Polarization controlled nonlinear transmission of light through semiconductor microcavities

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We report on a pronounced nonlinear optical effect in a GaAs microcavity operating in the strong-coupling regime: cavity transmission in circular polarization is found to be much stronger than in linear polarization. This behavior has its origin in the spin-dependent repulsive interaction between exciton polaritons. Quantitative analysis allows estimating the strength of interaction between polaritons with parallel spins. The observed effect shows the potentiality of microcavities for circular polarization sensing essential for transmission of polarization encoded signals.

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I. INTRODUCTION

It is well known that a circularly polarized light wave can be represented as a linear combination of two linearly polarized light waves. The intensity of a circularly polarized light transmitted through any optically passive media cannot exceed the sum of intensities of its linear components transmitted independently, in linear optics. In nonlinear optics, it is not necessarily so, in principle, but deviations from this rule are very rare and require sophisticated installations like nonlinear optical loop mirrors.[1] Here we show that in conventional planar semiconductor microcavities, the nonlinear transmission in a circular polarization (right or left) may strongly exceed the transmission in any linear polarization.

Semiconductor microcavities in the strong-coupling regime demonstrate remarkable nonlinear optical effects including the parametric amplification and oscillation of light,[2,3] polariton lasing,[4,5] and Bose-Einstein condensation,[6] self induced Faraday rotation,[7] etc. All these effects are due to polariton-polariton interactions. Exciton-polaritons, mixed light-matter quasiparticles,[8] interact via the excitonic part of their wave-functions,[9] which results in the elastic polariton-polariton scattering and in the blueshift of the polariton eigenfrequencies.[10] Despite of an impressive theoretical effort, the interactions of exciton-polaritons still remain poorly understood. The complication comes from their apparent spin-dependence: there are strong experimental indications that polaritons with parallel spins interact with each other much stronger than polaritons with anti-parallel spins,[10–12] while the values of interaction constants and their wave-vector dependence are still a subject to debate.[13]

Here we report a surprising nonlinear optical effect in a microcavity: the transmission of the cavity in circular polarization is much stronger than in linear polarization. The system does not show significant optical birefringence or dichroism, the transmission in X-linear and Y-linear polarizations is nearly the same both at low and high excitation power. On the other hand, at strong excitation,[14] the transmission of light in any circular polarization is significantly stronger than in any linear polarization. Besides this, the shape of the transmission spectra in linear and circular polarizations is different. These surprising effects may originate from the polarization dependence of the blueshift of the exciton states in the system. We propose a simple model, where different blueshifts in linear and circular polarizations result in different detunings between exciton and photon modes in a microcavity. This has a dramatic impact on the transmittivity. The potentiality of microcavities as circular polarization sensors is straightforward from these measurements.

II. EXPERIMENT

We have studied two samples containing GaAs $\lambda/2$ cavities sandwiched between $AlAs/Al_{0.1}Ga_{0.9}As$ Bragg mirrors (22/28 and 23/29 pairs for samples 1 and 2, respectively), grown on GaAs substrates. An $In_{0.05}Ga_{0.95}As$ quantum well of 8 nm width has been embedded in the center of each cavity, at the electric-field antinode position. Both samples have been grown on a wedge but have different cavity thickness gradients (9 and 3 meV/mm). In the strong-coupling regime, the cavities show the vacuum field Rabi splittings of 3.3 and 3.8 meV, respectively.

In order to study the polarization-resolved transmission, we illuminate the sample with the square pulses of light of 12 meV spectral width, obtained by spatial filtering of 150 fs pulses of a Ti-Sapphire laser. The helicity of the incident

