Ultrafast Stark-Induced Polaritonic Switches

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A laser pulse, several meV red detuned from the excitonic line of a quantum well, has been shown to induce an almost instantaneous and rigid shift of the lower and upper polariton branches. Here we demonstrate that through this shift ultrafast all-optical control of the polariton population in a semiconductor microcavity should be achievable. In the proposed setup, a Stark field is used to bring the lower polariton branch in or out of resonance with a quasiresonant continuous-wave laser, thereby favoring or inhibiting the injection of polaritons into the cavity. Moreover, we show that this technique allows for the implementation of optical switches with extremely high repetition rates.

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Systems made of quantum wells embedded in semiconductor microcavities, where light and matter are strongly coupled, provide a versatile area for the study of fundamental physics and new states of matter such as out-of-equilibrium polariton condensates. Because of the strong nonlinear interaction between polaritons, they also have great potential for the implementation of next-generation all-optical computational technologies. Moreover, the very short lifetime of cavity polaritons can, in principle, guarantee extremely fast operation rates. For these reasons, in recent years significant efforts have been devoted to the dynamical control of polaritonic systems, and several proposals have been made to implement switches, spin switches, transistors, and resonant tunneling diodes on cavity-polariton systems [1–9].

The general idea underlying all of these proposals is to use polariton-polariton interactions to control the blueshift of the lower polariton branch directly with the driving laser and, in this way, to manipulate the number of polaritons in a microcavity. The main disadvantage of this technique is that when the duration of the laser pulses used to trigger the desired operations is in the subpicosecond regime, the corresponding bandwidth is of the order of the Rabi splitting of the system. Therefore, the effect of short pulses is not only to inject polaritons but also exciton reservoirs with relatively long lifetimes that relax into polaritons and considerably decrease the repetition rates at which polariton devices can work. The slowing down of the system dynamics severely limits the interest in devices based on polariton-polariton interaction blue shift since their performances do not overcome those attainable in other systems.

Instead, the idea underlying the present work is to control the energy of the polariton branches using the Stark shift due to a laser far red detuned from the excitonic line. The far red detuned laser, in fact, cannot excite reservoirs of long-lived particles and ensures an ultrafast control of the dynamics of the system. Recently, pump-probe experiments have shown that the Stark effect can be used to shift both the lower polariton (LP) and upper polariton (UP) branches almost rigidly [10]. In this Letter, we propose a new setup and use the Stark shift to implement polariton switches. We show that with this technique it is theoretically possible to overcome the previous limitations.

In the proposed setup, a continuous-wave (cw) and quasiresonant laser injects polaritons into the microcavity and a Stark field is used to control the energy difference between the injecting laser and the LP branch. Once the parameters of the injecting laser (frequency, angle of incidence on the microcavity, and intensity) are fixed, the Stark field is used to take the lower polariton branch in or out of resonance with the frequency of the injecting laser, thereby increasing or decreasing the number of polaritons in the system, respectively. Here, two cases are addressed: first, the steady-state case, in which the laser intensities are changed adiabatically, and second, the case in which a rapid change of the Stark field intensity, in the subpicosecond range, is used to implement an ultrafast all-optical polariton switch. When the Stark field takes the LP branch into resonance with the injecting laser, polaritons efficiently enter into the cavity, and a bright "on" state (corresponding to a high transmission from the cavity) can be defined in contrast to a dark "off" state (corresponding to a LP branch and an injecting laser out of resonance and to a low transmission from the cavity).

We describe the system of a quantum well embedded in a semiconductor microcavity by means of a two-component wave function where the excitonic field of the quantum well (ψ_X) is strongly coupled to the photonic field confined in the microcavity (ψ_C) through the vacuum Rabi coupling $\Omega_R = d_{XC}\sqrt{2\omega_C/\hbar\epsilon_0 V}$ between a dipole with matrix element d_{XC} and the vacuum field in the cavity with volume V. The dynamics and steady state of the system are modeled by means of the generalized Gross-Pitaevskii equation [11,12],

$$i\hbar\partial_t\begin{pmatrix}\psi_X\\ \psi_C\end{pmatrix} = \begin{pmatrix}0\\ F\end{pmatrix} + \left[\hat{H}_0 + \begin{pmatrix}g_X|\psi_X|^2 & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\psi_X\\ \psi_C\end{pmatrix},$$

$$\hat{H}_0 = \hbar\begin{pmatrix}\omega_X^0 - i\kappa_X & \Omega_R/2\\ \Omega_R/2 & \omega_C - i\kappa_C\end{pmatrix}. \quad (1)$$

