Energy relaxation of exciton-polariton condensates in quasi-one-dimensional microcavities


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We present a time-resolved study of energy relaxation and trapping dynamics of polariton condensates in a semiconductor microcavity ridge. The combination of two nonresonant, pulsed laser sources in a GaAs ridge-shaped microcavity gives rise to profuse quantum phenomena where the repulsive potentials created by the lasers allow the modulation and control of the polariton flow. We analyze in detail the dependence of the dynamics on the power of both lasers and determine the optimum conditions for realizing an all-optical polariton condensate transistor switch. The experimental results are interpreted in the light of simulations based on a generalized Gross-Pitaevskii equation, including incoherent pumping, decay, and energy relaxation within the condensate.

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I. INTRODUCTION

Bose-Einstein condensation of quasiparticles in solid-state systems has been observed in excitons in quantum Hall bilayers, exciton polaritons in semiconductor microcavities, gases of magnons, cavity photons, and indirect excitons. Exciton polaritons, mixed light-matter quasiparticles behaving as bosons, form condensates which exhibit not only the fundamental properties of quantum gases, but also new fascinating phenomena related to their out-of-equilibrium character. The photonic component of polaritons is responsible for their light mass, which makes condensation possible up to room temperature, and for their easy creation, manipulation and detection by using simple optical-microscopy setups. On the other hand, their excitonic component yields strong Coulomb repulsive interactions that make them promising candidates for future nonlinear optical technologies.

The peculiar quantum fluid properties of polariton condensates are under intense research nowadays. Recent findings include robust propagation of coherent polariton bullets and elucidation of the validity of the Landau criterion for frictionless flow in the presence of weak structural defects, persistent quantized superfluid rotation, and solitary waves resulting from compensation between dispersion and particle interaction. Moreover, the intrinsic out-of-equilibrium character of polariton condensates has motivated recent theoretical studies on how to describe properly the energy flow from an optically injected hot-exciton reservoir to the coherent polariton modes, which we carefully address in this work.

The functionalities of microcavities in the strong coupling regime, as integrated optical elements, promote polaritons as an undreamt platform to create new logical devices. Thanks to their interactions with noncondensed excitons, polaritons can be easily accelerated, propagating over macroscopic distances in high finesse microcavities. In this case, new interferometric devices can be built by properly shaping the excitation profile as well as the microcavity etching.

Extra confinement can be achieved by lateral bounding the optical modes through patterning the microcavity, or by a combination of both methods. This paves the way for studies of atomlike scenarios in which the energy spectrum becomes discrete. In a recent work using quasi-one-dimensional (quasi-1D) microwave ridges, a polariton condensate transistor switch has been realized through optical excitation with two beams. One of the beams creates a polariton condensate which serves as a source (S) of polaritons; their propagation is gated using a second weaker gate beam (G) that controls the polariton flow by creating a local blue-shifted barrier (a list of symbols used in the paper is given in Appendix A). The ON state of the transistor (absence of G) corresponds to forming a trapped condensate at the edge of the ridge (collector C) labeled as C. The presence of G hinders the propagation of polaritons towards C, remaining blocked between S and G (OFF state). An insight of the energy relaxation and dynamics of the condensed polariton propagation in this system has been obtained lately by a time-resolved study of the ON/OFF states. In this work, we make a systematic study of the influence of the density of polaritons created in S and G on the propagation and the gating of polariton bullets, of their energy and density relaxation, and of the optimal conditions for realizing an all-optical polariton condensate transistor switch. Our experiments are compared with simulations of the polariton condensate dynamics based on a generalized Gross-Pitaevskii equation, modified to account for incoherent pumping, decay, and energy relaxation within the condensate.
and the arrival of a given laser beam takes place at an instant the time origin: the instant \( t = 0 \) is set at the maximum \( S \) intensity, the arrival of a given laser beam takes place at an instant \( t < 0 \).

II. SAMPLE AND EXPERIMENTAL SETUP

We investigate a high-quality 5\( \lambda / 2 \) AlGaAs-based microcavity with 12 embedded quantum wells, with a Rabi splitting of \( \Omega_R = 9 \) meV. Ridges have been sculpted through reactive ion etching with dimensions \( 20 \times 300 \) \( \mu \text{m}^2 \) (further information about this sample is given in Refs. 25 and 27). Figure 1(a) shows a scanning electron microscopy image of such a ridge, including the excitation scheme; a temporal scheme of the excitation and emission processes is given in Fig. 1(b). In our sample lateral confinement is insignificant compared to much thinner, 1D polariton wires.\textsuperscript{9,26} The chosen ridge is in a region of the sample corresponding to resonance (detuning between the bare exciton and bare cavity mode is \( \delta \sim 0 \)). The sample, mounted in a cold-finger cryostat at \( C = 0 \) and \( C = 9 \) meV , Ridges have been sculpted through reactive ion etching with dimensions 20 \( \mu \text{m} \times 300 \) \( \mu \text{m} \) (further information about this sample is given in Refs. 25 and 27).

Our study obtains intensity and energy dynamics of exciton and polariton emission in the ridge. In the former case varying \( P_S \), we modulate the polariton condensate trapping potential.\textsuperscript{19} In this work, we time resolve the different excitation configurations presented in Ref. 28: Fig. 2 (where the \( P_S \) is varied while \( P_G = 0 \)) and Fig. 3 (\( P_S = \text{const} \) and \( P_G \) is varied). Our study obtains intensity and energy dynamics of exciton and polariton emission in the ridge. In the former case varying \( P_S \), we fully characterize the ON state response of a polariton transistor switch; in the latter one, we modulate the polariton condensate trapping potential.\textsuperscript{19}

A. One-beam excitation

In this section, we present three time-resolved cases for different \( P_S \) pump powers (Figs. 3–5). Figure 3 shows the dynamics of the emission when \( P_S = P_{th} \). For each panel, the time is displayed at the right upper corner, being the temporal from the right ridge border; in the \( S + G \) beam excitation, \( G \) is placed \( \sim 35 \) \( \mu \text{m} \) away from the border [Fig. 2(b)]. In Fig. 2(a), exciting with a power \( P_S = P_{th} \), the blue-shifted (\( \sim 3 \) meV) emission at the source, together with a weak condensate emission \( \xi_{C,G} \), are clearly observed. \( \xi_{C,G} \) emits from an energy lower than that of the propagating polaritons as a result of an unintentional modification of the microcavity structure created by the etching process at the edge of the ridge. Polaritons propagate at a constant energy towards the left and right sides of the ridge. Exciting with both laser beams, under different excitation conditions for a typical OFF state, \( P_S = 7.2 \times P_{th} \) and \( P_G = 0.4 \times P_{th} \), the gating state of the switch is readily seen with the stopped, condensed polaritons just before the \( G \) position.

