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Logic Gates with Bright Dissipative Polariton Solitons in Bragg-Cavity Systems


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Optical solitons are an ideal platform for the implementation of communication lines, since they can be packed extremely close one to another without risking partial loss of the encoded information due to their interaction. On the other hand, soliton-soliton interactions are needed to implement computations and achieve all-optical information processing. Here we study how bright dissipative polariton solitons interact and exploit their interaction to implement AND and OR gates with state of the art technology. Moreover, we show that soliton-soliton interaction can be used to determine the sign of \( \alpha_2 \), the parameter describing the interaction between polaritons with opposite spin.

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I. INTRODUCTION

Solitons are self-reinforcing wavepackets that maintain their shape while propagating. Bright dissipative solitons are a particular class of solitons typical of out-of-equilibrium systems. Differently from their conservative counterpart, dissipative solitons are implemented by means of a continuous gain, compensating the loss of particles from the system, and by means of a trigger, which generates a bright wavepacket on top of a much less intense background. This kind of solitons has been extensively studied in a wide range of systems and single and multiple solitons states as well as oscillating bound states have been predicted and demonstrated\(^1\)–\(^4\). Surprisingly very little attention has been devoted to the study of interactions among bright dissipative solitons in dynamical systems\(^5\)–\(^6\) and, to the best of our knowledge, no attention has been devoted to the implementation of devices based on dissipative solitons, unlike for the conservative ones\(^7\).

Since the first observation of strong light-matter coupling in a semiconductor micro-resonator\(^8\) this system has been intensively studied for the implementation of a new generation of optical devices. In fact, the dual light-matter nature of polaritons, the particles emerging from the coherent strong coupling of cavity photons with quantum well excitons, provides significant advantages with respect to electronic as well as standard nonlinear optical systems. On the one hand the light component allows high propagation velocities and fast control and, on the other hand, the matter component guarantees strong nonlinearities, much stronger than in traditional optical systems with Kerr nonlinearities\(^9\). For these reasons several theoretical proposals have been advanced for the implementation of neural networks, switches and logic gates\(^10\)–\(^12\). And several experimental implementations such as switches, spin switches, resonant tunneling diodes and transistor have also been demonstrated\(^13\)–\(^17\).

To implement fast and efficient polariton devices, however, the major problem of the long reset-time of the device needs to be solved. In fact, in all these approaches after each “calculation” one needs either to completely turn off the device or to wait hundreds of picoseconds to allow long-lived excitonic reservoirs to decay. A possible way to address this problem is to use red-detuned ultrashort Stark pulses\(^18\) but with the major drawback that very high laser intensities are needed. Bright dissipative polariton solitons (BDPSs) can, in principle, solve this problem. In fact, BDPSs can be triggered with few ps-long pulses that do not excite excitonic reservoirs and, after the passage of a soliton, the system is left, by definition, in its OFF state.

In this work we study the interaction of dynamical BDPSs in circuits etched in planar Bragg-microcavities and show that AND and OR gates can be implemented by exploiting these interactions. Moreover, we show that by studying soliton-soliton interactions it is possible to evaluate the constant characterising the interaction of polaritons with different spins.

The main requirements for the implementation of BDPSs, predicted and observed in planar 2-dimensional cavities\(^19\)–\(^21\), are twofold: 1) the pump wavevector has to be above the point of inflection of the lower polariton branch; 2) the pump has to be blue-detuned from the polariton branch in order to guarantee a bistable regime. In fact, BDPSs can be qualitatively interpreted as spatially localised excited regions of the modulatonally unstable upper branch solution\(^20\). The main advantage of BDPSs is that they can propagate for very large distances determined by the size of the pump. The main drawback, instead, is that being part of the pump state their energy, velocity and direction of propagation are set by the pump itself. Therefore, the propagation paths of two BDPSs can never intersect, making impossible the implementation of logic gates. To solve this issue we propose to inject BDPSs moving from left to right in circuits with the shape of a Y [Fig. 1(a)]. In this way the two converging arms act as filters allowing only the part of the pump parallel to them to enter in the cavity and forcing two BDPSs to meet at the junction.

The paper is structured as follows. In section II we present the mean field approach used to describe the four components wavefunction (two exciton and two photon components, one for each spin/polarisation degree of
freedom). Section III describes the main results of our research. First it will be demonstrated that dissipative solitons can propagate in straight wires and, making use of this result, the possible implementation of OR and AND gates will be addressed. The final part of section III will deal with the interaction of dissipative polariton solitons with opposite polarisation and with an analysis of the role played by the TE-TM splitting on the possible implementation of the gates. Conclusions and outlooks will be given in section IV.

