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SUPPLEMENTARY INFORMATION

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Perfect energy-feeding into strongly coupled systems and interferometric control of polariton absorption

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Explicit expression of some quantities relevant in the coupled mode-theory.

The polaritonic poles appearing in Eq. (2) are

$$\omega_{\pm} = \omega_0 + \left[i(\gamma_r + \gamma_{nr} + \gamma_m) \pm \sqrt{4\Omega^2 - (\gamma_r + \gamma_{nr} - \gamma_m)^2} \right]/2,$$

while the determinant of the scattering matrix – apart from a phase factor - is given by

$$\det S(\omega) = \frac{(\omega - \varpi_+)(\omega - \varpi_-)}{(\omega - \omega_+)(\omega - \omega_-)}.$$

The determinant zeros are

$$\varpi_{\pm} = \omega_0 + \left[i(-\gamma_r + \gamma_{nr} + \gamma_m) \pm \sqrt{4\Omega^2 - (\gamma_r - \gamma_{nr} + \gamma_m)^2} \right]/2;$$

note the sign skew with respect to the poles. Real zeros, i.e. CPA, can be attained in two independent ways. The first one is when the argument of the square root is positive and the imaginary contribution involving the γ's is zero. This is the *strong critical coupling*, i.e. the situation where two zeros occur at

$$\tilde{\omega}_{\pm} = \omega_0 \pm \sqrt{\Omega^2 - \gamma_m^{\ 2}}$$

under the condition $\gamma_r = \gamma_{nr} + \gamma_m$.

The second is when the argument of the square root is negative and the imaginary result compensates for the γ's; this is the *weak critical coupling*, i.e. the situation where one zero occurs at ω_0 under the condition $\gamma_m(\gamma_r - \gamma_{nr}) = \Omega^2$.

Two-port coherent (perfect) absorption, C(P)A.

The response of a linear system to an external drive can be described by a scattering matrix connecting input with output amplitudes: $|s^- \rangle = S\,|s^+\rangle$. Enforcing reciprocity, the most general S can be written as

$$S = e^{i\vartheta}\begin{pmatrix} \rho_1 e^{i\psi_1} & i\tau \\ i\tau & \rho_2 e^{i\psi_2} \end{pmatrix}$$

where $0 \le \rho_1, \rho_2, \tau \le 1$. If $\det S = 0$, there exists a vector $|s^+\rangle$ for which $|s^-\rangle = |0\rangle$: this is CPA. Explicitly, the non-trivial solution requires $\rho_1\rho_2 = \tau^2$ and $\psi_1 + \psi_2 = (2m+1)\pi$, where m is an integer.

In general, if the system is excited from both ports with arbitrary amplitudes $|s^+\rangle = (s_1^+, s_2^+)$, the ratio (absorbed energy)/(input energy) is defined as *joint absorbance*

A_{joint}. As the dephasing between the input beams $\varphi = \arg(s_2^+/s_1^+)$ is swept, the joint absorbance oscillates sinusoidally with φ, reaching a minimum and a maximum in one period of the optical dephasing. If the input beams have the same intensity ($|s_1^+|^2 = |s_2^+|^2$), the joint absorbance reaches minimum and maximum values given by

$$A_{\mathrm{joint,\ min/max}} = (A_1+A_2)/2 \pm A_{\mathrm{mod}}$$

where $A_{1,2} = 1- \rho_{1,2}^2- \tau^2$ are the single beam absorbances, and the *modulating absorbance* is

$$A_{\mathrm{mod}} = \sqrt{(1-A_1)(1-A_2) - |\det S|^2}.$$

Note that the average joint absorbance is the arithmetic mean of the single-beam absorbances. If the system is symmetric ($\rho_1 = \rho_2$, $\psi_1 = \psi_2$), $\det S = 0$ implies $A_{joint} = 1$ (CPA); for an asymmetric system with $\det S = 0$, CPA is reached in general for different amplitude input beams. However, it can be shown that the effect of asymmetry is quadratic in ($A_1- A_2$), hence an asymmetric sample having $\det S = 0$ will anyway exhibit a very large joint absorbance even when driven with equal amplitude input beams.

While the individual phases $\psi_{1,2}$ can be experimentally accessed only if the absolute phase delay φ is known, the phase *sum* $\psi_1 + \psi_2$ can be directly deduced by measuring the phase *difference* between output intensities at the ports 1 and 2 in the coherent absorption set-up. Indeed, if the inputs satisfy $|s_1^+|^2 = |s_2^+|^2 = 1$, the following expressions hold:

$$|s_1^-|^2 = \rho_1^2 + \tau + 2\rho_1\tau\sin(\varphi - \psi_1 + \pi)$$
$$|s_2^-|^2 = \rho_2^2 + \tau + 2\rho_2\tau\sin(\varphi + \psi_2).$$

Hence, by defining $\Delta\psi$ as the output beam phase difference, one gets $\Delta\psi = \psi_1 + \psi_2 - \pi$. Since all the prefactors in the above equations are positive, CPA can be attained only if the output beams are in phase, and the condition $\Delta\psi = 2m\pi$ coincides with the above stated requirement $\psi_1 + \psi_2 = (2m+1)\pi$.