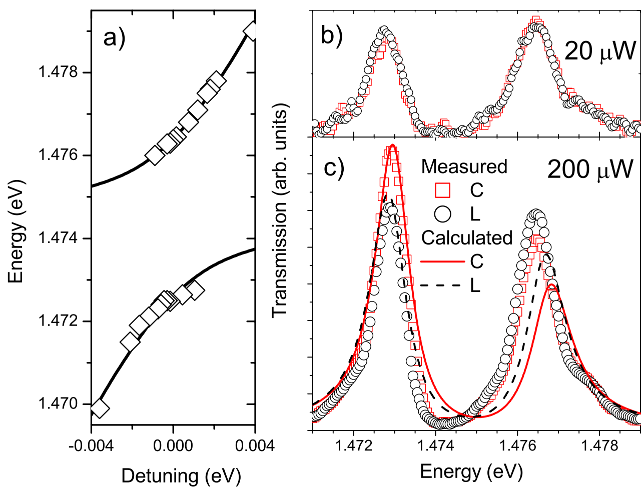

FIG. 1. (Color online) The energies of the lower and upper polariton modes, as functions of the detuning between exciton and cavity modes, obtained from transmission spectra. Solid lines are fit within the coupled oscillators model (a). Transmission spectra at (b) 20 and (c) 200 μW in linear (squares) and circular (circles) polarizations. Solid lines show the results of calculation using the transfer-matrix method.

light is modulated between circular and linear polarizations using an elasto-optical modulator. It modulates the retardation between two orthogonal components of linear polarization between $-\pi/2$ and $\pi/2$ at $f=50$ kHz frequency. Measuring differential signal at frequency 2 f (circularly minus linearly polarized) and total signal (circularly plus linearly polarized) allows recovering simultaneously the transmission in both linear and circular polarizations. The light beam at normal incidence is focused at 25-μm-diameter spot on the sample surface. The intensity of light transmitted within the solid angle of 1.5° is detected using a photomultiplier and spectrally resolved by a monochromator. The sample is placed in the cold finger cryostat at 4 K. The nonlinear effects discussed in this paper are clearly seen and qualitatively similar in both samples. We show below only the results obtained for sample 2.

The energies of the transmission maxima as functions of exciton-photon detuning are shown in Fig. 1(a). Because the samples are grown on a wedge, the cavity width changes with the position on the sample surface. This allows exploring different detuning between exciton and cavity mode. Figure 1(b) shows the transmission spectra (symbols) measured at nearly zero detuning. At low power (20 μW) the signal is identical in linear and circular polarizations [Fig. 1(b)]. One can see that the transmission intensity is the same at lower and upper polariton branches. Surprisingly, at higher power (200 μW) the spectrum is strongly modified in circular polarization, while in linear polarization it is much less affected [Fig. 1(c)]. Indeed, at lower polariton branch one can see the 30% increase in transmission in circular polarization. At upper branch the effect is less important, but its sign is inverted so that the linearly polarized light is transmitted better than the circularly polarized light. Further we refer to this phenomenon as a mixed dichroism, using the analogy with the linear dichroism, well known in crystalline structures. The mixed dichroism is accompanied by the blueshift of the transmission peak associated with the lower polariton in circular polarization of about 0.15 meV, while in linear polarization no pronounced blueshift is observed.

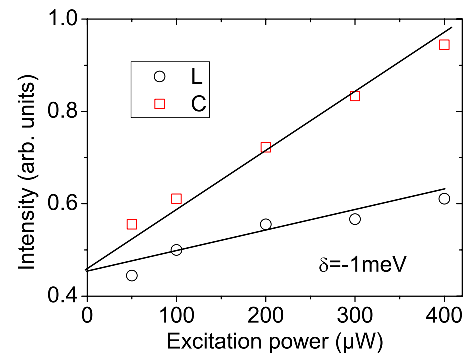

FIG. 2. (Color online) Polarization dependence of the transmission intensity at the lower polariton branch as a function of incident power. Squares stand for the circular and circles for the linear polarization, solid lines are guides for eyes. The data are taken at negative detuning $\delta=-1$ meV.

The power dependence of the transmittivity is illustrated in Fig. 2 for a negative detuning point ($\delta=-1$ meV). The maximum of transmission at lower polariton branch is plotted as a function of the incident power. One can see that the transmission increases linearly, but much faster in circular polarization. Further increase of the power (data not shown) is accompanied by the modification of the slope and the rise of the third transmission peak at the energy of the bare photon mode.[15,16]

Figure 3 shows color maps of the total transmission (a) and mixed dichroism (differential transmission normalized by total transmission) (b) spectra as a function of the detuning between exciton and cavity modes. Incident power is 200 μW. We underline three interesting and surprising features seen in Fig. 3. First, the microcavity is less transparent in the region of zero detuning, than at both positive and negative detuning. In contrast, the mixed dichroism reaches its maximum at zero detuning. Second, both lower and upper polariton transmission peaks are blueshifted in circular polarization spectrum, with respect to the linear one. Finally, at lower polariton branch the transmission of circularly polarized light is much stronger than the transmission of the linearly polarized light. This effect is inverted at the upper polariton branch while it becomes much weaker.

