Implementation of a logic AND gate with polariton condensate bullets

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We demonstrate the realization of an AND gate in a semiconductor microavity ridge by means of propagating polariton condensates excited non-resonantly. A combination of two pulsed excitation beams, with a proper choice of their spatial separation and time delay, produces a potential landscape modulation that traps a polariton condensate at the border of the ridge. The formation of this condensate takes place after energy relaxation, including stimulated scattering, of propagating ballistic polaritons. The experimental results are interpreted in the light of simulations based on a generalized Gross-Pitaevskii equation.

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In the last years, research on exciton-polariton condensates in semiconductor microcavities has initiated a quest for novel technological applications, which could set the basis for a new generation of devices in the next decades. Different groups have reported on the usefulness of polaritons to realize new lasers, and there is a strong focus on the development of elements for optical information processing, including: switches, transistors, diodes, amplifiers and integrated circuits.

The best features of photon and exciton properties are fused in these quasi-particles, constituting a unique quantum fluid with fast response time, long dephasing time and strong nonlinearities. Different fundamental properties of out-of-equilibrium polariton condensates have been profusely investigated, including coherence, robust propagation of polariton bullets, frictionless flow, persistent quantized superfluid rotation, and solitary waves. These phenomena form an ideal basis for the construction of optical information processing devices, in which low error rates would allow fast computation times. Furthermore, the capability of polariton condensates to couple to external light suggests near-future applications in signal processing.

The development of optical information processing is heavily dependent on their integrability with existing technologies, which may well require designs using incoherent or non-resonant carrier injection methods. In recent works using quasi-1D microwire ridges, a polariton condensate transistor switch has been realized through optical, non-resonant (effectively incoherent) excitation with two beams. Here we further develop this direction, realizing an all-optical AND type logic gate.

We use two pulsed beams that do not need to be tuned to resonance with the polariton modes, but rather have a wavelength exciting incoherent exciton levels. Such excitation creates compact polariton wave-packets (via polariton condensation), which propagate ballistically, as well as moderate repulsive potential barriers that control the propagation. A proper choice of the spatial-temporal configuration of the beams allows the engineering of an all-optical AND gate.

The sample used in the experiments is a high-quality 5A/2 AlGaAs-based microcavity containing 12 embedded quantum wells, giving a Rabi splitting of $\Omega_R = 9$ meV. Reactive ion etching has been applied to sculpt ridges with dimensions $20 \times 300$ µm$^2$ (further information is given in Refs. and ). We select a region on the sample where the detuning between the bare exciton ($E_X$) and bare cavity mode ($E_C$) in the ridge corresponds to resonance, i.e. $\delta = E_C - E_X \sim 0$. We keep the sample at 10 K in a cold-finger cryostat and excite it with 2 ps-long light pulses from a Ti:Al$_2$O$_3$ laser, tuned to the bare exciton energy level (1.545 eV). Two independent, twin beams, dubbed and , are split from the laser: their intensities, spatial positions and relative time delay ($\Delta t$) can be independently adjusted. We focus both beams on the sample through a high numerical-aperture (0.6) lens, to form 10-20 µm spots. The same lens is used to collect and direct the emission towards a 0.5 m spectrometer coupled to a streak camera, working in synchroscan mode, obtaining energy-, time- and space-resolved images, with resolutions of 0.4 meV, 10 ps and 1 µm, respectively. Every picture is the result of an average over millions of shots (laser repetition rate 82 MHz and integration time 1.1 s). The photoluminescence can be simul-
taneously resolved in the near- as well as in the far-field. The momentum space is simply accessed by imaging the Fourier plane of the lens used to collect the emission, taking advantage of the direct relation between the angle of emission and the in-plane momentum of polaritons.[43]

The power threshold to produce condensed polariton bullets is $P_{th} = 4.4$ mW. In the experiments described here we have used $P_A = 7 \times P_{th}$ and $P_B = 3 \times P_{th}$, which are the most appropriate values to obtain the AND response of the device. Although we have used a non-resonant excitation, the power requirements remain comparable to previous microcavity switch designs based on hysteresis control ($> 30$ mW) [11] or resonant blueshift ($\sim 5$ mW). [11]

The emission from pinges on the sample at $0$ (80) ps, see full (dashed) line. The squared boxes in panels (a-c): the emission, spatially-integrated in the enclosed areas by time, with its maximum emission obtained at $\sim \frac{1}{2}$ state ($\sim \frac{1}{2}$)

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FIG. 1: (Color online) Demonstration of the output state of the device. Real space intensity emission of the ridge at 1.539 eV: (a) scattered reflection of $A$ pulse impinging on the sample at $t = 0$ and at $x = 0$; (b) scattered reflection of a second $B$ pulse, with a temporal delay of $\Delta t = 80\text{ ps}$, at $x = 50\mu$m; (c) output polariton emission, $\mathcal{E}_{B,A}$, (at 175 ps after the arrival of the $A$ pulse) close to the border of the ridge, $x = 85\mu$m. The intensity is coded in a linear, false color scale. (d) Time evolution of the spatially integrated intensity from the boxes enclosing $A$, $B$ and $\mathcal{E}_{B,A}$.