Here, a cw injection laser field (IN), nearly resonant with the LP branch [$F = \hbar\sqrt{2\kappa_C}f(\mathbf{r})e^{i(\mathbf{k}_{\mathrm{IN}}\cdot\mathbf{r}-\omega_{\mathrm{IN}}t)}$], injects polaritons with wave vector $\mathbf{k}_{\mathrm{IN}}$ and frequency ω_{IN}. Throughout the Letter, spatially homogeneous pumps $f(\mathbf{r}) = f$ are assumed, along with a flat exciton dispersion ω_X^0 and a quadratic cavity dispersion $\omega_C(\mathbf{k}) = \omega_C^0 - (\hbar^2\mathbf{k}^2/m_C)$, with $m_C = 2.3\times10^{-5}m_0$, where m_0 is the electron mass. The vacuum Rabi frequency is set to 10.0 meV, and κ_X and κ_C are the excitonic and photonic decay rates. The exciton-exciton interaction strength g_X is of the order of 40 μeV μm^2 [13], and for the sake of generality, we rescale the fields $\psi_{X,C} \to \psi_{X,C}\sqrt{g_X}$ and the pump field $f \to f\sqrt{g_X}$. For the implementation of the proposed setup, a value of g_X of 40 μeV μm^2 implies powers of the quasiresonant laser in the range of 100 mW for a spot of 100×100 μm^2. Throughout the Letter, the zero energy is set to the bare exciton frequency and the exciton-photon detuning is taken to be equal to zero [$\omega_X^0 = \omega_C(\mathbf{k}=0)$]. Because of the Rabi coupling Ω_R, the two eigenmodes of $\hat{H}_0$ are the LP and UP branches:

$$E_{\mathrm{LP,UP}}(\mathbf{k}) = \frac{\hbar}{2}\left[\omega_X^0 + \omega_C(\mathbf{k}) \pm \sqrt{\Omega_R^2 + [\omega_X^0 - \omega_C(\mathbf{k})]^2}\right]. \quad (2)$$

The effect of a Stark field coupled to a quantum well exciton embedded in a microcavity can be fully described by a three-dimensional Hamiltonian including the excitonic and photonic components and the nonresonant Stark pump:

$$H = \hbar\begin{pmatrix}\omega_X^0 & \Omega_R/2 & \Omega_p/2\\ \Omega_R/2 & \omega_C(\mathbf{k}) & 0\\ \Omega_p/2 & 0 & \omega_p\end{pmatrix}, \quad (3)$$

where the decay rates have been omitted for the sake of clarity, and where $\hbar\omega_p = -50$ meV (below the excitonic line) is the frequency of the Stark laser and $\Omega_p = d_{Xp}|\varepsilon_p|$ is the Rabi coupling between the exciton and the Stark field, with dipole matrix element d_{Xp} and electric field ε_p. The full diagonalization of Eq. (3) gives two new blueshifted LP and UP modes since the Stark frequency is red detuned with respect to the excitonic frequency. As shown in Fig. 1(a), for $\hbar\Omega_p = 20$ meV the two dressed states are blueshifted by about 2.5 meV with respect to the bare LP and UP, at $\mathbf{k}=0$. For weak Stark intensities, it has been shown [14] that the dressed polariton modes are well approximated by the polariton modes obtained from Eq. (2) with the excitonic line blueshifted as