III. MODEL

We suggest that the polarization-dependent renormalization of the exciton energy is at the origin of the observed effects. Indeed, the exciton blueshift originates from the exciton-exciton interactions. Following the terminology of Ref. 17 we introduce two parameters α_1 and α_2 describing the interactions of excitons with parallel and anti-parallel spins, respectively. According to Refs. 10–12, $\alpha_1>0$, $|\alpha_1| \gg |\alpha_2|$. At circularly polarized pumping, all excitons in a quantum well are created with parallel spins so that the shift of the exciton eigenenergy is given by $\Delta_{circ}=\alpha_1 n$, where n is

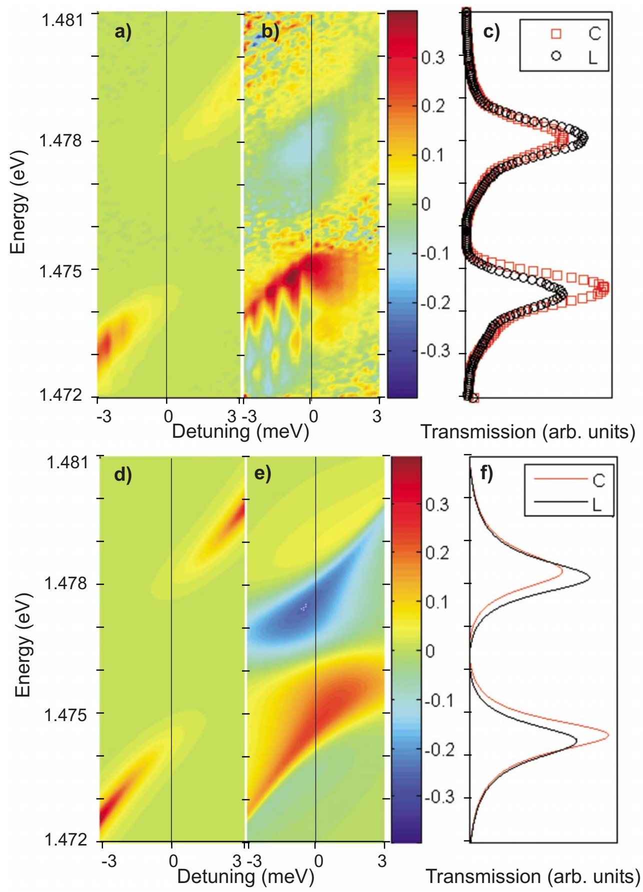

FIG. 3. (Color online) (a) and (b) Measured and (d) and (e) calculated maps of the (a) and (d) total (T_c+T_l) and (b) and (e) normalized differential transmission $(T_c-T_l)/(T_c+T_l)$ also referred to as the mixed dichroism. (c) Measured and (f) calculated transmission spectra in linear and circular polarizations at the position indicated by the black line. The spectra have been measured at 200 μW excitation power. The parameters of calculation are given in the text.

the exciton concentration. At linearly polarized pumping, each photon excites the linear combination of spin-up and spin-down excitons; that is why the energy shift writes $\Delta_{\rm lin}=\frac{(\alpha_1+\alpha_2)}{2}n$. The polarization- and power-dependent exciton blueshift leads to the variation of the detuning between exciton and photon modes in a microcavity, which is responsible for the effects we observe.

The detuning effect on the transmittivity of a microcavity can be understood in the simplest two-coupled oscillator model.[8] In this model, the eigenstates of the cavity polaritons are given by an algebraic equation,

$$(\omega_0-\omega-i\gamma)(\omega_c-\omega-i\gamma_c)=V^2, \tag{1}$$

where ω_0 and ω_c are the eigenfrequencies of bare exciton and photon modes, γ and γ_c are the exciton and photon broadenings, respectively, V is the exciton-photon coupling constant. Equation (1) yields the complex eigenfrequencies of two exciton-polariton modes $\omega_{l,u}$. It also allows finding of the Hopfield coefficients $X_{l,u}$, and $C_{l,u}$ describing the exciton and photon contributions to the lower and upper polariton

