) is longer than the switching time between the stability branches, $\tau_{sw}=\hbar/\gamma=40$ ps [11]. Therefore, to explain the switching observed, we will consider the stationary response functions $V[I\psi^2,|\alpha|^2f^2]$ with instantaneous perturbations of $D$.

The calculated S-shaped dependences of $V[I\psi^2]$ at several $D$ are displayed in Fig. 2. From the dependence $V[I\psi^2]$ vs $|\alpha|^2f^2$ at $D=140$ meV, it follows that the observed 13-fold increase in $I_{LP}$ when the LP system is switched to the upper stability branch at $t=74.6$ ns occurs.

**Figure 1.** Time evolution of the LP emission in the time range of excitation with strain pulses The insert shows the time dependence of strain in the middle of the active layer caused by arriving of the incident and reflected strain pulses. $t=0$ ns corresponds to the moment when the femtosecond laser pulse excites the substrate backside.

**Figure 2.** S-curves calculated for various $D$: initial ($D=140$ $\mu$eV, black line) and produced in the experiment by the incident (blue) and reflected (red) strain pulses. The numbered arrows indicate the subsequence of the LP system evolution caused by the reflected strain pulse.
at |α|^2/β^2=F_3=0.06 eV^2/cm^2<F_4^* (D=140 μeV)=0.1 eV^2/cm^2. Further, a short-term increase in the ILP by half, caused by the compression peak in the incident pulse at t=73.2 ns, is realized when D decreases to ~115 μeV (point A in Fig. 2), i.e. this peak causes ΔEILP ~25 μeV. (An independent estimate of ΔEILP for W = 1.6 mJ/cm^2, based on the data from [9] with taking into account the fact that the strain pulse simultaneously compresses only half of the 12 quantum wells in the MC, gives a very close value of ~20 μeV.)

The scheme of transitions in the LP system caused by a reflected pulse is shown in Fig. 2. Insert in Fig. 1 shows that the compression peak in the reflected strain pulse is twice as large, while the tension peak is almost equal to the compression peak in the incident pulse. Thereby they should result in ΔEILP ~50 and ~25 μeV, or D=165 and 90 μeV, respectively. The leading stretching peak, which causes a short-term increase in D to 165 μeV, leaves the LP system in a lower stability branch (arrow “1”). The following compression peak, which causes a short-term decrease in D to 90 μeV, leads to a fall of F_4 to 0.04 eV^2/cm^2, which is lower than F_3=0.06 eV^2/cm^2 and, thus, initiates the transition of the LP system to the upper stability branch with V|ψ|^2(D=90 μeV) ~130 μeV (arrow “2”) so that the LP system turns out in the region of attraction of the upper stability state corresponding to D = 140 μeV and, finally, remains on it after the end of the strain pulse (arrow “3”). Figure 1 shows that ILP increases by an order of magnitude in less than 250 ps. Taking into account that the dependence ILP(t) was recorded with a time resolution of 200 ps, the actual switching time τsw is within 100 ps, which is in an agreement with theoretically predicted τsw~ℏ/γ~40 ps [11].

5. Conclusion.

In conclusion, an ultrafast controlled switching between the stability branches of the bistable LP mode by picosecond-long strain pulses causing reversible perturbations of exciton energy was experimentally investigated in the high Q GaAs based MC under fixed resonant excitation above the LP resonance. A 13-fold enhancement of ILP was obtained, the switching time being less than 100 ps. The switching by strain pulses is possible at D>3γ.

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