The $A$ beam is located $\sim 100\mu$m far from the right border of the ridge, Fig. 1 (a). The $A$ and $B$ beams are spatially separated by $\sim 50\mu$m, and the relative time delay is set to $\Delta t = t_B - t_A \approx 80\text{ ps}$ for these experiments, Fig. 1 (b). As described in Ref. [11] the photo-generated excitons within the excitation area of a given beam, $A$ ($B$), create a repulsive potential barrier; in our case at $(x,t) = \{0,0\}$ ($\{x,t\} = \{50\mu$m, $80\text{ ps}\}$), labelled as $V_A$ ($V_B$). As we will discuss below, $V_A$ and $V_B$ determine the dynamics of the propagating polaritons in the ridge. Under the experimental conditions ($B,A = (1,1)$ (indicating that both beams excite the sample) we obtain at long times a quasi-static, trapped polariton condensate, dubbed as $\mathcal{E}_{B,A}$, Fig. 1 (c), which constitutes the [ON] state ($B \wedge A = 1$) of the device. The other states, given by ($B,A = (0,1)$ and $(1,0)$, correspond to the [OFF] states ($B \wedge A = 0$). Figure 1(d) shows the evolution of the emission, spatially-integrated in the enclosed areas by the squared boxes in panels (a-c): the $A$ ($B$) pulse impinges on the sample at 0 (80) ps, see full (dashed) line. The emission from $\mathcal{E}_{B,A}$ (filled area) displays a fast rise time, with its maximum emission obtained at $\sim 200\text{ ps}$; this is followed by a decay, evidencing a weakly oscillating behaviour.

Figure 2 summarizes the truth table of the device in real- (left group of panels) and momentum-space (right group of panels). The emission along the perpendicular coordinate, $y/k_y$, has been integrated. The energy-resolved detection is essential to obtain a full understanding of the device operation: the polariton emission is compiled at three-selected different energies, in the rows (a) 1.5415, (b) 1.5400 and (c) 1.5392 eV. For the sake of clarity, we have included an additional row, labelled (b[t]), where the trajectories in real- and momentum-space are sketched with colored arrows. The $A$ ($B$) beam creates two, initially, left/right propagating bullets along the $x$-axis, named $A_L/A_R$ ($B_L/B_R$).

We start describing the dynamics of the system under only one beam excitation. Columns (i) and (ii) show, for the different detection energies, the configuration ($B,A = (0,1)$, where the output address level reads zero, [OFF]. Panel (a-1) displays hot polaritons propagating rapidly away from the $A$ excitation area (the large intensities at very short times arise partially from scattered laser light), and subsequently decaying into lower energy states, panel (b-1), where an elastic reflection of the $A_R$ polariton bullet at the ridge border is clearly observed at $\sim 125$ ps. $A_R$ reaches the hill of $V_A$ at $\{x[\mu$m],t[ps]\} \approx \{0.225\}$, as depicted in panel (b[t]-1) (at this instant the emission is very weak). It is remarkable the existence of interference fringes in the polariton emission following the elastic reflection, see the zoomed inset in panel (b-1). They evidence the system coherence, even after the energy loss processes experienced by the original condensate created close to $A$. Panel (c-1) shows only scattered light arising from the $A$ pulse at $(x,t) = \{0,0\}$; the absence of any emission establish the [OFF] state.

The momentum space dynamics corresponding to this configuration is compiled in the fourth column, (i), of Fig. 2. Hot polaritons at 1.5415 eV show a quasi homogeneous distribution of momenta in a $k$-space ring (see Supplemental Movie 1); these polaritons rapidly decay in energy, panel (b-i) (1.540 eV): in the time interval 50 to 100 ps, $A_L$ and $A_R$ propagate at $k_x = \pm 1.1\text{ m}\mu$^{-1}, as sketched in panel (b[t]-i). The elastic reflection of $A_R$ at $\sim 125$ ps is evidenced by the jump observed in $k$-space from $+1.1$ to $-1.1\text{ m}\mu$^{-1} (horizontal segment of the dashed yellow arrow in (b[t]-i)). Panel (c-i) (1.5392 eV) demonstrates the [OFF] state, where only scattered light by $A$ is present.