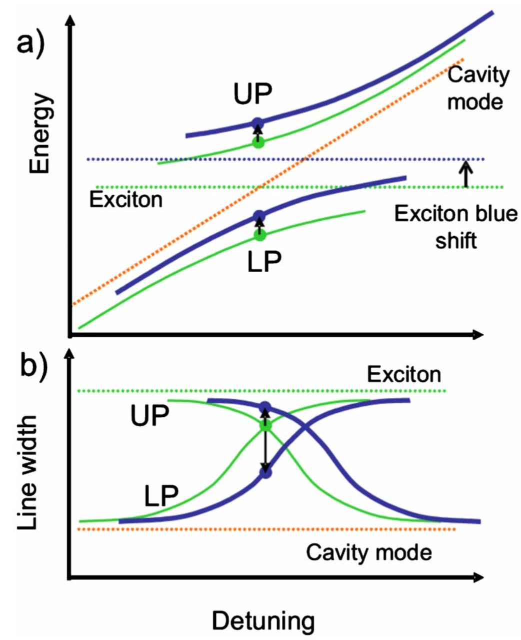

FIG. 4. (Color online) Effect of the exciton blueshift on the (a) energies and (b) line-widths of the exciton-polariton eigenstates in microcavities (scheme). The thin solid lines correspond to the linear regime (no blueshift). The thick solid lines indicate the positions and broadenings of the polariton modes in the nonlinear regime, when the exciton resonance is blueshifted.

states, $|X_{l,u}|^2+|C_{l,u}|^2=1$. The transmittivity T_l of the lower mode is dependent on the photonic Hopfield coefficient of this mode and on the broadening of this mode γ_l as

$$T_l \propto \frac{|C_l|^2}{\gamma_l}. \tag{2}$$

Introducing the detuning parameter $\delta=(\omega_0-\omega_c)/2V$ and assuming it to be small, one can write $|C_l|^2\approx(1+\delta)/2$, $\gamma_l\approx(\gamma+\gamma_c)/2-\delta(\gamma-\gamma_c)/2$, which allows to express

$$T_l \propto \frac{1}{\gamma+\gamma_c}\left(1+\frac{2\gamma\delta}{\gamma+\gamma_c}\right). \tag{3}$$

In high quality microcavities such as the one we study $\gamma \gg \gamma_c$ so that a 50% increase in the transmittivity can be provided by the increase in the detuning parameter by about 1/4, which means the exciton blueshift on the order of 1 meV.

Figure 4 illustrates the mechanism of nonlinear transmission in microcavities. At zero detuning, the blueshift of the exciton eigenenergy [Fig. 4(a)] brings the system to the negative detuning state. This leads to the increase of the photonic component of the lower polariton, at the expense of the upper polariton. As $\gamma\gg\gamma_c$, this induces the reduction in the linewidth of the lower polariton and the increase in the upper polariton linewidth [Fig. 4(b)]. This explains the transmission enhancement at the lower polariton branch, and the reversed sign of this effect at the upper branch. As the blueshift is much stronger at circular than at linear pumping, the circularly polarized light easier goes through the microcavity at the lower polariton branch in the nonlinear regime, while at the upper polariton branch the effect is reversed. The difference of the polariton eigenenergies at linear and circular pumping is responsible for a peculiar spectral shape of the mixed dichroism shown in Figs. 3.

IV. COMPARISON WITH EXPERIMENT

In order to reproduce quantitatively the experimental results, we have performed a numerical simulation of the transmission spectra at different polarizations, detunings, and pumping powers using the transfer-matrix method. We have used the following set of parameters: the exciton energy $\hbar\omega_0=1.4747$ eV (Fig. 1) and $\hbar\omega_0=1.4761$ eV (Fig. 3),[18] the exciton non-radiative broadening $\hbar\gamma=1$ meV, its radiative broadening $\hbar\Gamma_0=0.03$ meV, the difference between exciton energies in circular and linear polarizations $\Delta=0.23$ meV (Fig. 1), and $\Delta=0.26$ meV (Fig. 3). The blueshift is assumed to be dependent on the exciton-cavity detuning and to vary as the integrated absorption of the structure. The cavity thickness and refractive index are $d_c=237.7$ nm ($d_c=236.7$ nm for Fig. 3) and $n_c=3.54$. Bragg mirror layers thicknesses and refractive indexes are $d_1=60.4$ nm, $d_2=71.1$ nm, $n_1=3.48$, and $n_2=2.96$.