III. EXPERIMENTAL RESULTS AND DISCUSSION

FIG. 2. (Color online) Energy vs real-space \((X)\) image of a cross section along the ridge under nonresonant CW excitation. (a) Only one beam \((S)\) at \( \sim 75 \) \( \mu \text{m} \) from the right edge border. (b) Two beams \((S + G)\) placed at \( \sim 75 \) \( \mu \text{m} \) and \( \sim 35 \) \( \mu \text{m} \) from the border, respectively; the dashed vertical line indicates the gate position. The intensity is coded in a logarithmic false color scale shown on the right.

FIG. 3. (Color online) Energy vs real space \((X)\) for \( P_S = P_{th} \) at different times shown by the labels. \( S \) and \( C \) mark the source and collector positions, respectively. The intensity is coded in a false color scale shown on the right of each panel.
origin set at the instant when the $S$ intensity is maximum. Figure 3(a) shows that the emission from $S$ at $-24$ ps occurs at $1.545$ eV; at $31$ ps [Fig. 3(b)], the emission red-shifts and a small spatial expansion around $0 \mu$m is observed; propagating polaritons, expanding more rapidly towards the border, at an energy of $1.542$ eV, are detected at $194$ ps [Fig. 3(c)], eventually reflecting backwards, interfering coherently and creating the $C$ condensate, weakly emitting at $1.539$ eV at later times, $483$ ps [Fig. 3(d)]. Since the pump power is at threshold, the emission intensity of polaritons is weak and slightly higher than the noise level in all panels of Fig. 3.

Let us note that at early times, the emission observed in Fig. 3 appears blue-shifted from the lower polariton minimum by an amount comparable to one-half of the Rabi splitting. This suggests that the emission at the source comes from polaritons with a strong excitonic character. For this reason, we will refer to the emission from the source as arising from excitons, although the decrease in the blue-shift over time corresponds to a continuous transition from excitonic polariton states to those with roughly equal excitonic and photonic fractions. The emission from the propagating states and collector region, at lower energy, is clearly a polaritonic emission.

It is also important to note that the duration over which the condensate is present greatly exceeds the polariton lifetime. This is because the condensate is continuously fed by high-energy excitons (not visible in the spectrum and distinct from the excitonic states emitting at the source) excited by the nonresonant pulse. The emission at $S$ is determined by repulsive interactions with hot excitons which contribute a blue-shift to the potential energy. As hot excitons decay from the system, either through recombination or condensation, this potential energy decreases over time. Once the polariton condensate has formed, due to the low density of polaritons, there are minimal energy-relaxation processes, such that the propagating polaritons tend to conserve their energy as they spread out from the source [see Fig. 3(d)].

The dynamics of the emission increasing $P_S$ to $1.7 \times P_{th}$ is shown in Fig. 4: the initial excitonic emission at the source takes place at $1.546$ eV [Fig. 4(a)], slightly higher than before, due to increased blue-shift due to a larger hot-exciton repulsion. At $t = 73$ ps [Fig. 4(b)], an essential difference with respect to the case of Fig. 3(b) is revealed: polaritons emit from a lower energy than that of the source, which is $\sim 2$ meV blue-shifted; this situation holds during the first $\sim 200$ ps of the decay process. Figure 4(c) shows the arrival of polaritons at the ridge border at $140$ ps, and the eventual condensation of $C$ [Fig. 4(d)]. This final relaxation phase in the dynamics takes place into a state defined in a minimum of the wire structural potential located at the wire edge. A clear indication of the polariton coherence is evidenced by the interference at $1.540$ eV between counterpropagating wave packets. The source population at $S$, still $1$ meV blue-shifted with respect to propagating polaritons, expands around $X = 0$ as it decays in energy, and continuously feeds the propagating polariton condensate, increasing its effective lifetime [Fig. 4(e)]. Finally, as shown in Fig. 4(f) at $617$ ps, polaritons at $S$ merge with those propagating along the ridge. The emission is still observed for times as large as $\sim 1$ ns (not shown).

The case of the highest source power used in our experiments is shown in Fig. 5: at $-9$ ps the excitonic source population emits at $1.547$ eV [Fig. 5(a)]. The progressive spatial expansion of the excitonic population and the fast relaxation of the polariton condensate, as it propagates towards the right side, at $1.541$ eV, reaching the ridge edge at $35$ ps, is shown in Figs. 5(b) and 5(c). $C$ is now slightly blue-shifted, with respect to its energy at lower $P_S$ conditions, to $1.540$ eV, due to the higher density condensate population at this place of the ridge [Fig. 5(d)]. At later times, as those shown in Figs. 5(e) and 5(f) for $300$ and $508$ ps, the population at $S$ decreases and expands in space, while $C$ red-shifts its energy emission due to its reduced occupancy.

Movies corresponding to Figs. 3–5 are provided as Supplemental Material.30

B. Two-beam excitation

The introduction of a new secondary pulse, dubbed before as gate (G), between $S$ and $C$, adds new interaction phenomena. The existence of two condensates becomes very clear in this case: one of them located initially between $S$–$G$, $C_{S-G}$, which
eventually becomes propagating, and a second one, already labeled as $\mathcal{C}_G$. The polariton propagation towards $C$ along the ridge can be hindered with a below-threshold intensity gate beam [see Figs. 2(b) and 6], rendering the ridge can be hindered with a below-threshold intensity $P_{th}$ respectively. The intensity is coded in a false color scale shown on the right of each panel.

Condensate becomes propagating and coherent interference patterns are generated from counterpropagation [see Fig. 7(f)].