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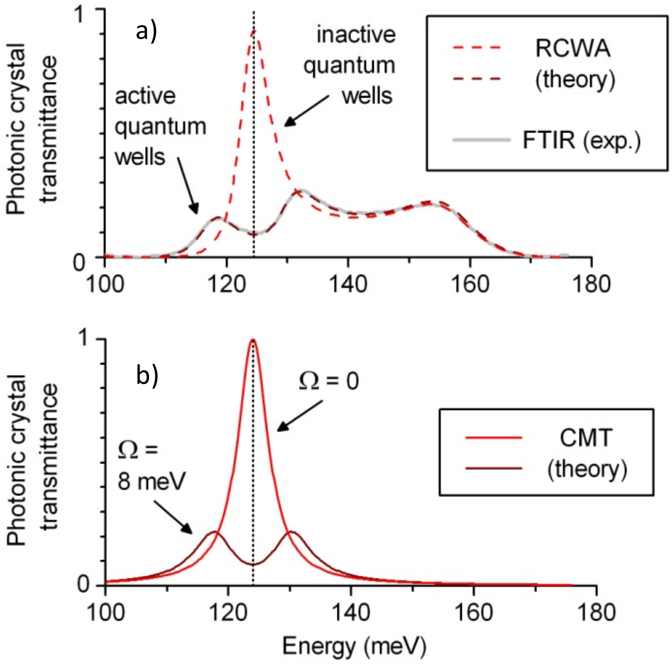
Single beam transmission and model parameters.



Panel (a): The experimental transmission spectrum is measured by means of Fourier-transform spectrometry (FTIR) and shows the polariton doublet plus a third peak at ~ 155 meV attributed to a further photonic resonance (gray line). A rigorous coupled wave analysis (RCWA) simulation is performed to fit the FTIR curve (dark-red dashed line). In this model the only real free parameter is the actual charge density n, while the photonic resonance is tuned to the intersubband transition frequency ω_0. The latter and the intersubband transition decay rate γ_m are deduced from absorption measurements at the Brewster angle, performed on similar unprocessed QW samples, revealing the Lorentzian character of the intersubband transition [1]. This procedure gave the parameters $n = 5.2\cdot10^{11}$ cm^{-2} , $\omega_0 = 124.5$ meV, and $\gamma_m = 5$ meV. In a further simulation (light-red dashed line), the QWs are instead considered to be inactive, by setting to zero the charge density in the wells [2]. This gives the purely photonic response of the structure and confirms the origin of the 155 meV peak. Furthermore, from the width of the transmittance peak, the photonic cavity lifetime can be retrieved: $\gamma_c = \gamma_r + \gamma_{nr} = 3$ meV. In panel (b) we report the spectra obtained with the coupled mode theory (CMT). Here, the bare photonic cavity response (i.e. that for $\Omega = 0$, corresponding to the inactive QWs), is reproduced by inserting in Eq. 2 of the main text the parameters $\omega_0 = 124.5$ meV, $\gamma_r = 3$ meV, $\gamma_{nr} = 0$. The last assumption is needed for reproducing a fully contrasted transmittance feature, and reveals that there are no non-resonant losses in the system. The spectrum differs from the corresponding one obtained by RCWA owing to the absence of the second photonic mode in the coupled mode theory. Finally, by setting $\Omega = 8$ meV in the CMT, the double-peaked polaritonic spectrum is retrieved. The choice $\Omega = 8$ meV gives a good agreement with the absorption lineshapes reported in Figs. 2 and 3 of the main text, and is consistent with the usual expression linking the charge density with the Rabi splitting (see, e.g. Ref. [1]).

References.

[1] Zanotto, S., Degl'Innocenti, R., Sorba, L., Tredicucci, A., & Biasiol, G. Analysis of line shapes and strong coupling with intersubband transitions in one-dimensional metallo-dielectric photonic crystal slabs. *Phys. Rev. B* **85**, 035307 (2012).

[2] Degl'Innocenti, R., Zanotto, S., Biasiol, G., Sorba, L., & Tredicucci, A. One-dimensional surface-plasmon gratings for the excitation of intersubband polaritons in suspended membranes. *Solid State Commun.* **151**, 1725-1727 (2011).