

Coherent perfect absorption: Zero reflection without linewidth suppression

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Motivated by recent claims, we revisit how coherent perfect absorption (CPA) influences cavity and polaritonic linewidths. Using standard input-output theory and measurements on single-port bare microwave cavities and cavity-magnon hybrids, we find that CPA drives the on-resonance reflection amplitude to zero while the spectral width remains set by the total decay rate. Apparent narrowing observed near CPA is found to be a visual artifact that does not remain upon quantitative analysis. Extending the analysis to cavity magnomechanics, we show that logarithmic plots can exhibit apparent polaromechanical “normal-mode splitting,” whereas linear-scale spectra display no true splitting. These results clarify when CPA modifies amplitudes versus spectral poles, offer practical guidance for data presentation, and indicate that CPA alone is not a route to linewidth suppression or polaromechanical mode splitting in the linear, weak-probe regime.

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I. INTRODUCTION

Hybrid quantum systems provide a versatile platform for exploring quantum phenomena and advancing quantum information processing [1–3]. By coherently interfacing disparate degrees of freedom—optical or microwave photons, superconducting circuits, and collective spin or mechanical excitations—these systems enable controlled energy exchange and access to nonclassical states. Reaching the strong-coupling regime, where the coherent interaction rate exceeds the relevant dissipation rates, is a central objective [4–9].

In many platforms, the intrinsic interaction is weak. For example, in cavity optomechanics the radiation-pressure coupling typically requires strong coherent driving to realize an effective, linearized interaction, at the cost of added noise and possible parametric instabilities [10–14]. Magnon-based hybrids—cavity magnonics and cavity magnomechanics—have recently emerged as compelling alternatives [4–6,15–20]. In these systems, microwave photons couple strongly to magnons in ferrimagnets such as yttrium iron garnet (YIG), forming cavity-magnon polaritons [4–6,15–18]. Via magnetostriction, polaritons can further couple to mechanical vibrations [19,20], opening a path to polaromechanics and, ultimately, to quantum control of phonons.

Beyond driven-enhanced coupling, dissipation and reservoir engineering have been used to tailor system dynamics—e.g., to create entangled steady states or enable quantum-limited amplification and nonreciprocity [21–24]—and to improve cooperativity by reducing intrinsic or effective

linewidths [9,24–26]. Recently, Shen *et al.* [26] argued that coherent perfect absorption (CPA), which has been used advantageously in quantum optics as an interference effect [27–30], can be realized in cavity magnonics by tuning the external coupling and can lead to a reduction of the polariton decay rate. They further claimed that this suppression of the polariton decay rate enables polaromechanical normal-mode splitting.

Here, we revisit how CPA affects spectral widths in the linear, weak-probe regime. We begin with a single-port bare microwave cavity in which the external coupling (e.g., pin depth) sets the external dissipation rate. Using standard input-output theory together with measurements, we find that CPA coincides with critical coupling at resonance: Destructive interference drives the on-resonance reflection to zero, while the spectral width remains fixed by the total decay rate $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$, where κ_{int} and κ_{ext} indicate the internal and external dissipation rates, respectively. Importantly, even in quantum optics where it finds its origin, CPA is used to modify the on-resonance amplitude but does not change the spectral poles that determine the linewidth or total decay rate. As CPA drives the minimum of the reflection spectrum toward zero, logarithmic plots make the dip appear visually sharper and can give the impression of linewidth narrowing. The same spectra plotted in linear units show that the full width at half maximum (FWHM) is set by κ_a and, for fixed κ_{int} , is largest in the overcoupled regime and smallest in the undercoupled regime, confirming that the cavity linewidth/decay rate is not reduced at CPA.

We then apply the same analysis to a cavity-magnonics system. Again, although logarithmic plots can suggest linewidth narrowing at CPA, linear-scale spectra together with input-output theory confirm that CPA does not narrow the polariton linewidth; the damping remains set by the dissipation rate of the hybrid mode.

Finally, in the context of cavity magnomechanics, we show that logarithmic plots can also suggest an apparent polaromechanical “normal-mode splitting” under CPA, whereas

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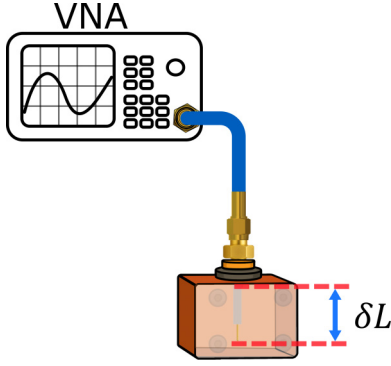


FIG. 1. Schematic of the single-port reflection measurement of a bare cavity. The external coupling is tuned by adjusting the adapter-pin insertion depth.

linear-scale spectra display no true splitting. In these systems, CPA modifies amplitudes at resonance without shifting the spectral poles that determine the linewidth; hence, no linewidth narrowing or splitting attributable to CPA is observed.