II. METHODS

The system of a quantum well embedded in a semiconductor microcavity can be modelled by means of a four-component wave function where the spin up and spin down excitonic fields ($\psi^{\pm}_{ex}$) are strongly coupled to the two $\sigma_+$ and $\sigma_-$ circularly polarised photonic fields ($\psi^{\pm}_{ph}$) through the vacuum Rabi coupling $\hbar \Omega_R$ (2.55 meV in our case). The dynamics of the system can be modelled by means of the generalised Gross-Pitaevskii equation:

$$i\hbar \partial_t \psi^{\pm}_{ph} = \left[ \hbar \omega_{ph}(k) + U_x - i\hbar \gamma_{ph}/2 + \beta (ik_x \pm k_y)^2 \right] \psi^{\pm}_{ph} + F_{\pm} + \hbar \Omega_R \psi^{\pm}_{ex},$$

$$i\hbar \partial_t \psi^{\pm}_{ex} = \left[ \hbar \omega_{ex}(k) - i\hbar \gamma_{ex}/2 + \alpha_1 |\psi^{ex}_{\pm}|^2 + \alpha_2 |\psi^{ex}_{\mp}|^2 \right] \psi^{\pm}_{ex} + \hbar \Omega_R \psi^{\pm}_{ph}. \quad (1)$$

Here $\omega_{ph}(k) = \omega^0_{ph} + \hbar k^2 / 2m_{ph}$, with $m_{ph} = 5.0 \times 10^{-5} m_0$, is the dispersion of the confined photon mode and $m_0$ is the free electron mass. Since the exciton mass is much higher than $m_{ph}$ a flat exciton dispersion is taken ($\omega_{ex}(k) = \omega^0_{ex}$). Throughout the paper the zero energy is set to the bare exciton frequency and exciton-photon detuning is taken to be equal to zero ($\omega_{ph}(0) = \omega^0_{ph} = 0$). The terms $U_\pm$ describe wires etched in the top cavity-mirror. All the results shown here correspond to $U_{\pm}(r) = \frac{1}{2} m_{ph} \hbar^2 d^2$, where $\omega_{ph}$ determines the potential strength and $d$ is the distance from the wires centre. In order to test the robustness of the proposed device we numerically confirmed the implementation OR and AND gates using potentials proportional to $d_1$ and $d_2$.

The parameters $\gamma_{ph}, \gamma_{ex}, \alpha_1$ and $\alpha_2$ respectively describe the photon and exciton decay rates, and the interaction between excitons with identical and opposite spin. For the sake of generality we rescale field densities and interaction constants to have $\alpha_1 = 1$ and $\alpha_2 = -0.123$. Finally, the terms proportional to $\beta$ describe the TE-TM splitting, while the terms $F_{\pm}$ describe a continuous wave (CW) and a pulsed laser fields. Throughout the paper the CW terms will be taken equal to $F^0_{\pm} f(r) e^{i(k_p r - \omega_p t)}$, where $f(r)$ has a top-hat spatial profile, $\omega_p$ is the pump frequency and $k_p = (k_p,0)$ is the pump wavevector. The pulsed terms have the same frequency and wavevector of the CW ones, intensity $f^p_{\pm}$, and Gaussian profiles in space and time: $f^p_{\pm}(r,t) = e^{-x^2/2\sigma^2_{x} - t^2/2\sigma^2_{t}}$, with $\sigma_t = 1.5$ ps and $\sigma_{sp} = 1 \mu$m.

III. RESULTS

A. Straight Wires

We first consider the case of a single wire with zero TE-TM splitting and demonstrate the existence of solitonic solutions for harmonic potentials (see24 for super-Gaussian profiles). In analogy with19,20 we fix the CW-pump frequency and angle in order to be blue-detuned ($\Delta E = 0.166$ meV) from the lower polariton dispersion at a wavevector above its point of inflection. Here, however, the relevant polariton dispersion is the one corresponding to the lowest confined mode of the harmonic trapping potential [Fig. 1(b)]. Here and in the following we numerically simulate the time evolution of the system with a pump linearly polarised parallel to the wire and a trigger circularly polarised $\sigma_+$. Figure 1(b) shows the typical solitonic linear dispersion while panel (c) shows 1-dimensional cuts along the propagation direction of the $\sigma_+$-polarised cavity emission ($\psi^p_{\pm}$). After an initial transient time, in which the excited Gaussian-
shaped wavepacket transforms into a solitary wave (9–88 ps), the profile does not change until the wavepacket exits the CW-pump, therefore demonstrating the existence of BDPS solutions (animation in supplementary material  SVwire).

B. Logic gates: OR and AND

Let us now address the case of Y junctions still considering $\beta = 0$. Since the CW-pump is set in order to inject polaritons moving from left to right, the region of the device downstream the junction is analogous to the case of the single wire. Therefore, considering the same CW-pump as before we are sure that BDPSs can propagate in this part of the device. The question is whether BDPS solutions exist in the two oblique wires. As already said, these wires essentially act as filters allowing only the components of the CW-pump parallel to them to enter into the microcavity. Therefore, inside the oblique wires the polariton wavevector is: $k_\parallel = k_p \cos(\theta/2)$, where $\theta$ is the angle between the two wires. If $\theta$ is small enough so that $k_\parallel$ is above the point of inflection of the polariton dispersion soliton propagation is permitted. For our choice of the parameters ($\theta = 16^\circ$) $k_\parallel = 2.47 \, \mu m^{-1}$ is still above the point of inflection.