For completeness, Fig. 8 depicts the case corresponding to large values of $P_G$. Figure 8(a) depicts the excitonic emission at 1.547 eV when the laser beams arrive at $S$ and $G$. $\mathcal{E}_{S,G}$ is trapped around $X = 20 \mu m$, blue-shifted up to 1.542 eV, due to repulsive interactions [Fig. 8(b)], while polaritons between $G$ and $C$ propagate towards the border. At 76 ps, a new condensate $\mathcal{E}_C$ becomes trapped at 1.540 eV, and the emission energy of $S$ and $G$ reaches that of $\mathcal{E}_{S,G}$ [Fig. 8(c)]. Due to the barrier reduction at $G$, $\mathcal{E}_{S,G}$ propagates along the ridge from 0 to 60 $\mu m$ [Fig. 8(d)]. $\mathcal{E}_C$ remains confined for later times at a constant energy, whereas $\mathcal{E}_{S,G}$ decays and interferes with itself [Figs. 8(e) and 8(f)].

Movies corresponding to Figs. 6–8 are provided as Supplemental Material.30

C. Power dependence of the energy/intensity decays

In our sample, the emission above 1.544 eV is coming from excitonic states. The polariton emission lies at lower energies, down to 1.538 eV at the collector region. In this section, we analyze the dynamics of the energy and population relaxation along the full region of propagation of the condensates between $S$ and $C$ both in the presence or absence of $G$, obtaining quantitative values for the energy time decays and the optimal working conditions for the ON state.

Figures 9 and 10 show spatial-temporal maps of the energy [(a)–(c)])/intensity [(d)–(f)] evolution of the map for the same power values as those used in Figs. 3–5 and 6–8, respectively. Figures 9(a)–9(c) and 10(a)–10(c) have been obtained identifying the time at which the maximum emission intensity takes place, at a given $X$ position on the ridge, for every energy: this gives a point in the map whose energy is coded with the false color scale shown on the right-hand side of the upper row. Note that all the information concerning the strength of the emission, and therefore the polariton population, is lost in this representation. The complementary information is encoded in the second row in Figs. 9 and 10, giving in this case the polariton population from integrating all
is given by the arrival of polaritons at different positions along the ridge. Another discontinuity is observed between the decay of carriers at $S$ and the propagating polaritons $\mathcal{D}^{S-P}$. The power dependence of both discontinuities is evident in these panels and gives information about the speed of propagation of different emitting species. At $P_{th}$, the border $\mathcal{D}^{S-P}$ between carriers at $S$ and polaritons, whose propagation is seen for $X \gtrsim 15 \mu m$, is absent [Fig. 9(a)] because the energy of excitons and polaritons decay at the same rate, but it becomes very clear in Figs. 9(b) and 9(c). The speed of propagation of the carriers can be obtained from the slope of $\mathcal{D}^{S-P}$ and $\mathcal{D}^{P}$ lines. For the carriers at $S$ in Fig. 9(b), $\mathcal{D}^{S-P}$ is almost straight, therefore a mean speed value $v^S(\simeq 1.7 \times P_{th})$ can be obtained amounting to $\sim 0.02 \mu m/ps$. At the highest power [Fig. 9(c)], $v^S(\simeq 0.5 \times P_{th})$ initially has increased by a factor of $\sim 3$ as compared to $v^S(\simeq 1.7 \times P_{th})$, but the strong nonlinearities associated with the high carrier densities lead to the appearance of deceleration rendering a gradual decrease of $v^S$. The spatial extension of the carriers around $S$ also widens with increasing power, almost doubling its value from $\sim 30$ to $\sim 60 \mu m$ at 400 ps as seen in Figs. 9(b) and 9(c). It is also noticeable that the energy decay of the carriers is spatially flat in the region enclosed by $\mathcal{D}^{S-P}$.

The acceleration/deceleration of the propagating polaritons is distinct in the slope changes of $\mathcal{D}^{P}$ [Figs. 9(a)–9(c)]. For $P_S = P_{th}$, a rough estimation of the speed obtains $v^P(\simeq P_{th}) = 0.4 \mu m/ps$; $v^P$ increases to 0.6(1) and 1.1(1) $\mu m/ps$ for $P_S = 1.7 \times P_{th}$ and $10.5 \times P_{th}$, respectively. In the latter case $v^P$ amounts to 0.3% of the speed of light in vacuum. The formation of $\mathcal{E}_C$ at threshold [Fig. 9(a)] is seen by the purple (1.539 eV) oval shape at (\sim 60 \mu m, 400–600 ps). The enhancement of $v^P$ together with that of stimulated scattering processes with power give rise to an earlier appearance of $\mathcal{E}_C$ at \sim 280 ps lasting for 400 ps, almost doubling its spatial extent, at $P_S = 1.7 \times P_{th}$ [Fig. 9(b)]. The values for $v^P$ are in agreement with others reported in the literature (see, for example, Ref. 9). The much smaller values for $v^S$ are due to the larger exciton mass compared to that of polaritons. The energy gap between $\mathcal{E}_C$ and the propagating polaritons dissolves at $P_S = 10.5 \times P_{th}$ due to the very large number of polaritons and the very fast formation of this condensate. Finally, let us remark that the ballistic propagation of polaritons is evidenced in Fig. 9(b) by the constant energy (same color), for a given time, seen in the region enclosed by the $\mathcal{D}^{S-P}$ border and $C$. However, in case Fig. 9(c) a gradual change in energy (color) is observed, indicating the energy loss during the polariton propagation towards $C$.

We briefly discuss now the density maps for different power excitation shown in the lower row of Fig. 9, in a normalized, logarithmic false color scale shown on their right-hand side. Figures 9(d)–9(f) show that the main emission intensity arises from the population at $S$, with a gradual expansion towards $C$ with a much lower polariton population. The emission-intensity decay becomes faster with increasing $P_S$ power. For $P_S = 1.7 \times P_{th}$ [Fig. 9(b)], an enhanced emission following the $\mathcal{D}^{S-P}$ is apparent; interferences of polaritons in the region between \sim 20 and \sim 60 $\mu m$ are visible; the formation of $\mathcal{E}_C$ appears at 280 ps. Figure 9(f) shows several reflections of condensed polaritons between the ridge edge and the left-bouncing positions marked with white bars, which are
determined by the potential delimited by $g^{S-P}$ and the energy of the bouncing condensates; the longer the time, the larger the energy loss of the polaritons, which become less able to climb the barrier side, as borne out by the progressively increasing distance between the bars and the $g^{S-P}$ line, obtained from Fig. 9(c) and depicted with a white dotted line. At $\sim 60 \mu m$ and 100 ps, a considerable amount of population forms the $\epsilon_C$ condensate.