We discuss now the second configuration where the output address level reads zero under only $B$ excitation, ($B,A = (1,0)$, shown in columns (ii) and (ii), for the three detection energies. Panel (a-2) displays hot polaritons created at $t = 80$ ps, propagating rapidly away from the $B$ area and subsequently decaying to lower energy states, panel (b-2), in a similar fashion to what has been described before in the ($B,A = (0,1)$) configuration, but
with a more conspicuous $B_R$ trajectory due to the vicinity of $V_B$ and the ridge border. $B_L$ moves at a constant speed of $v_x = -0.74 \mu m/ps$ and the elastic, quantum reflections of $B_R$ take place at $\{x[\mu m],t[ps]\}$: $\{95, 150\}$-1st, $\{50, 200\}$-2nd, $\{95, 250\}$-3rd and $\{50, 305\}$-4th, see the sketch of the trajectory in panel (b[t]-2). At each reflection against $V_B$, where a reservoir of excitons exist, an amplification of $B_R$ is observed, as previously reported in Refs. 21, 41. Panel (c-2) shows information concerning only the scattered light by the $B$ pulse at $\{x[\mu m],t[ps]\} = \{50, 80\}$.

The corresponding momentum-space dynamics for the configuration $(B, A) = (1, 0)$ is compiled in the fifth column, (ii), of Fig. 2. The momenta of hot polaritons at 1.5415 eV show a similar behaviour to that discussed previously for the $(B, A) = (0, 1)$ case, see panel (a-i). The evolution of the emission in $k$-space, appearing in panel (b-i), evidences the four reflections of $B_R$ in the same instants as those in panel (b-2). The 1st and 3rd reflections show a sudden reversal in the propagation direction during an elastic scattering process (horizontal dashed segments of the arrow in b[t]-ii): $B_R$ propagates towards $V_B$ decelerating until it comes to a halt, and then it flows back towards the edge of the ridge; the continuous conversion of kinetic into potential energy are observed as continuous lines in the $k_x$ vs. time diagram from $-1.1$ to $+1.1 \mu m^{-1}$. Panel (c-ii), shown for completeness, displays only the scattered light by $B$.

The [ON] state of the device is demonstrated in columns (3) and (iii); the input address level reads now $(B, A) = (1, 1)$. Panel (a-3) displays the real-space dynamics of hot polaritons at 1.5415 eV, propagating rapidly and decaying to lower energy states: it is clearly seen that $A_R$ surpasses the position of the $B$ pulse, before the latter impinges on the sample, in its way towards the edge of the ridge. Now, this edge and the double excitonic barrier, composed by $V_A$ and $V_B$, determine the trajectories of the polariton bullets, as shown in panel (b[t]-3). The creation of $V_B$ is delayed by $\Delta t$, which is precisely set to 80 ps in order to allow the passage of the $A_R$ bullet and its subsequent trapping together with $B_R$, panel (b-3). The combination of $V_A$ and $V_B$ constitutes a potential trap, in which $B_L$ oscillates periodically. Its amplification by the excitons at $A$ and $B$ is proven by a significantly stronger emission intensity than that shown in b[t]-ii): $B_R$ propagates towards $V_B$ decelerating until it comes to a halt, and then it flows back towards the edge of the ridge; the continuous conversion of kinetic into potential energy are observed as continuous lines in the $k_x$ vs. time diagram from $-1.1$ to $+1.1 \mu m^{-1}$. Panel (c-ii), shown for completeness, displays only the scattered light by $B$. The [ON] state of the device is demonstrated in columns (3) and (iii); the input address level reads now $(B, A) = (1, 1)$. Panel (a-3) displays the real-space dynamics of hot polaritons at 1.5415 eV, propagating rapidly and decaying to lower energy states: it is clearly seen that $A_R$ surpasses the position of the $B$ pulse, before the latter impinges on the sample, in its way towards the edge of the ridge. Now, this edge and the double excitonic barrier, composed by $V_A$ and $V_B$, determine the trajectories of the polariton bullets, as shown in panel (b[t]-3). The creation of $V_B$ is delayed by $\Delta t$, which is precisely set to 80 ps in order to allow the passage of the $A_R$ bullet and its subsequent trapping together with $B_R$, panel (b-3). The combination of $V_A$ and $V_B$ constitutes a potential trap, in which $B_L$ oscillates periodically. Its amplification by the excitons at $A$ and $B$ is proven by a significantly stronger emission intensity than that shown
in panel (b-2) for $B_L$, where $V_A$ was absent. The confinement of polaritons in a potential trap $V(r)$ increases their density and when polaritons exceed an occupation threshold (at a certain high energy level), they scatter, relaxing into lower energy states.\textsuperscript{44} This stimulated scattering process mediates the creation of $\mathcal{E}_{B \wedge A}$: it occurs only when $A_R$ and $B_R$ are simultaneously confined between $V_B$ and the ridge border, resulting in an overpopulated energy state at 1.540 eV compared to that shown in panel (b-2), where only $B_R$ was present. The former situation, shown in panel (b-3), evolves so that part of the population of the $A_R$ and $B_R$ bullets relaxes and gives rise to the $\mathcal{E}_{B \wedge A}$ condensate, panel (c-3), which lasts for $\sim 200$ ps displaying weak oscillations. The $\mathcal{E}_{B \wedge A}$ lifetime, as already shown in Fig. 4(d), is notably larger than that of those bullets expelled far away from the laser position, since the presence of the excitonic reservoir continually feeds $\mathcal{E}_{B \wedge A}$.