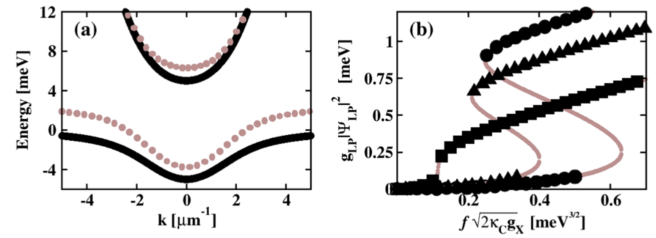

FIG. 1 (color online). (a) LP and UP branches as a function of the wave vector k_x with $k_y = 0$. The bare case (solid black line) is compared with the dressed case obtained fully diagonalizing Eq. (3) with $\hbar\Omega_p = 15$ meV (dotted brown line). (b) Polariton density as a function of the quasiresonant injecting laser intensity f when $\mathbf{k}_{\mathrm{IN}} = 0$ μm^{-1} and $\Delta = 0.7$ meV. The stable solutions of the systems are represented for three Stark fields $\hbar\Omega_p = 0.0$, 6.0 and 10.0 meV (circles, triangles, and squares) for linewidths $\hbar\kappa_C = \hbar\kappa_X = 0.10$ meV. The brown curves indicate the unstable solutions of the system.

$$\omega_X(\Omega_p,\omega_p) = \frac{1}{2}\left(\omega_X^0 + \omega_p + \sqrt{(\omega_X^0-\omega_p)^2 + \Omega_p^2}\right). \quad (4)$$

This approximation, valid for blueshifts smaller than about 1 meV, considerably simplifies the analytical treatment of the system and will be adopted throughout the rest of this Letter. In order to understand the underlying mechanism governing the system, its steady-state stable solutions are evaluated following the same perturbative Bogoliubov-like analysis already used for resonantly pumped polaritons in Refs. [11,12,15]. In the present case, however, the excitonic energy is a function of the parameters of the Stark field as described in Eq. (4). Within this approach the homogeneous profile of the pump determines the spatially homogeneous stationary states $\psi_{X,C}^{(0)}e^{-i(\omega_{\mathrm{IN}}t-\mathbf{k}_{\mathrm{IN}}\cdot\mathbf{r})}$ of the exciton and photon, by means of the mean-field equations,

$$0 = \left[\omega_X(\Omega_p,\omega_p) - \omega_{\mathrm{IN}} - i\kappa_X + \frac{g_X}{\hbar}|\psi_X^{(0)}|^2\right]\psi_X^{(0)} + \frac{\Omega_R}{2}\psi_C^{(0)},$$

$$f\sqrt{2\kappa_C} = -[\omega_C(\mathbf{k}_{\mathrm{IN}}) - \omega_{\mathrm{IN}} - i\kappa_C]\psi_C^{(0)} - \frac{\Omega_R}{2}\psi_X^{(0)}. \quad (5)$$

In order to evaluate the stability of the solutions of Eq. (5), fluctuations around the mean-field state are introduced and both exciton and photon fields are expanded above their mean-field homogeneous stationary states as $\psi_{X,C}(\mathbf{r},t) = e^{-i\omega_{\mathrm{IN}}t}[e^{i\mathbf{k}_{\mathrm{IN}}\mathbf{r}}\psi_{X,C}^{(0)} + \delta\psi_{X,C}(\mathbf{r},t)]$. As has been shown [11,15], the fluctuations above the stationary state can be rewritten in terms of particlelike ($u_{X,C}$) and holelike ($v_{X,C}$) excitations: $\delta\psi_{X,C}(\mathbf{r},t) = \sum_{\mathbf{k}}(e^{-i\omega t}e^{i\mathbf{k}\mathbf{r}}u_{X,C;\mathbf{k}} + e^{i\omega t}e^{-i(\mathbf{k}-2\mathbf{k}_{\mathrm{IN}})\mathbf{r}}v_{X,C;\mathbf{k}})$, and the stability of the system obtained studying the imaginary part of their spectrum [15]. The spectrum needed for this evaluation is obtained simply by solving the eigenvalue equation: $[(\omega+\omega_{\mathrm{IN}})\mathbb{I} - \mathbb{L}](\,u_{X;\mathbf{k}}\quad u_{C;\mathbf{k}}\quad v_{X;\mathbf{k}}\quad v_{C;\mathbf{k}}\,)^T = 0$, where $\mathbb{I}$ is the identity matrix and $\mathbb{L}$ is the matrix