We turn now to the two-beam excitation compiled in Fig. 10. Figure 10(a) displays the energy decay of the polaritons in the OFF state for $P_S = 7.2 \times P_{th}$ and $P_G = 0.4 \times P_{th}$. The $\epsilon_{S-G}$ condensate, extending 20 $\mu m$, reveals an almost constant energy emission in time. The contrast of the OFF state is high as assessed by the negligible amount of polaritons that goes through the $G$ potential [Fig. 10(d)]; only a hint of the polaritons that were able to tunnel through is seen at (80 $\mu m$, 400 ps) in Fig. 10(a), that codifies the energy but not the intensity of the signal. The ratio $I(\epsilon_{S-G})/I(S)$ is much larger than $I(\epsilon_C)/I(S)$, obtained in the one-beam case since $\epsilon_{S-G}$ is trapped closer to $S$ and its feeding process is more efficient. Increasing $P_G$ to $1.8 \times P_{th}$ both $S$ and $G$ beams contribute to the formation and trapping of polariton condensates [Fig. 10(b)] $\epsilon_{S-G}$ and $\epsilon_C$. Figure 10(c), for $P_G = 9.0 \times P_{th}$, shows that, for the first $\sim 100$ ps, the energy decays at $S$ and $G$ are much faster than those of the polariton condensates. For longer times $t \geq 100$ ps, the energy decay of the populations at $S$, $\epsilon_{S-G}$, and $G$ is almost identical; however, $\epsilon_C$ is always at a lower energy due to the trapping at $C$.

A further inspection of the energy-integrated intensity maps shows that in Fig. 10(e), at 300 ps, when the $G$ barrier has considerably decayed, so that its energy coincides with that of $\epsilon_{S-G}$, the $\epsilon_{S-G}$ condensate starts expanding along the ridge; concomitantly a slanted interference pattern is obtained, revealing the dynamics of merging counterpropagating polaritons. The $\epsilon_{S-G}$ formation time ($\sim 70$ ps) is much shorter than that of $\epsilon_C$ ($\sim 350$ ps) due to the fact that $P_S$ is much larger than $P_G$ and that both beams contribute to feed $\epsilon_{S-G}$ while only the population at $G$ refills the $\epsilon_C$ condensate, which reaches its maximum intensity emission at 400 ps. In Fig. 10(f), the high $S$- and $G$-pump powers make the $\epsilon_{S-G}$ condensate very intense at 40 ps. The confluence of the $S$ and $G$ populations with $\epsilon_{S-G}$ takes place at 100 ps and 1.542 eV. Then, $\epsilon_{S-G}$ doubles its spatial width, as observed by the spreading cone of polaritons extending $20 \mu m$ at 40 ps to $40 \mu m$ at 250 ps. A clear back and forth bouncing of the $\epsilon_C$ condensate between the $G$ barrier and the ridge edge is observed during the first 100 ps. After losing its kinetic energy at $t \sim 150$ ps, $\epsilon_C$ stops and emits for more than 600 ps, as its population is continuously fed by propagating polaritons at $\sim 1.541$ eV.

The energy maps shown in Figs. 9(a)–9(c) and 10(a)–10(c) allow us to quantitatively analyze the energy decay at every $X$ position; in particular we present in Fig. 11(a) this decay at the $S$ position for $P_S = 10.5 \times P_{th}$. The solid white line in Fig. 11(a) corresponds to its best fit to the sum of two exponentially decaying functions, shown separately by the dashed and dotted-dashed lines. The double fashion decay is attributed to two different physical processes: a fast decay due to relaxation driven by exciton-exciton interactions and a slow one, attributed to the decreasing blue-shift caused by the diminishing exciton and polariton populations. The rate of condensation can be expected to be faster at early times due to larger densities of carriers resulting in stronger stimulated scattering processes. A fast condensation rate results in an initial fast drop in the exciton density since excitons condense rapidly into polaritons that quickly decay. This drop in the exciton population gives a corresponding drop in the polariton population and so both blue-shifts, due to polariton-exciton and polariton-polariton repulsion, drop sharply at early times. At longer times, polariton condensation proceeds slower due to weaker stimulated scattering and the exciton populations decay with a slow exponential dependence due to exciton recombinaction. Figure 11(b) compiles the power dependence of the decay times: both decrease with increasing power, more markedly for $\tau_{fast}$ (circles), which decreases by $\sim 65\%$ for a 20-fold increase of power, while $\tau_{slow}$ (squares) only diminishes by $\sim 20\%$, revealing the larger influence of density in exciton-exciton scattering processes than in exciton-polariton ones.

The spatial integration of the data shown in Figs. 3–8 reveals the total energy and intensity decay dynamics for the different configurations under study as shown in Fig. 12.
Figures 12(a)–12(c)/Figs. 12(i)–12(iii) correspond to one-beam/two-beam excitation under different $P_S/P_G$ powers. The addition of contributions from different population species gives rise to a very rich dynamics. Figures 12(a)–12(c) exhibit a critical difference in the power dependence of the total decay: Fig. 12(a) shows a collective energy decay for all spatial positions along the ridge. Figures 12(b) and 12(c) show a low-energy streak corresponding to a polariton condensate drop that propagates along the ridge with an almost constant energy, unveiling the ballistic propagation of the condensate. The two streaks presented in Fig. 12(i) correspond to the decay of population at S (high-energy one) and the emission of $\mathcal{E}_{S-G}$ for a typical switch OFF state (low-energy one): the dynamics of both streaks is similar to those shown in Fig. 12(c), with the difference, not appreciated in the figure, that polaritons now are stopped just before the G barrier.

