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Optical diode based on exciton-polaritons

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We propose theoretically an optical diode based on exciton-polaritons in semiconductor microcavities. A flow of polaritons in the bistable regime is used to send signals through an asymmetric fixed potential that favours the bridging of particles in one direction. Through dynamic modelling of the coherent polariton field, we demonstrate the characteristics of an ideal diode, namely, that the forward signal is fully transmitted while the transmission in the reverse direction tends to zero, without any additional external control. Moreover, the system proves to be robust to the presence of disorder, intrinsic to microcavities, and can function at gigahertz repetition rates. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4829363>]

The engineering of optical microprocessors would open the door for a new generation of computers, allowing fast calculations, where the low carrier resistance would reduce heat losses. The search for the optimal systems to develop this technology has increased the interest in non-linear optical controlled systems such as exciton-polaritons in semiconductor microcavities.^{1,2}

Polaritons are quasi-particles resulting from the strong coupling of photons and quantum well excitons. This origin has provided them with a low mass and strong nonlinear interactions—characteristics that have made them successful building blocks for multiple photonic devices, such as lasers,^{3–6} interferometers,^{7,8} holographic devices,⁹ terahertz emitters,^{10,11} optical routers,¹² transistors,^{13,14} and integrated photonic circuits,^{15,16} among others.¹⁷ With such a variety of applications, it would seem that a new era of polaritonics is close.

A common problem for the linking of polaritonic devices is the compensation of loss due to photon emission. The amplification of polariton states by bosonic stimulation^{18–21} was one of the first nonlinear effects studied in these systems, and propagating polariton wavepackets were recently amplified through a non-resonant excitation of reservoir states.²² An alternative approach to amplification has been based on the bistable behaviour of polaritons,^{23–25} which itself has been used to create polariton switches^{26,27} and ultrafast memories.²⁸ In the bistable regime, a switched state survives indefinitely²⁸ where the loss is compensated by a continuous wave laser that, together with interactions, sets the bistability in the system. By exploiting the propagation of a domain wall, it has been predicted theoretically that one can transport loss-less signals in the microcavity plane.^{29,30} Structured potentials control the signal propagation along wires or “polariton neurons” and signals can cover distances that go far beyond the limits expected of the polariton lifetime.

To be competitive, a signal processing device needs to achieve a low error rate, which may require the suppression of feedback. A useful element to reduce feedback would be a polaritonic analogue of the diode—a device that ideally allows full signal transmission in one direction, with signal

suppression in the other. Very recently, a double barrier resonant diode based on polaritons was constructed,³¹ where a high contrast gating of the transmission was achieved through the application of a gating laser. This design was based on ballistically propagating polariton wavepackets.³²

In this paper, we present a design for an optical diode compatible with propagating domain walls (polariton neurons). An asymmetric response is achieved without using an additional gating laser, instead making use of a fixed spatially patterned potential, which favours the bridging of particles in one direction only. We show that it is possible to achieve 100% transmission for the forward signal, while the backward signal is fully blocked by the static potential. Without the action of any external electric or optical control potential, the device can operate as a tunnel diode or as a backward diode, depending on the direction of the incoming flow of polaritons. Finally, we test the functionality of the system when disorder in the microcavity is present and show that both signal propagation along polariton neurons and the diode itself is fully robust to realistic levels of disorder.

The system consists of an optical microcavity, shown in Fig. 1, where the polaritons within are subjected to a fixed potential $V(\mathbf{r})$, which takes the pattern shown in Fig. 2(a). A similar shaped potential was considered for the design of vortex guns³³ and can be achieved by a variety of different techniques, such as: varying the thickness of the cavity layers,³⁴ etching the cavity structure,³² using optically induced potentials,^{35,36} or placing metallic plates on the top of the microcavity,³⁷ as shown in Fig. 1.

In order to describe the dynamics of the system, we use the mean-field approximation that leads to the Gross-Pitaevskii equation³⁸

$$i\hbar \frac{\partial \Psi}{\partial t} = \left(\hat{E}_{LP}(\hat{\mathbf{k}}) + V(\mathbf{r}) - \frac{i\hbar}{2\tau} + \alpha |\Psi|^2 \right) \Psi + \mathfrak{F}(\mathbf{r}, t) e^{-\frac{i\epsilon_p t}{\hbar}}, \quad (1)$$

where Ψ is the coherent polariton field; $V(\mathbf{r})$ is the spatial potential; τ is the polariton lifetime; α is the nonlinear polariton-polariton interaction strength; and $\mathfrak{F}(\mathbf{r}, t)$ is the incident optical field amplitude with energy ϵ_p . The kinetic energy