$$\begin{pmatrix} \omega_X(\Omega_p,\omega_p)+2\frac{g_X}{\hbar}|\psi_X^{(0)}|^2-i\kappa_X & \Omega_R/2 & \frac{g_X}{\hbar}\psi_X^{(0)2} & 0 \\ \Omega_2/2 & \omega_C(\mathbf{k})-i\kappa_C & 0 & 0 \\ -\frac{g_X}{\hbar}\psi_X^{(0)2*} & 0 & 2\omega_{\rm IN}-\omega_X(\Omega_p,\omega_p)-2\frac{g_X}{\hbar}|\psi_X^{(0)}|^2-i\kappa_X & -\Omega_R/2 \\ 0 & 0 & -\Omega_R/2 & 2\omega_{\rm IN}-\omega_C(2\mathbf{k}_{\rm IN}-\mathbf{k})-i\kappa_C \end{pmatrix}.$$

The stability curve of the system, in the case of two cw laser fields, is plotted in Fig. 1(b) as a function of the strength of the quasiresonant pump and for three different values of the Stark field. Without lack of generality, here and in the following, the frequency of the quasiresonant injecting laser is assumed to be slightly blue detuned with respect to the LP mode when both laser intensities are vanishing: $\Delta = \omega_{\rm IN} - E_{\rm LP}(\mathbf{k}_{\rm IN}) > 0$. This choice, in fact, allows for the study of both the bistable and the optical limiter regimes. Finally, for the sake of generality, here and in the following, we will plot the polariton density $|\psi_{\rm LP}|^2$ multiplied by the polariton-polariton interaction constant $g_{\rm LP}$, using the relations $g_{\rm LP} = g_X/4$ and $\psi_{\rm LP} = (1/\sqrt{2})(\psi_X - \psi_C)$ valid for $\mathbf{k}_{\rm IN} = 0$. We will refer to the resulting quantity (the mean field energy $g_{\rm LP}|\psi_{\rm LP}|^2$) simply as polariton density. In Fig. 1(b), two features can be noticed. First, the width of the bistable region decreases until it disappears above a critical Stark intensity. This decrease is related to the fact that the width of the bistable region is proportional to the detuning between the injecting laser and the LP branch at $f = 0$, and this detuning decreases for higher Stark fields. Second, when the system is highly populated (upper part of the stability curve), the number of polaritons in the cavity for fixed intensity f is lower for stronger Stark fields. This can be understood considering that the number of polaritons in the cavity when the LP branch is in resonance with the injecting laser is proportional to the detuning between the injecting laser and the bare LP branch. The effect of the Stark field is to decrease this detuning by independently dressing the LP branch, and therefore the number of polaritons in the "on" state must be smaller.

Still in the steady-state case, in order to get better insight into the effect of the Stark field, instead of fixing Ω_p and changing f, it is possible to study the stability of the system in the opposite way by fixing the injecting laser intensity f and changing the Stark intensity Ω_p. We study this in two cases: weak and strong intensities of the quasiresonant injecting laser, plotted in Figs. 2(a) and 2(b), respectively. As will be explained below, these two cases correspond to two kinds of switches that can be implemented using the Stark effect.

In the first case few polaritons are present in the cavity when $\Omega_p = 0$ since the injecting laser is weak and $\Delta > 0$, and, therefore, it is possible to define an "off" state for the corresponding switch. When Ω_p is increased, the LP branch shifts toward higher energies until it becomes resonant with the injecting laser, at a given value $\Omega_p = \Omega_p^{\rm on}$. At this point, polaritons are efficiently injected into the cavity and the switch turns "on." Now, if Ω_p is kept fixed at $\Omega_p^{\rm on}$, the switch remains in the "on" state; if, instead, Ω_p is decreased or further increased, the switch turns "off" since the LP and the injecting laser are no longer in resonance. This behavior is clearly visible in the peaklike shape of the polariton density plotted as a function of Ω_p in Fig. 2(a). As also shown in Fig. 2(a), the switching-on intensity $\Omega_p^{\rm on}$ increases with higher detuning Δ of the injecting laser with respect to the bare LP branch (curves with different symbols). This is because higher Ω_p are needed to blueshift the LP to higher values and to reach the frequency of the injecting laser. The shifts considered here, between 0.3 and 0.7 meV, have been experimentally achieved for values of the Stark pump fluence between 0.75 and 2.0 mJ/cm^2, therefore confirming the feasibility of the proposed switches [10]. Note that shifts of this order imply a change between 0.5% and 1.0% of the effective Rabi splitting due to the increased detuning between the exciton and the cavity modes. This justifies the approximation that we have made of taking a Rabi splitting constant.