II. REFLECTION SPECTRA AND CPA IN A SINGLE-PORT BARE MICROWAVE CAVITY

A. Experimental data

We consider a single-port bare microwave cavity with resonance frequency $\omega_a/2\pi \approx 7.33$ GHz. The input-output coupling is tuned by adjusting the insertion depth of the pin-coupler adapter's center pin (Fig. 1), which sets the external dissipation rate κ_{ext} . Representative reflection spectra $|S_{11}|$ measured with a vector network analyzer (VNA) are shown in Fig. 2 on both log and linear scales. As the coupling is varied, the on-resonance reflection can be driven close to zero by destructive interference between the incident wave and the field leaking from the cavity—This is identical to the concept of CPA in optical systems [27–30]. When displayed logarithmically,

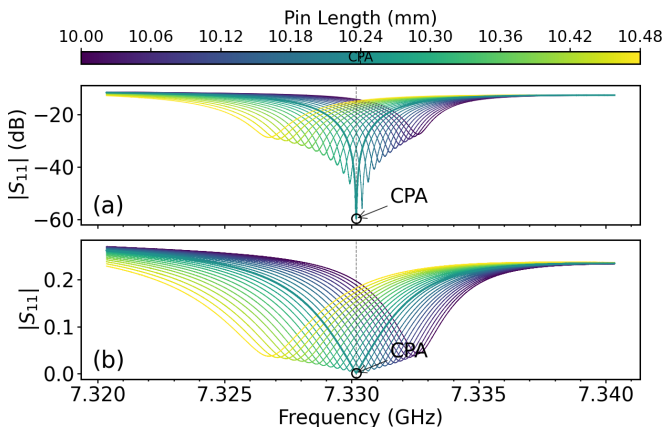


FIG. 2. Reflection spectra of a single-port bare microwave cavity for several pin insertion length δl (equivalently, external dissipation rate κ_{ext}): (a) magnitude in logarithmic and (b) magnitude in linear units. The arrow marks CPA, realized at critical coupling $\kappa_{\text{ext}} = \kappa_{\text{int}}$, where the on-resonance dip ideally vanishes. The linewidth scale is set by the total decay rate $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$.

mically, the deep dip at CPA appears visually “sharper,” which can suggest a narrowed linewidth; plotting the same data in linear units makes clear that the full width at half maximum does not shrink at CPA.

B. Theoretical model

Now, we theoretically derive the reflection spectrum of a single-port bare microwave cavity. We then analyze the conditions for zero reflection, $S_{11}(\omega_p) = 0$, and compare the theoretical results with the experimental data extracted from Fig. 2. With a weak probe at frequency ω_p and amplitude ε_p , the driven cavity is described by

$$\frac{H}{\hbar} = \omega_a \hat{a}^\dagger \hat{a} + i\sqrt{\kappa_{\text{ext}}} \varepsilon_p (\hat{a}^\dagger e^{-i\omega_p t} - \hat{a} e^{i\omega_p t}). \quad (1)$$

The corresponding Langevin equation for the intracavity field is

$$\dot{\hat{a}} = -(i\omega_a + \kappa_a/2) \hat{a} + \sqrt{\kappa_{\text{ext}}} \varepsilon_p e^{-i\omega_p t}, \quad (2)$$

with $\kappa_a \equiv \kappa_{\text{int}} + \kappa_{\text{ext}}$. Using the Fourier transform, the above equation is obtained as

$$-i\omega_p a(\omega_p) = -(i\omega_a + \kappa_a/2) a(\omega_p) + \sqrt{\kappa_{\text{ext}}} \varepsilon_p. \quad (3)$$

The steady-state intracavity amplitude is

$$a(\omega_p) = \frac{\sqrt{\kappa_{\text{ext}}} \varepsilon_p}{\kappa_a/2 + i(\omega_a - \omega_p)}. \quad (4)$$

In a one-port reflection geometry, the input-output theory [31],

$$a_{\text{out}} = \varepsilon_p - \sqrt{\kappa_{\text{ext}}} a, \quad (5)$$

leads to the following reflection spectrum:

$$S_{11}(\omega_p) \equiv \frac{a_{\text{out}}}{\varepsilon_p} = \frac{\kappa_{\text{ext}} - \kappa_{\text{int}} - 2i(\omega_a - \omega_p)}{\kappa_{\text{ext}} + \kappa_{\text{int}} + 2i(\omega_a - \omega_p)} \quad (6)$$

and

$$|S_{11}(\omega_p)|^2 = \frac{4(\omega_a - \omega_p)^2 + (\kappa_{\text{ext}} - \kappa_{\text{int}})^2}{4(\omega_a - \omega_p)^2 + (\kappa_{\text{ext}} + \kappa_{\text{int}})^2}. \quad (7)$$