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FIG. 1. A microcavity formed by two distributed Bragg mirrors (DBRs). The excitons in the quantum well will strongly couple to the photons injected by the normal incident optical pump, forming polaritons. The metallic plates in the top will provide the fixed potential.

corresponds to the non-parabolic lower polariton dispersion band $\hat{E}_{LP}(\hat{\mathbf{k}}) = (E_0(\hat{\mathbf{k}}) + E_X - \sqrt{(E_0(\hat{\mathbf{k}}) - E_X)^2 + 4\Omega^2})/2$, where $E_0(\hat{\mathbf{k}})$ is the photon dispersion, E_X is the exciton energy, and Ω is the exciton-photon coupling strength. For simplicity, we neglect the exciton dispersion, which is flat compared to the photon dispersion and shift the origin of energy to $E_{LP}(0)$. We also neglect the spin degree of freedom, noting that the interaction strength between polaritons with opposite spins is typically weaker than that between parallel spins.³⁹

Before understanding how polaritons at different points in the microcavity are coupled, it is instructive to first consider the local response of the system. This can be done by first neglecting the kinetic energy term, in which an analytical expression relates the local polariton density of a stationary state to the optical pump intensity²³

$$|\mathfrak{F}|^2 = \left[(\varepsilon_p - V(\mathbf{r}) - \alpha|\Psi|^2)^2 + \frac{\hbar^2}{4\tau^2} \right] |\Psi|^2. \quad (2)$$

When $(\varepsilon_p - V(\mathbf{r})) > \sqrt{(3)\hbar}/(2\tau)$, the above equation describes an “S” shaped response curve, and the polariton

density can take either of the values given by the upper or lower branch (the middle branch is unstable²³), as shown in Fig. 2(b). Therefore, by varying the laser intensity, it is possible to drive the system into a bistable regime. Now, when the kinetic energy is taken into account, a coupling of the dynamic response of spatially separated domains allows the sending of signals, as will be described briefly.

The microcavity will be subjected to both a continuous wave (cw) optical pump $F_{cw}(\mathbf{r})$ and a pulsed excitation $\mathfrak{P}(\mathbf{r}, t)$, both with Gaussian shape and the same energy. The total field is then given by the superposition $\mathfrak{F}(\mathbf{r}, t) = F_{cw}(\mathbf{r}) + \mathfrak{P}(\mathbf{r}, t)$. The optical pump $F_{cw}(\mathbf{r})$, will provide the whole area with a constant wave to compensate the finite lifetime of polaritons; the intensity F_{cw}^2 can be increased steadily until the value marked by the black vertical line in Fig. 2(b), so the initial state will be given by the black dot in the lower bistable branch.

The pulse $\mathfrak{P}(\mathbf{r}, t)$ will be used to send the signals. It will locally increase the intensity of the optical field, which will cause the polaritons in the lower bistable branch to “jump” to the upper branch. After a time δt , the pulse $\mathfrak{P}(\mathbf{r}, t)$ will vanish and the polaritons remaining in the upper branch will relax to the corresponding intensity F_{cw}^2 [black dot in the upper branch in Fig. 2(b)]. The kinetic energy term then couples neighbouring points in space, such that neighbouring polaritons will jump successively to the upper bistable branch,⁴⁰ allowing signal propagation in the form of a propagating domain wall.²⁹

Notice that the optical pump will excite polaritons mainly in the blue region of Fig. 2(a) where $V(\mathbf{r}) = 0$. This is due to the energy detuning of the pumps with respect to the potential energy, which will be smaller in this region, compared to the detuning for polaritons in the area where $V(\mathbf{r}) = -3.5$ meV [see Eq. (2)]. This choice of the potential, instead of a confinement well, is done to avoid the interference of reflected waves.

First, we consider the case of *forward operation*, where the signal originates from the extreme left in Fig. 2(a). In the first column of Fig. 3, we show the numerical results of Eq. (1) at different times. In the first row, we show the moment when the pulse $\mathfrak{P}(\mathbf{r}, t)$ is sent. The slides below show the system evolving after $\mathfrak{P}(\mathbf{r}, t)$ has vanished. When the signal arrives at the “C” looking shape of the potential, polaritons begin to ballistically propagate from all points on the semicircle across the gap. They constructively interfere in the center of the semicircle, giving a sufficient intensity to switch the state of the second part of the channel. The signal then continues propagating to the right, as shown in Fig. 3.