The three traces appearing in Fig. 12(ii), ordered by decreasing energy, compile the emission from the population at the source and the gate (S + G), the $\mathcal{E}_{S-G}$ condensate, and the $\mathcal{E}_C$ condensate, respectively. It is worthwhile noting the identical decay dynamics of the S and G populations, observed by the existence of only one streak for both populations. The $\mathcal{E}_C$ condensate shows an emission at $\sim 1.539$ eV, with a dynamics similar to that shown in Fig. 12(b). As the S power is kept constant in this subset of experiments, the G power permits manipulating on demand the amount of condensed polaritons at $\mathcal{E}_{S-G}$: if it would have been formed only by the S pulse, its energy should decay slightly; however, the extra population injected by the G pulse contributes with an additional blue-shift giving rise to an increase of the $\mathcal{E}_{S-G}$ emission energy, hinted at 300 ps in Fig. 12(ii), which becomes clearly visible in Fig. 12(iii). In this latter figure, the $S + G$ decays are also superimposed and $\mathcal{E}_C$ emits at a constant energy of 1.540 eV for $t > 50$ ps. It is important to note that in Fig. 12(ii) and Fig. 12(iii), the additional polaritons provided by the G pulse make the $\mathcal{E}_{S-G}$ condensate the highest populated state in the device with an emission intensity even larger than that of $S + G$ together.

1. Optimization of the switching time

Let us consider the optimal power conditions for the ON state for a S-C spatial separation of $\sim 60 \mu m$. We present in Fig. 13 the main effects of the $P_S$ power on the transistor switch ON state, which was illustrated before in Figs. 3–5. Figure 13(a) plots the normalized intensity dynamics of the source, at $X = 0$ (shadowed traces), and that of $\mathcal{E}_C$, at $X = 60 \mu m$ (full lines), for different $P_S/P_{th}$ values. We define the switch ON time $T_{ON}$ as the temporal delay between the S maximum intensity and that of $\mathcal{E}_C$. It is clearly observed that $T_{ON}$ decreases, and the shape of the $\mathcal{E}_C$ time evolutions becomes more asymmetric with increasing $P_S$. The asymmetry of the $\mathcal{E}_C$ temporal evolution [see Fig. 13(a)], which strongly depends on $P_S$, is characterized in Fig. 13(b), where we define a raise time $t_{up}$ (up triangles), given by the time spent to raise from an intensity of 0.5 up to the maximum value of 1. Similarly, $t_{down}$ (down triangles) is given by the time interval in which the intensity falls from a value of 1 to 0.5. A nonmonotonic dependence of $t_{down}$ on power is observed with a sharp raise at low $P_S$ values and a gradual fall for high ones: if the aim is to create a long-lived ON state, the optimal power corresponds to $P_S/P_{th} \approx 7$, where $t_{down} \approx 175$ ps. On its own hand, the raise time $t_{up}$ decreases monotonically with increasing $P_S$, reaching a minimum value of $\sim 50$ ps: a marked dependence at small powers, followed by an almost negligible decay at high ones, results in an optimum power to create a fast response transistor at similar powers than those required for a long-lived ON state. Figure 13(c) shows the power dependence of $T_{ON}$ (full circles) together with the initial energy shift of the emission at S. Same color legend for the values of $P_S$ are used in (a), (b), and (c).

FIG. 13. (Color online) (a) Integrated intensity at S position in filled lines and integrated intensity at C in full line for $P_S = 1,0,1,7,4,6,10,5,19.4 \times P_{th}$. (b) Up/down triangles show the raise/decay time $t_{up}/t_{down}$ from 0.5 to 1/0.5. (c) Full circles show the temporal separation between S and C intensity peaks; open diamonds depict the initial energy shift of the emission at S. Same color legend for the values of $P_S$ are used in (a), (b), and (c).

IV. MODEL

To model our experimental results theoretically, we make use of a phenomenological treatment of polariton energy-relaxation processes taking place in the system. Such processes
are not only responsible for the relaxation of hot excitons (injected by the pump) into polaritons in the form of a condensate, but also for the further relaxation in energy of the polariton condensate as it propagates. This latter energy-relaxation process can be strongly influenced by a spatially dependent potential coming from repulsion from the hot excitons. Let us first introduce the description of the polariton condensate, which we will later couple to a description of higher-energy excitons.

A fundamental feature of Bose-Einstein condensates is their spatial coherence that allows them to be well described with a mean-field approach. The Gross-Pitaevskii equation has been developed to describe the nonequilibrium dynamics of condensed polaritons, where losses due to the short polariton lifetime and gain due to nonresonant pumping were included phenomenologically. In such form, a variety of recent experiments can be modeled, including, for example, experiments on polariton transport, spatial pattern formation, and spin textures. The Gross-Pitaevskii equation for the polariton wave function \( \psi(x,t) \) is

\[
\frac{i\hbar}{d t} \frac{d \psi(x,t)}{d t} = \left[ \hat{E}_{LP} + \alpha |\psi(x,t)|^2 + V(x,t) \right. \\
+ \left. i\hbar \left( r N_A(x,t) - \frac{\Gamma}{2} \right) \right] \psi(x,t) \\
+ i\hbar \text{Re}[\psi(x,t)]. \tag{1}
\]

Here, \( \hat{E}_{LP} \) represents the kinetic energy dispersion of polaritons, which at low wave vectors can be approximated as \( \hat{E}_{LP} = -\hbar^2 \nabla^2 / (2m) \), with \( m \) the polariton effective mass. \( \alpha \) represents the strength of polariton-polariton interactions. Being repulsive (\( \alpha > 0 \)), these interactions allow both a spatially dependent blue-shift of the polariton condensate energy and energy-conserving scattering processes. Our analysis shows, however, that neither of these effects plays a dominant role in our experiments. The effective potential acting on polaritons caused by repulsive interactions between polaritons and higher-energy excitons is more significant, and is responsible for the blocking of polariton propagation in the presence of a gate pump. The effective potential \( V(x,t) \) can be divided into a contribution from three different types of hot-exciton states, which will be described shortly, as well as a static contribution due to the wire structural potential \( V_0(x) \):

\[
V(x,t) = \hbar [g_R N_A(x,t) + g_I N_I(x,t) + g_D N_D(x,t)] + V_0(x). \tag{2}
\]

\( N_A, N_I, \) and \( N_D \) correspond to density distributions of “active,” “inactive,” and dark excitons, respectively, as described in the following.