The results of the simulation are shown in Fig. 1(c) (solid lines) and Figs. 3(d) and 3(e). One can see a good agreement between theory and experiment. Indeed, the blueshift of the exciton energy is responsible for the blueshift of both polariton branches, accompanied by the mixed dichroism having the different sign at lower and upper branches. However, some discrepancy between the experiment and the calculation can be seen at the upper branch. The model underestimates the transmittivity in both polarizations, and overestimates the mixed dichroism. A more sophisticated modeling taking into account rapid polariton dynamics at the upper branch is required to obtain a better agreement with the data.

The set of experiments we performed allows estimation of the difference between the polariton interaction constants α_1 and α_2. It is given by $2\Delta/\bar{n}$, where $\bar{n}=\frac{1}{\tau}\int_{-\tau/2}^{\tau/2}n(t)dt$ is the density of polaritons in the cavity averaged over a pulse duration τ. The total polariton density is given by the sum $n(t)=n_l(t)+n_u(t)$ of the two branches. The time evolution of the polariton density at each branch $n_{l,u}(t)$ is determined by both pulse duration τ and polariton lifetime τ_l (τ_u) at lower (upper) branch,

$$n_{l,u}=\frac{n_0A_{l,u}}{\sqrt{\pi}\tau}\int_{-\infty}^{t}dt'^{-(t'/\tau)^2}e^{-t-t'/\tau_{l,u}}. \quad (4)$$

Here n_0 is the power-dependent density of photons generated by each pulse of the laser. $A_{l,u}$ is the absorption of each polariton branch, estimated from the combined reflectivity and transmission spectra as $A=1-R-T$. At zero detuning we obtained $A_l=A_u=0.005$. Assuming $\tau_l\approx 2$ ps and $\tau_u\approx 0.3$ ps yields $\alpha_1-\alpha_2\approx(3\pm2)\times10^{-10}$ meV$\times$cm^2. The uncertainty of these numbers comes both from the uncertainty in the polariton lifetimes and the distribution of power-dependent blueshift values. Since $|\alpha_1|\gg|\alpha_2|$,[10–12] this value can be considered as a good estimation for α_1. It appears to be an order of magnitude larger than what has been predicted theoretically[9] but confirms reasonably well the estimations from other experimental works.[19,20] It is also close to the value $\alpha_1=1.5\times10^{-10}$ meV$\times$cm^2 given in Ref. 21.

In conclusion, we have observed a peculiar mixed dichroism effect in a semiconductor microcavity resulting in the polarization controlled nonlinear transmission of light. In particular, we detected a strong enhancement of the transmittivity of the sample in the circular compared to linear polarization. The spin dependence of the polariton-polariton interaction strength is at the origin of this effect: it is directly connected with the difference of the blueshifts of the exciton resonance frequency in circular and linear polarizations. Our measurements have allowed an estimation of the difference between interaction constants of the polaritons with parallel and antiparallel spins $\alpha_1-\alpha_2$. This parameter is crucial for the polariton spin dynamics in microcavities. In particular, it governs the frequency of the self-induced Larmor precession of the polariton pseudopsin.[17,11] The next step would be to extract the constants α_1 and α_2 from the direct measurements of the blueshift of the transmission line in the circular and linear polarization. Combined with the measurement reported in this paper, this would allow an accurate measurement of both interaction constants. In the present experiment, the precision of our measurement is limited by uncertainty with the measurement of the concentration of exciton-polaritons, thus we do not have enough accuracy for a reliable estimation of α_2. Besides its fundamental importance the effect we observed may have several practical applications. A microcavity in the strong-coupling regime behaves as a micro-size circular polarization sensor, and may be used as a polarization detector. In particular, it allows enhancing significantly the signal-to-noise ratio of polarization modulated optical signals. At present, the losses of polarization in optical fibers prevent their use for transmission of polarization-encoded signals. Incorporation of microcavity-based circular polarization detectors may help resolving this important technological problem. Resulting improvement of the performance of optical communication lines is hard to overestimate.

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