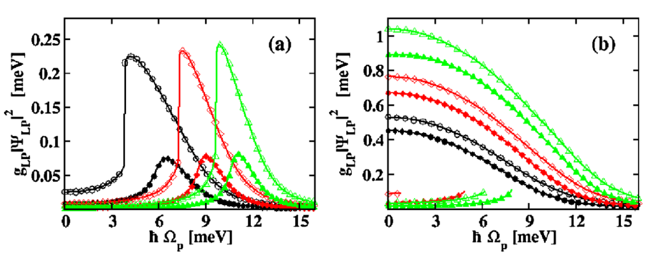

FIG. 2 (color online). Polariton density as a function of the Stark field intensity Ω_p. The injecting laser is taken to have $\mathbf{k}_{\rm IN} = 0\ \mu{\rm m}^{-1}$ and the three cases (black circles, red squares, and green triangles) correspond to $\Delta = 0.3$, 0.5 and 0.7 meV [from left to right in (a) and from bottom to top in (b)]. (a) First class of switches with injecting laser intensity $f\sqrt{2\kappa_C g_X} = 0.075, 0.130\ {\rm meV}^{3/2}$ (filled and empty symbols). (b) Second class of switches with injecting laser intensity $f\sqrt{2\kappa_C g_X} = 0.25, 0.30\ {\rm meV}^{3/2}$ (filled and empty symbols). For $\Delta = 0.5$ and 0.7 states at low density are present in (b) since for these sets of parameters the system displays bistability at $\Omega_p = 0$. The linewidths are $\hbar\kappa_C = \hbar\kappa_X = 0.10$ meV. Note that in the $\Delta = 0.3$ case no low-density stable solutions are available at low Ω_p since, in this case, the intensities f considered are above the bistability threshold.

At this point it is worth noting two things. First, since the injecting laser intensity f is weak, the peak density of the "on" state is weakly dependent on the initial detuning, as when the LP and the injecting laser are in resonance, the number of polaritons that are injected into the cavity depends only on f and on the polariton lifetime. Second, the $\Omega_p^{\rm on}$ at which the polariton intensity peaks shifts slightly toward lower values when the pump intensity f is increased [change from filled to empty symbols in Fig. 2(a)]. This can be understood by observing that the LP branch is shifted by both the Stark field and the polariton population in the cavity. Therefore, if the polariton density is higher, the LP is in resonance with the injecting laser at smaller Stark intensities.

In the second case, when the injecting laser is strong, the corresponding switch, contrary to the first case, lies in an "on" state when $\Omega_p = 0$ and is turned "off" at high Stark field intensities. As before, the frequency of the injecting laser is quasiresonant and blue detuned ($\Delta > 0$) from the bare LP branch but, in this case, the pump intensity f is strong enough to blueshift the LP branch into resonance. As shown in Fig. 2(b), when Ω_p increases, the switch is turned "off" since, due to the Stark field, the LP branch is taken out of resonance with the injecting laser. When Ω_p is decreased back to zero, the polariton branch is shifted back into resonance with the injecting laser and the switch turns "on" again. While in the previous case the effect of the Stark field was to bring the LP from values below the energy of the injecting laser into resonance with it, here the device works in exactly the opposite way: the LP branch starts in resonance with the injecting laser and the Stark field takes it out of resonance. As for the first class of devices, the switching intensity ($\Omega_p^{\rm off}$ in this case rather than $\Omega_p^{\rm on}$) is higher for higher detunings Δ, since the polariton branches have to be shifted more. However, unlike the previous case, here the peak intensity of the "on" state depends strongly on the detuning Δ [curves with different symbols and colors in Fig. 2(b)] since it is the detuning that determines the number of polaritons that the quasiresonant laser has to inject into the cavity in order to keep the LP dressed and in resonance. It is also worth noting that in this case, once the intensity f is sufficiently high to sustain the "on" state at $\Omega_p = 0$, the intensity of the "on" state depends only weakly on a further increase of f since the system is in an optical limiter regime (curves with filled and empty symbols).