Experimental characterization has revealed that the static potential \( V_0(x) \) is nonuniform along the wire and exhibits a slight dip in the potential near the wire edge. \( g_R \), \( g_I \), and \( g_D \) define the strengths of interaction with the various hot-exciton states.

\( N_A \) represents the density distribution of an “active” hot-exciton reservoir. These excitons have the correct energy and momentum for direct stimulated scattering into the condensate and so appear as an incoherent pumping term in Eq. (1) with \( r \) the condensation rate. To describe the dynamics of the system, it is important to note that not all excitons in the system are in this active form. In fact, the nonresonant pumping creates excitons with very high energy and they must first relax in energy before becoming active. We can thus identify an “inactive” reservoir of hot excitons that is excited by the nonresonant pump, but not directly coupled to the condensate.

The dynamics of the exciton densities are described by rate equations

\[
\frac{d N_A(x,t)}{dt} = -\left( \Gamma_A + r |\psi(x,t)|^2 \right) N_A(x,t) + (\Gamma_I + t_R N_I(x,t)) N_I(x,t), \tag{3}
\]

\[
\frac{d N_I(x,t)}{dt} = -\left( \Gamma_I + t_R N_I(x,t) + t_D N_D(x,t) \right) N_I(x,t), \tag{4}
\]

\[
\frac{d N_D(x,t)}{dt} = t_D N_I(x,t) - \Gamma_D N_D(x,t). \tag{5}
\]

When solving the equations, we start from the initial condition \( N_A(x,0) = 0, N_D(x,0) = 0 \) and introduce a density proportional to the pump intensity profile in the inactive reservoir \( N_I(x,0) \). This represents an instantaneous injection by the nonresonant ultrashort pulse used in the experiment. The inactive reservoir is coupled by both linear and nonlinear terms to the active reservoir, described by \( t_R \) and \( t_D \), respectively.

We also account for a linear coupling to a dark exciton reservoir \( N_D(x,t) \), described by coupling rate \( t_D \). Dark excitons are long-lived states that are optically inactive yet can nevertheless be populated as high-energy excitations from the nonresonant pump relax in energy. The dark excitons introduce a long-lived repulsive contribution to the effective polariton potential \( V(x,t) \), and are thus efficient at gating propagating polaritons at long times. \( \Gamma_A, \Gamma_I, \) and \( \Gamma_D \) describe the decay rates of each of the reservoirs.

The feeding of dark excitons from the inactive reservoir represents processes where higher-energy electron-hole pairs relax in energy forming dark exciton states. We have neglected any further conversion between bright and dark excitons. Nonlinear conversion has been shown to generate oscillations between bright and dark excitons. However, these processes require coherent excitation of exciton polaritons near the dark exciton resonance. In our case, we do not expect accumulation of exciton polaritons at such an energy. Furthermore, the fact that no oscillations in the polariton condensate density were observed suggests that any coupling between bright and dark states is slower than the condensation rate.

It is worthwhile mentioning that we have also considered hot-exciton diffusion along the wire when solving Eqs. (3)–(5), using typical exciton diffusion rates; however, no noticeable effect on polariton dynamics was observed.

Returning to Eq. (1), the decay of polaritons is accounted for by the decay rate \( \Gamma \). The final term in Eq. (1) accounts for energy-relaxation processes of condensed polaritons. Polaritons are expected to condense at the source into the lowest-energy state, where they have zero kinetic energy and potential energy given by \( V(x,t) \) (and an additional blue-shift due to polariton-polariton interactions). While this is the lowest-energy state available at the source, one notes that the potential energy can be reduced if polaritons propagate away from the source.
where the reservoir densities are weaker. If polaritons were to conserve their energy, then they would convert this potential energy into kinetic energy as they move away from the source, accelerating down the potential gradient. However, the polariton kinetic energy can be lost as polaritons scatter with acoustic phonons or hot excitons. Surface scattering could be also responsible for this loss; however, since we have considered a phenomenological energy relaxation, the actual mechanism that causes that relaxation does not play a direct role in our calculations.

Previous methods to introduce energy relaxation into a description of polariton condensates have been based on the introduction of an additional decay of particles depending on their energy (occasionally known as the Landau-Khalatnikov approach). The polariton number can be conserved in such a process via the introduction of an effective energy-relaxation term.

The energy-relaxation term is

\[ \mathcal{R}[\psi(x,t)] = -(\nu + \nu')|\psi(x,t)|^2(E_{LP} - \mu(x,t))\psi(x,t), \]

where \( \nu \) and \( \nu' \) are phenomenological parameters determining the strength of energy relaxation. We do not attempt here a microscopic derivation of the energy-relaxation terms, we only note that we can expect some energy relaxation at low polariton densities (described by the parameter \( \nu \)) as well as a stimulated component of the relaxation proportional to the polariton density \( |\psi(x,t)|^2 \) (described by the parameter \( \nu' \)). Note that the energy-relaxation rate is assumed proportional to the kinetic energy of polaritons; polaritons will relax in energy until they decay from the system or until their kinetic energy is zero (such that they have zero in-plane wave vector).

The local effective chemical potential \( \mu(x,t) \) can be obtained from the condition

\[ \frac{\partial \sqrt{n(x,t)}}{\partial t} \bigg|_{\mathcal{R}} = 0, \]

where \( \psi(x,t) = \sqrt{n(x,t)} e^{i\theta(x,t)} \) for \( n(x,t) \) real, and

\[ \frac{d\psi(x,t)}{dt} \bigg|_{\mathcal{R}} \equiv \mathcal{R}[\psi(x,t)] = \frac{\partial \sqrt{n(x,t)}}{\partial t} \bigg|_{\mathcal{R}} e^{i\theta(x,t)} + i\sqrt{n(x,t)} e^{i\theta(x,t)} \frac{\partial \theta(x,t)}{\partial t} \bigg|_{\mathcal{R}}. \]

\( \mathcal{R} \) denotes the components of the derivatives due to the term \( \mathcal{R}[\psi(x,t)] \) in Eq. (1). Note that other terms in Eq. (1), namely, the pumping and loss terms, do not conserve the number of condensed polaritons. Although it would be desirable to define a mean-free path between scattering events, this is not trivial because the energy-relaxation rate is both energy and density dependent.