FIG. 2. (a) Potential $V(\mathbf{r})$. (b) Eq. (2), for $V(\mathbf{r}) = 0$; the lower (blue) and the upper (red) branches are the possible states of the system, the dashed line indicates an unstable state and the vertical line indicates the value of F_{cw}^2 chosen for our subsequent calculations.

FIG. 3. In the first column, we show the forward signal; in the subsequent rows, we appreciate the transition of the signal beyond the semicircle due to constructive interference. The second column corresponds to the backward signal. In this case, the signal cannot propagate to the left side. The parameters used are, $\tau = 18\text{ps}$, $\Omega = 2.5\text{meV}$, $\epsilon_p = 0.5\text{meV}$, $\alpha = 0.004\text{meV}\mu\text{m}^2$. The photon dispersion was taken as parabolic with an effective mass 10^{-5} of the free electron mass.

The transmitted signal has the same intensity as the incident one, corresponding to 100% transmission, since optical losses are fully compensated by the cw pump.

In contrast to devices and experiments based on ballistic polariton propagation,⁸ the polariton neuron mechanism of signal propagation gives rise to smooth polariton density patterns in the channel,²⁹ even when signals reach the entrance to the “C” shaped part. The switched state is given approximately by the stationary solution to Eq. (2), resulting in a polariton intensity limited to the red curve in Fig. 2(b). The switched state is composed mainly of long wavelength polaritons (injected by the optical pump with zero in-plane wave-vector) and is known to be modulationally stable to fluctuations.⁴²

The *reverse operation* corresponds to the case where the signal starts in the extreme right (second column in Fig. 3). The mechanism for signal propagation is completely analogous to the previous case, nevertheless, here the signal cannot propagate beyond the semicircle. This is partly because the smaller size of the edge of the right-hand channel causes fewer polaritons to be emitted. More importantly, any polaritons that are emitted and attempt to cross the gap in the reverse direction are not focused, in contrast to the forward operation case. While a few polaritons can cross the gap, their intensity is not enough to switch the signal in the semicircle region. In other words, the potential’s shape completely blocks the reverse signal. Note that this asymmetric response does not rely on any additional external electric or

FIG. 4. We show a small area of the disorder potential [Eq. (3)]. The parameters characteristic of the disorder are $\sigma = 1.5\mu\text{m}$ and $A_w = 0.052\text{meV}$.

optical field, as in traditional diodes, but merely in the direction of the incoming flow of polaritons.

Disorder is unavoidable in all realistic microcavity structures⁴¹ and represents a potential feedback mechanism given that it causes the Rayleigh scattering of polaritons⁴³ in all directions and enhanced backscattering.⁴⁴ Consequently, we tested the robustness of our system when defects are present in the potential. We add to the potential $V(\mathbf{r})$ [Fig. 2(a)], a random potential of the form

$$W(\mathbf{r}) = \frac{A_w}{\sqrt{\pi}\sigma} \int_0^\infty \text{Exp} \left[-\frac{(\mathbf{r} - \mathbf{r}')^2}{2\sigma^2} \right] v(\mathbf{r}) d\mathbf{r}', \quad (3)$$

with $v(\mathbf{r})$ being a random white noise potential with uncorrelated points, σ being the correlation length, and A_w being the root mean squared (rms) fluctuation (see Fig. 4).

The numerical calculations show that the diode functionality is not compromised for a realistic disorder with rms fluctuation of 0.052 meV (Fig. 5). For a hypothetical disorder

FIG. 5. The same as Fig. 3, but in the presence of the random potential [Eq. (3)].

with much stronger fluctuations, the transmission of the signals is eventually affected and the diode loses its asymmetric response.

Finally, it is worth to remark that the power demand on the system is determined by the optical pump that injects polaritons in the bistable regime; it has been experimentally achieved⁴⁵ with a power consumption of 50 W cm^{-2} , although it could be improved by several orders of magnitude, by increasing the lifetime of polaritons.

In conclusion, we have demonstrated theoretically how an optical diode based on exciton-polariton bistability can be constructed. Numerical calculations prove that a forward propagating signal is fully transmitted, while the transmission for a reverse propagating signal tends to zero. Moreover, the asymmetric response is inherent to a fixed potential and the system proves to be robust in the presence of disorder. These characteristics make our design a promising candidate for future applications.

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¹Exciton Polaritons in Microcavities: New Frontiers, edited by D. Sanvitto and V. Timofeev (Springer-Verlag, Berlin, Heidelberg, 2012).

²I. Carusotto and C. Ciuti, *Rev. Mod. Phys.* **85**, 299 (2013).