The dynamics of the [ON] state in k-space is summarized in the sixth column, (iii), of Fig. 2. In panel (a-iii), the two populations of hot polaritons, delayed with respect to each other, manifest the same behavior as that obtained for the individual emissions, reported separately in panels (a-i-ii). Panel (b-iii) displays a complex distribution of polariton momentum from $t \approx 100$ ps to $t \approx 400$ ps, since $A_R$, $B_L$, and $B_R$ momenta are superimposed in a range of $|k_x| \leq 1.5 \, \mu m^{-1}$. $A_R$ and $B_R$ suffer elastic collisions almost simultaneously against the ridge border at $\sim 150$ and $\sim 250$ ps (dashed segments in (b[t]-iii)); their dynamics is similar to the one of $B_R$ reported in panel (b[t]-ii). On its own account, $B_L$ shows a zig-zag movement in k-space, since it suffers continuous accelerations/decelerations in the $V_A + V_B$ potential sculpted by the $A$ and $B$ beams. In this case, the absence of collisions against a hard-well potential (as described for $A_R$ and $B_R$) yields only slanted trajectories from $\pm 1.0$ to $\mp 1.0 \, \mu m^{-1}$ for the $B_L$ movement. The conspicuous interference patterns around $|k_x| \leq 0.9 \, \mu m^{-1}$ arise from the mutual coherence between different bullets. Finally, panel (c-iii) shows the quasi-steady dynamics of the $\mathcal{E}_{B \wedge A}$ condensate ([ON] state): the confined population sustains an oscillatory movement with a period of 25 ps and an amplitude of $\sim 0.75 \, \mu m^{-1}$. The $\mathcal{E}_{B \wedge A}$ effective lifetime is determined by the excitons at $B$, which feed the scattering process towards this final state, lasting for more than 200 ps, as reported in Fig. 1(d).

Polariton dynamics can be modelled using a generalized Gross-Pitaevskii description in which evolution equations for the polariton mean-field wavefunction are coupled to a system of semiclassical rate equations for higher energy excitations.\textsuperscript{46} Further details on the model are described in the Supplemental Information.\textsuperscript{17} At high energies, the pulses create polariton condensates at their impinging positions, which spread out over time. After a time delay, the polaritons relax their energy entering trapped states, which undergo multiple reflections depending on the excitation configuration, as in the experimental case.

In the case when both pulses are present, $(B, A) = (1, 1)$, an enhanced polariton density in a trapped state near the wire edge allows further stimulated energy relaxation, populating the low energy condensate, $\mathcal{E}_{B \wedge A}$, seen in Fig. 3(c-3). The localization of this condensate is partly due to a static potential $V_0(x)$, which is known to have a minimum near the wire edge.\textsuperscript{44}

Note that the theory only reproduces the emission from condensed polaritons; it does not show the scattered light responsible for the peaks at the pulse positions and arrival times seen in Fig. 2.

We have studied the time-resolved, energy relaxation of polaritons in a potential created by the edge of a semiconductor microcavity ridge and two delayed laser pulses, giving rise to a signal that can be considered as the [ON] state of a logic AND gate. The total dynamics in real- and momentum-space has been tracked yielding the modus operandi of the device. Theoretical simulations based on a generalized Gross-Pitaevskii description reproduce the experimental dynamics and confirm our understanding of the system. The account of energy-relaxation processes, the non-uniform wire structural potential and long-lived exciton states contributing to the effective potential is essential.

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