Equations (1)–(5) were solved numerically for different initial density profiles \( N_I(x,0) \), corresponding to the different source and gate configurations studied experimentally. We used the following parameters in the theory \( m = 7.3 \times 10^{-5} m_e \) (obtained from fits to the dispersions measured in Ref. 28, \( m_e \) is the free-electron mass), \( \alpha = 2.4 \times 10^{-3} \text{meV} \mu \text{m}^2 \) (Ref. 37), \( \Gamma_i = 1/18 \text{ps}^{-1}, \Gamma = \Gamma_D = 10^{-3} \text{ps}^{-1}, \gamma_r = 10^{-4} \text{ps}^{-1}, \gamma = \frac{2}{2} \times 10^{-4} \text{ps}^{-1}, \gamma_{IL} = 10^{-4} \text{ps}^{-1}, g_R = g_I = 0.04 \text{ps}^{-1} \mu \text{m}^2, g_D = 0.5 \text{ps}^{-1} \mu \text{m}^2, A = 0.014, \hbar \nu' = 0.075 \mu \text{m}^2.\)

**FIG. 14.** (Color online) Energy vs real space (X) for \( P_S = P_{th} \) at different times shown by the labels. The white dashed curves show the evolution of the effective potential \( V(x,t) \) due to hot-exciton repulsion as well as the ridge structural potential (same for Figs. 15–17). S and C mark the source and the collector positions, respectively. The intensity is coded in a false color scale shown on the right of each panel.

**FIG. 15.** (Color online) Energy vs real space (X) for \( P_S = 1.7 \times P_{th} \) at different times shown by the labels. S, C, and \( \tilde{E}_C \) mark the source, the collector, and the trapped condensate at C positions, respectively. The intensity is coded in a false color scale shown on the right of each panel.
power. This is because even though the injected hot-exciton population can be expected to increase linearly, the increased carrier density results in a faster condensation rate due to the stimulation of scattering processes (hot-exciton relaxation processes as well as processes that cause excitons to relax into condensed polaritons). Polaritons decay much faster than uncondensed hot excitons, such that a high-intensity pumping into condensed polaritons). Polaritons decay much faster than uncondensed hot excitons, such that a high-intensity pumping of hot excitons is quickly depleted, giving rise to a limited blue-shift of polaritons at the source.

B. Simulations for the two-beam excitation

In the presence of the gating pulse, the propagation of the \( C_{S,G} \) condensate is blocked, as shown in Fig. 17. This is due to the injected hot-exciton density at the gate position that adds to the polariton effective potential profile \( V(x,t) \). At long times, the theory predicts a small transmission across the gate pulse, due to the decay of the potential barrier.

C. Simulations on the power dependence of the energy/intensity decays

Spatial-temporal maps of the peak emission energy with one-beam excitation are shown in Fig. 18. In Fig. 18(a), there is a fast propagation of a high-energy mode from the source followed by a decrease in energy of the emission over the whole space. At longer times, one identifies relaxation into \( C_C \), near the wire edge. This behavior is in qualitative agreement with the experimental result, however, it can be noted that the speed of propagation appears overestimated in the theory.

This is because the theory neglects changes in the shape of the polariton dispersion caused by the hot-exciton-induced blue-shift, which can be particularly important at early times when the particles are strongly excitonic with a larger effective mass and slower group velocity. Figures 18(b) and 18(c) show the peak emission energy maps for increasing source intensity, where the relaxation into an extended state with lower energy than the source can be identified. The relaxation is stronger at the highest pump power, due to increased stimulated energy-relaxation processes. This is also evidenced by the shorter time required for \( C_C \) to appear with increasing pump power.

We discuss now the simulated energy and intensity maps under two-beam excitation conditions compiled in Fig. 19. Figure 19(a) shows the case when a gate pulse \( P_G = 0.4 \times P_{th} \) is present. At short times, the energy of the collector state is low, although it should be noted that it is populated with a negligible density [Fig. 19(d)]. The weak tunneling of particles across the gate is better evidenced by the increase of the collector state energy since the tunneling particles have higher energy than the collector ground state. At these low gate powers, the theory appears to predict a high number of polaritons passing the gate. These polaritons have relatively high momentum and are expected to be less visible experimentally due to reduced photonic fractions. An increase of the gate power above threshold [Figs. 19(b), 19(c), 19(e), and 19(f)] leads to an enhanced collector signal, as in the experimental case [see Figs. 10(b), 10(c), 10(e), and 10(f)], and the device leaves the OFF state. This is expected as additional excited polaritons move directly from the gate to the collector.

Figure 20 shows the time evolution of the spatially integrated spectra. In agreement with the experimental results (Fig. 12), there is a two-time-scale decay of the emission energy. At early times, the fast drop is due to the fast condensation rate in the presence of strong stimulated scattering. As mentioned earlier, this fast condensation rapidly depletes the hot-exciton reservoir and the total particle density quickly
drops as polaritons quickly decay. At longer times, reduced relaxation between the active and inactive reservoirs limits the effective condensation rate. The condensate is continuously fed while the reservoir intensities slowly decay. The short lifetime of the condensate for pumping at threshold [Fig. 20(a)] is expected from the theoretical definition of threshold where the incoming rate \( r N_A(x,t) \) is slightly larger than the polariton decay rate \( \Gamma \) in Eq. (1). As soon as condensation starts, the reservoir density \( N_A \) drops below threshold such that continued condensation can not take place. For higher pump powers, Figs. 20(b) and 20(c) show that both emission into a high-energy mode, corresponding to the source, and a lower-energy emission coexist. This fact is in close agreement with the experimental data shown in Figs. 12(b), 12(c), and 12(i), with the relaxation into the lower-energy state occurring earlier for increased pumping power.