In order to demonstrate the implementation of logic gates we define the base of the binary logic as follows: 1 corresponds to the presence of a BDPS polarised $\sigma_+$, and 0 to the absence of it. Note that since we are considering $\beta = 0$ and linearly polarised CW pumps, a BDPS polarised $\sigma_-$ as 1 is an equivalent choice. Linearly polarised BDPSs, instead, cannot be used since the interaction of excitons with opposite spin components makes them unstable.\(^{21}\)

Figure 2 demonstrates the implementation of an OR gate. The top panel shows the $\sigma_+$ polarised emission from the cavity at different times: when the soliton is in the upper arm, when is just after the junction, and when is propagating downstream the junction. This panel shows that the first line of the OR logic table can be implemented using travelling BDPSs in Y junctions (supplementary material SVOR1). What is it worth noticing is that at $t = 60$ ps the polariton distribution does not have the typical BDPS-like distribution as at $t = 26$ ps (a bright peak followed by a few less intense peaks). This can be understood by observing that in the junction the laser-lower polariton detuning ($\Delta E$) is not the same as in the wires, and therefore BDPSs entering the junction will need to adapt to the new conditions. For the specific set of parameters chosen here the bright wavepacket is able to pass through the junction, to enter into the downstream wire and, after few ps, to stabilise to the usual BDPS shape. However, if in the junction the deviation from the optimal condition for soliton formation is too large (i.e. $\Delta E$ is too big), the BDPS will disappear because the pump is too weak to sustain its excess population while in the junction.

The lower panel in figure 2 shows the implementation of the third line of the OR logic table. Here, two BDPSs simultaneously arriving at the junction transform into a single BDPS downstream the junction (supplementary material SVOR3). What is worth noticing here is that the two solitons merge into a single BDPS having lower intensity than the sum of the two initial ones. This is because the CW-pump is fixed in order to sustain a single BDPS, and is too low to sustain the population of two BDPSs and. Therefore, the population forming two BDPSs is bound to decrease down to the population of a single soliton. Finally, the second and fourth lines of the OR logic table are trivial if the first and third are satisfied.

In order to implement an AND gate it is useful to recall what was just said about $\Delta E$ being, in the junction, too big to allow for the pump to sustain a BDPS. A possible way to implement an AND gate is to increase $\Delta E$ enough to forbid one soliton to pass, but keeping it small enough for two solitons to pass. Since we want to build a complex circuit we would like to use the same
Let us now address the case of the interaction of BDPSs with different spin. From equation (1) it can be seen that the effect due to the presence of a population of polaritons $\sigma_- (\sigma_+)$-polarised is to shift the opposite-polarised polariton branch by an amount $\alpha_2 |\psi_+|^2 \pm |\psi_-|^2 |\alpha_2|$, with a positive or negative shift depending on the sign of $\alpha_2$. Figure 4 shows the same situation as in the lower panel of Fig. 2 but with a $\sigma_-$ polarised BDPS in the lower arm (this is possible since the CW-pump is linearly polarised). When the two BDPSs with different polarisation interact, they mutually annihilate (supplementary material SVALPHA2). In fact, since $\alpha_2$ is negative, the $\sigma_+$ polarised soliton red-shifts the $\sigma_-$ polarised polariton branch out of resonance with the CW-pump by an amount $\alpha_2 |\psi_+|^2$, therefore inducing the decay of the $\sigma_-$ polarised soliton. The same is valid for the $\sigma_-$ polarised soliton that induces the decay of the $\sigma_+$ polarised one. The situation would have been completely different for $\alpha_2 > 0$. In that case both BDPSs would have blue-shifted the polariton branch with opposite polarisation therefore helping the CW-pump to sustain the excess population.

D. Effect of TE-TM splitting

Finally let us comment on the effect of TE-TM splitting ($\beta \neq 0$). The case of BDPSs travelling in wires is not qualitatively different from the case of planar Bragg-microcavity. If the splitting induced by $|\beta|$ at the pump wavevector $k_p$ is small relatively to the detuning $\Delta E$, both $\sigma_+$ and $\sigma_-$ polarised BDPSs can be excited\(^{21}\). This is understood in terms of an “effective” quenching of the TE-TM splitting. However, even if TE-TM splitting does not forbid, in principle, the implementation of the proposed logic gates, the condition $\Delta E > |\beta| k_p^2$ can be rather restrictive, specially for weak lateral confinement of the wires. In this case, in fact, the different polariton branches are quite close one to another and therefore the maximum allowed value for $\Delta E$ is small (we confirmed the feasibility of our devices for realistic values of $\beta = 0.02 \text{meV} \mu \text{m}^2$).

IV. CONCLUSION

In summary, we have theoretically demonstrated that high speed travelling BDPSs can cross junctions about 10 $\mu \text{m}$ wide and travel through Y-shaped devices. Moreover, we showed that two BDPSs meeting at the junction show effective interactions that can be exploited to implement OR and AND gates with repetition rates up to 100 GHz. This result is achieved in devices that allow BDPSs to move one towards another, overcoming the limitations in propagation direction typical of BDPSs in planar microcavities. Moreover, we showed that with the proposed...
devices it is possible to investigate the sign of $\alpha_2$, the parameter describing the interaction between excitons with opposite spin.

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