³S. Christopoulos, G. B. H. von Högersthal, A. J. D. Grundy, P. G. Lagoudakis, A. V. Kavokin, J. J. Baumberg, G. Christmann, R. Butté, E. Feltin, J.-F. Carlin, and N. Grandjean, *Phys. Rev. Lett.* **98**, 126405 (2007).

⁴D. Bajoni, P. Senellart, E. Wertz, I. Sagnes, A. Miard, A. Lematre, and J. Bloch, *Phys. Rev. Lett.* **100**, 047401 (2008).

⁵S. Kéna-Cohen and S. R. Forrest, *Nature Photon.* **4**, 371–375 (2010).

⁶C. Schneider, A. Rahimi-Iman, N. Y. Kim, J. Fischer, I. G. Savenko, M. Amthor, M. Lerner, A. Wolf, L. Worschech, V. D. Kulakovskii, I. A. Shelykh, M. Kamp, S. Reitzenstein, A. Forchel, Y. Yamamoto, and S. Hoffing, *Nature* **497**, 348 (2013).

⁷I. A. Shelykh, G. Pavlovic, D. D. Solnyshkov, and G. Malpuech, *Phys. Rev. Lett.* **102**, 046407 (2009).

⁸C. Sturm, D. Tanese, H. S. Nguyen, H. Flayac, E. Galopin, A. Lemaître, I. Sagnes, D. Solnyshkov, A. Amo, G. Malpuech, and J. Bloch, e-print [arXiv:1303.1649](https://arxiv.org/abs/1303.1649).

⁹T. C. H. Liew, *Phys. Rev. B* **86**, 235314 (2012).

¹⁰K. V. Kavokin, M. A. Kaliteevski, R. A. Abram, A. V. Kavokin, S. Sharkova, and I. A. Shelykh, *Appl. Phys. Lett.* **97**, 201111 (2010).

¹¹O. Kyriienko, A. V. Kavokin, and I. A. Shelykh, *Phys. Rev. Lett.* **111**, 176401 (2013).

¹²H. Flayac and I. G. Savenko, [arXiv:1307.6552](https://arxiv.org/abs/1307.6552).

¹³I. A. Shelykh, R. Johne, D. D. Solnyshkov, and G. Malpuech, *Phys. Rev. B* **82**, 153303 (2010).

¹⁴T. Gao, P. S. Eldridge, T. C. H. Liew, S. I. Tsintzos, G. Stavrinidis, G. Deligeorgis, Z. Hatzopoulos, and P. G. Savvidis, *Phys. Rev. B* **85**, 235102 (2012).

¹⁵D. Ballarini, M. De Giorgi, E. Cancellieri, R. Houdre, E. Giacobino, R. Cingolani, A. Bramati, G. Gigli, and D. Sanvitto, *Nat. Commun.* **4**, 1778 (2013).

¹⁶T. Espinosa-Ortega and T. C. H. Liew, *Phys. Rev. B* **87**, 195305 (2013).

¹⁷T. C. H. Liew, I. A. Shelykh, and G. Malpuech, *Physica E* **43**, 1543 (2011).

¹⁸P. G. Savvidis, J. J. Baumberg, R. M. Stevenson, M. S. Skolnick, D. M. Whittaker, and J. S. Roberts, *Phys. Rev. Lett.* **84**, 1547 (2000).

¹⁹A. I. Tartakovskii, D. N. Krizhanovskii, and V. D. Kulakovskii, *Phys. Rev. B* **62**, R13298 (2000).

²⁰M. Saba, C. Ciuti, J. Bloch, V. Thierry-Mieg, R. André, L. S. Dang, S. Kundermann, A. Mura, G. Bongiovanni, J. L. Staehli, and B. Deveaud, *Nature* **414**, 731 (2001).

²¹P. G. Lagoudakis, P. G. Savvidis, J. J. Baumberg, D. M. Whittaker, P. R. Eastham, M. S. Skolnick, and J. S. Roberts, *Phys. Rev. B* **65**, 161310 (2002).

²²E. Wertz, A. Amo, D. D. Solnyshkov, L. Ferrier, T. C. H. Liew, D. Sanvitto, P. Senellart, I. Sagnes, A. Lematre, A. V. Kavokin, G. Malpuech, and J. Bloch, *Phys. Rev. Lett.* **109**, 216404 (2012).

²³D. M. Whittaker, *Phys. Rev. B* **71**, 115301 (2005).

²⁴A. Baas, J. Ph. Karr, H. Eleuch, and E. Giacobino, *Phys. Rev. A* **69**, 023809 (2004).

²⁵N. A. Gippius, S. G. Tikhodeev, V. D. Kulakovskii, D. N. Krizhanovskii, and A. I. Tartakovskii, *Europhys. Lett.* **67**, 997 (2004).