V. CONCLUSIONS

In summary, we have time resolved the energy and intensity relaxation processes of excitons and polaritons in a microcavity ridge. Two different excitation configurations have been studied with one and two nonresonant, pulsed laser beams, permitting polariton condensate trapping on demand. A detailed analysis of the decay processes has been accomplished by mapping the energy and intensity emission along the ridge. Decay times of the source emission are reported under one-beam excitation, where we show the acceleration of the decaying processes as a function of increasing \( P_S \). The time response of the polariton transistor switch is characterized and optimized. We used a generalized Gross-Pitaevskii model to describe the spatial dynamics of our propagating polariton condensates, which includes a phenomenological treatment of energy-relaxation processes that cause condensates to further thermalize as they travel in a nonuniform effective potential. The nonlinearity of energy-relaxation processes throughout the system, those causing relaxation between polariton states as well as relaxation between higher-energy exciton states, is necessary to explain features of the experimental results. Approximating the system as a 1D system, we are able to describe the main qualitative features of the experiment. While the system is essentially 1D, lateral expansion could result in a lower propagation speed than that predicted theoretically. We intend to investigate lateral propagation effects in future work.

The optimization of individual condensate transistor elements, as we have reported here, is an essential step towards developing information processing devices with the present scheme. In the future, an important goal is the achievement of cascadability and fan-out of multiple elements for the construction of extended circuits. Such a feat was very recently achieved in polariton-based systems with coherent near-resonant excitation. Achieving the same with the gating of incoherently generated polariton condensates, as we study here, would be particularly promising as it would open up routes toward electrically injected devices and consequently hybrid electro-optical processing systems.

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APPENDIX: LIST OF SYMBOLS

In this Appendix, we define the symbols used as abbreviations along the paper.
TABLE I. List of symbols used to describe the experiments.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆E_s</td>
<td>Energy shift of the emission at the source position</td>
</tr>
<tr>
<td>τ_fast</td>
<td>Energy fast decay time at the source</td>
</tr>
<tr>
<td>τ_slow</td>
<td>Energy slow decay time at the source</td>
</tr>
<tr>
<td>C</td>
<td>Collector</td>
</tr>
<tr>
<td>γ_C</td>
<td>Polariton condensate trapped at the collector</td>
</tr>
<tr>
<td>γ_C,G</td>
<td>Polariton condensate trapped between source and gate positions</td>
</tr>
<tr>
<td>g_P</td>
<td>Horizon of propagating polaritons along the ridge</td>
</tr>
<tr>
<td>g_P-G</td>
<td>Horizon given by the interface between carriers at the source and propagating polaritons</td>
</tr>
<tr>
<td>G</td>
<td>Gate</td>
</tr>
<tr>
<td>I(G)</td>
<td>Emission intensity of the condensate trapped at the collector</td>
</tr>
<tr>
<td>I(S)</td>
<td>Emission intensity at the source position</td>
</tr>
<tr>
<td>P_G</td>
<td>Gate beam power</td>
</tr>
<tr>
<td>P_S</td>
<td>Source beam power</td>
</tr>
<tr>
<td>P_th</td>
<td>Pump power threshold for polariton condensation</td>
</tr>
<tr>
<td>S</td>
<td>Source</td>
</tr>
<tr>
<td>t_down</td>
<td>Time for the collector intensity to drop from 1 to 0.5</td>
</tr>
<tr>
<td>T_ON</td>
<td>Time delay between maxima of the source and collector intensities</td>
</tr>
<tr>
<td>t_up</td>
<td>Time for the collector intensity to rise from 0.5 to 1</td>
</tr>
<tr>
<td>v_P</td>
<td>Mean speed of propagating polaritons</td>
</tr>
<tr>
<td>v_S</td>
<td>Mean speed of carriers at the source position</td>
</tr>
</tbody>
</table>

TABLE II. List of symbols used on Sec. IV Model.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>Polariton-polariton interaction strength</td>
</tr>
<tr>
<td>Γ</td>
<td>Polariton decay rate</td>
</tr>
<tr>
<td>Γ_A</td>
<td>Decay rate of the active exciton reservoir</td>
</tr>
<tr>
<td>Γ_D</td>
<td>Decay rate of the dark exciton reservoir</td>
</tr>
<tr>
<td>Γ_I</td>
<td>Decay rate of the inactive exciton reservoir</td>
</tr>
<tr>
<td>v/l_v</td>
<td>Phenomenological parameters for the strength of energy relaxation</td>
</tr>
<tr>
<td>ψ(x,t)</td>
<td>Polariton wave function</td>
</tr>
<tr>
<td>E LP</td>
<td>Lower polariton branch energy dispersion</td>
</tr>
<tr>
<td>g_P</td>
<td>Polariton-exciton interaction strength for dark excitons</td>
</tr>
<tr>
<td>g_I</td>
<td>Polariton-exciton interaction strength for indirect excitons</td>
</tr>
<tr>
<td>g_R</td>
<td>Polariton-exciton interaction strength for active reservoir excitons</td>
</tr>
<tr>
<td>m</td>
<td>Polariton effective mass</td>
</tr>
<tr>
<td>m_r</td>
<td>Free-electron mass</td>
</tr>
<tr>
<td>N_A</td>
<td>Density distribution of active excitons</td>
</tr>
<tr>
<td>N_I</td>
<td>Density distribution of inactive excitons</td>
</tr>
<tr>
<td>N_D</td>
<td>Density distribution of dark excitons</td>
</tr>
<tr>
<td>r</td>
<td>Polariton condensation rate</td>
</tr>
<tr>
<td>τ_D</td>
<td>Linear coupling to the dark exciton reservoir</td>
</tr>
<tr>
<td>τ_R</td>
<td>Linear coupling to the inactive exciton reservoir</td>
</tr>
<tr>
<td>t_g</td>
<td>Nonlinear coupling to the inactive exciton reservoir</td>
</tr>
<tr>
<td>V(x,t)</td>
<td>Effective polariton potential</td>
</tr>
<tr>
<td>V_0(x)</td>
<td>Wire structural potential</td>
</tr>
</tbody>
</table>
The energy maps consider a cutoff based on the experimental background noise, leaving white points when the intensity is below that noise level.