Finally, we have studied the dynamics of the system for the first class of switches described above, by numerically solving the radial component of the Gross-Pitaevskii equation (note that, due to the circular symmetry of the infinite and homogenous system, the radial component of the wave function carries all the information needed for the full solution of the problem). Figure 3 shows the response of a system, initially in its steady state, after the arrival of a Gaussian (in time) Stark pulse ($\sigma_t = 1.0$ ps), for three different polariton lifetimes. The arrival of the Stark pulse (gray solid line in Fig. 3) triggers the blueshift of the LP branch toward the resonance with the cw laser, thereby enhancing the polariton population. After the end of the Stark pulse, the polariton population decreases back to its original steady-state value, displaying fast oscillations with a period of about 8 ps that corresponds to the detuning ($\Delta = 0.5$ meV) between the injecting laser and the bare LP branch. These oscillations are the same as those displayed by the system when a laser field is suddenly turned "on" (steplike) on an empty microcavity, and their duration is proportional to the polariton lifetime. While the switching "on" of the device is determined by the rate at which photons are transformed into polaritons (the Rabi frequency), the switching "off" is determined by the polariton lifetime since the system goes back to its initial condition as polaritons decay. Therefore, longer polariton lifetimes (curve with black circles), slowing down the process of restoring of the initial condition, decrease the repetition rate at which the device can work. On the other hand, longer lifetimes allow for more efficient polariton injection, and yield higher polariton densities in the "on" state. This is a principal figure of merit for switches since higher brightness ratios (the ratio between the population of the state "on" and the population of the state "off") lead to better device performance. Following this discussion, let us note that the increase of the Rabi splitting, due to the nonzero detuning between the exciton and the cavity, makes the switching "on" of the device even faster; therefore, our results can be considered as lower bounds for the effective repetition rate of the switching operation.

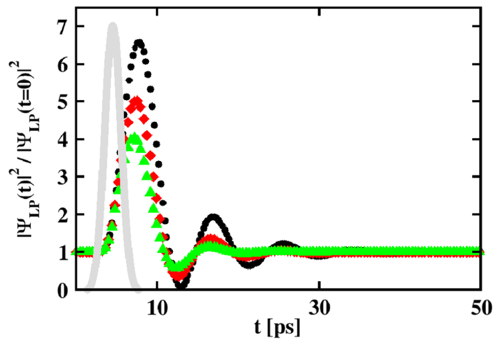

FIG. 3 (color online). Time evolution of the polariton population in the cavity after the arrival of a Stark pulse (schematically represented by the gray line) with values normalized to the population before the arrival of the pulse. The curves with green triangles, red squares, and black circles correspond respectively to plariton lifetimes of $2/(\kappa_C + \kappa_X) = 3.3$, 4.4, and 6.6 ps. The detuning between the cw laser and the LP branch is $\Delta = 0.5$ meV, the cw pump intensity is $f\sqrt{2\kappa_C g_X} = 0.13$ meV$^{3/2}$, and the Stark intensity is $\hbar\Omega_p = 20$ meV.

In conclusion, we have shown that a Stark field far red detuned from the excitonic resonance of a semiconductor microcavity can control the number of polaritons injected into the cavity by a quasiresonant cw laser. In this way, two classes of switches can be defined depending on whether the "on" state corresponds to low or high Stark field intensities. Interestingly, we have also demonstrated that the switch between the "on" and "off" states can be performed with repetition rates never before reached in these systems. In fact, the injection of a polariton is limited solely by the vacuum Rabi frequency, while the resetting of the initial condition depends only on the time needed for polaritons to decay. This technique not only allows for the implementation of switches with high modulation depth, but may also be used to study the response of a polaritonic fluid to fast control fields.

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