²⁶M. De Giorgi, D. Ballarini, E. Cancellieri, F. M. Marchetti, M. H. Szymanska, C. Tejedor, R. Cingolani, E. Giacobino, A. Bramati, G. Gigli, and D. Sanvitto, *Phys. Rev. Lett.* **109**, 266407 (2012).

²⁷C. Adrados, T. C. H. Liew, A. Amo, M. D. Martín, D. Sanvitto, C. Antón, E. Giacobino, A. Kavokin, A. Bramati, and L. Via, *Phys. Rev. Lett.* **107**, 146402 (2011).

²⁸R. Cerna, Y. Léger, T. K. Paraíso, M. Wouters, F. Morier-Genoud, M. T. Portella-Oberli, and B. Deveaud, *Nat. Commun.* **4**, 2008 (2013).

²⁹T. C. H. Liew, A. V. Kavokin, and I. A. Shelykh, *Phys. Rev. Lett.* **101**, 016402 (2008).

³⁰T. C. H. Liew, A. V. Kavokin, T. Ostatnický, M. Kaliteevski, I. A. Shelykh, and R. A. Abram, *Phys. Rev. B* **82**, 033302 (2010).

³¹H. S. Nguyen, D. Vishnevsky, C. Sturm, D. Tanese, D. Solnyshkov, E. Galopin, A. Lemaître, I. Sagnes, A. Amo, G. Malpuech, and J. Bloch, *Phys. Rev. Lett.* **110**, 236601 (2013).

³²E. Wertz, L. Ferrier, D. D. Solnyshkov, R. Johne, D. Sanvitto, A. Lemaître, I. Sagnes, R. Grousson, A. V. Kavokin, P. Senellart, G. Malpuech, and J. Bloch, *Nat. Phys.* **6**, 860 (2010).

³³H. Flayac, G. Pavlovic, M. A. Kaliteevski, and I. A. Shelykh, *Phys. Rev. B* **85**, 075312 (2012).

³⁴R. I. Kaitouni, O. El Daif, A. Baas, M. Richard, T. Paraíso, P. Lugan, T. Guillet, F. Morier-Genoud, J. D. Ganiere, J. L. Staehli, V. Savona, and B. Deveaud, *Phys. Rev. B* **74**, 155311 (2006).

³⁵A. Amo, S. Pigeon, C. Adrados, R. Houdre, E. Giacobino, C. Ciuti, and A. Bramati, *Phys. Rev. B* **82**, 081301 (2010).

³⁶G. Tosi, G. Christmann, N. G. Berloff, P. Tsotsis, T. Gao, Z. Hatzopoulos, P. G. Savvidis, and J. J. Baumberg, *Nat. Phys.* **8**, 190 (2012).

³⁷C. W. Lai, N. Y. Kim, S. Utsunomiya, G. Roumpos, H. Deng, M. D. Fraser, T. Byrnes, P. Recher, N. Kumada, T. Fujisawa, and Y. Yamamoto, *Nature (London)* **450**, 529 (2007); M. Kaliteevski, S. Brand, R. A. Abram, I. Iorsh, A. V. Kavokin, and I. A. Shelykh, *Appl. Phys. Lett.* **95**, 251108 (2009).

³⁸I. Carusotto and C. Ciuti, *Phys. Rev. Lett.* **93**, 166401 (2004).

³⁹C. Ciuti, V. Savona, C. Piermarocchi, A. Quattropani, and P. Schwendimann, *Phys. Rev. B* **58**, 7926 (1998).

⁴⁰I. A. Shelykh, T. C. H. Liew, and A. V. Kavokin, *Phys. Rev. Lett.* **100**, 116401 (2008).

⁴¹V. Savona, W. Langbein, and G. Kocherscheidt, *Phys. Status Solidi (c)* **1**(3), 501–505 (2004).

⁴²I. A. Shelykh, A. V. Kavokin, Y. G. Rubo, T. C. H. Liew, and G. Malpuech, *Semicond. Sci. Technol.* **25**, 013001 (2010).

⁴³W. Langbein and J. M. Hvam, *Phys. Rev. Lett.* **88**, 047401 (2002).

⁴⁴M. Gurioli, F. Bogani, L. Cavigli, H. Gibbs, G. Khitrova, and D. S. Wiersma, *Phys. Rev. Lett.* **94**, 183901 (2005).

⁴⁵T. K. Paraíso, M. Wouters, Y. Leger, F. Morier-Genoud, and B. Deveaud-Pledran, *Nature Mater.* **9**, 655 (2010).