Equations (6) and (7) make two points explicit: (1) CPA ($S_{11}(\omega_p) = 0$, zero reflection) occurs only at resonance,

$$\omega_p = \omega_a, \quad (8)$$

and at critical coupling,

$$\kappa_{\text{ext}} = \kappa_{\text{int}}, \quad (9)$$

(2) the spectral width is set by the pole of the response,

$$\tilde{\omega}_a = \omega_a - i\kappa_a/2, \quad (10)$$

hence by the total decay rate $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$, independent of the numerator. Therefore, achieving CPA does not reduce the cavity linewidth/decay rate. For fixed κ_{int} , the FWHM (in angular frequency) equals κ_a and is smallest in the undercoupled regime $\kappa_{\text{ext}} < \kappa_{\text{int}}$ and largest in the overcoupled regime $\kappa_{\text{ext}} > \kappa_{\text{int}}$.

From the fits to Eq. (7), we extract κ_{int} , κ_{ext} , and $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$. Figure 3 shows that κ_{int} is nearly independent of pin length (small variations attributable to changes in internal absorption with pin insertion), while κ_{ext} is strongly tunable. The FWHM of Lorentzian fits coincides with κ_a across all

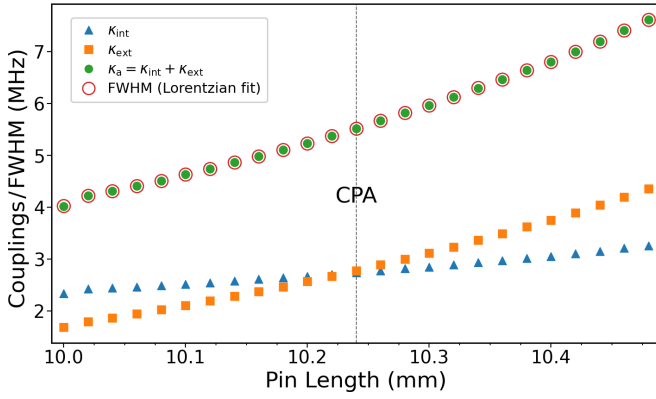


FIG. 3. Dissipation rates of the bare microwave cavity as a function of pin insertion length δl (equivalently, external dissipation rate κ_{ext}). Blue: κ_{int} (nearly constant); orange: κ_{ext} (tunable); green: $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$. The rates κ_{ext} , κ_{int} , and κ_a are extracted by fitting the spectra to Eq. (7). Red circles show the FWHM from Lorentzian fits to the measured data (equal to κ_a). The vertical dashed line indicates CPA (critical coupling).

couplings, including at the CPA point where $\kappa_{\text{ext}} = \kappa_{\text{int}}$. Taken together, both these results verify that FWHM is set by the total decay rate κ_a and establish that CPA is realized precisely at critical coupling ($\kappa_{\text{ext}} = \kappa_{\text{int}}$), confirming that CPA modifies on-resonance amplitudes without shifting the spectral poles.

Common pitfall and the pole. A tempting shortcut is to impose the CPA condition $a_{\text{out}} = 0$ and substitute $\varepsilon_p = \sqrt{\kappa_{\text{ext}}}$ back into the equation of motion, Eq. (3), which would suggest an “effective” decay

$$\kappa'_a = \kappa_a - 2\kappa_{\text{ext}} = \kappa_{\text{int}} - \kappa_{\text{ext}}, \quad (11)$$

so one misinterpretation is that under the CPA condition where $\kappa_{\text{int}} = \kappa_{\text{ext}}$, an effective zero linewidth, $\kappa'_a = 0$, is achievable. $a_{\text{out}} = 0$ is valid only at the single frequency $\omega_p = \omega_a$ where CPA holds; it does *not* change the system pole at $\tilde{\omega} = \omega_a - i\kappa_a$ that determines the spectral width. The physical linewidth is therefore always governed by $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$.

III. REFLECTION SPECTRA AND CPA IN A CAVITY-MAGNONICS SYSTEM

A. Experimental data

We consider a single-port cavity-magnonics system with cavity resonance $\omega_a/2\pi \approx 7.32$ GHz. A single-crystal YIG sphere, with a radius of 200 μm and an intrinsic magnon dissipation rate $\kappa_m/2\pi = 2.49$ MHz, is positioned near the magnetic-field antinode of the cavity mode. The magnon mode couples to the cavity field via magnetic-dipole interaction, and the magnon-photon coupling strength is $g_{ma}/2\pi \approx 5.50$ MHz. As in the case of bare cavity, varying the insertion of the adapter pin δl tunes the external dissipation rate κ_{ext} (Fig. 4). The bias magnetic field $B_0 = 262$ mT is held fixed, thereby setting the magnon frequency to $\omega_m/2\pi = 7.334$ GHz according to $\omega_m = \gamma|B_0|$, where $\gamma/2\pi = 28$ GHz T $^{-1}$ is the gyromagnetic ratio.

Figure 5 shows $|S_{11}|$ measured for different δl . On a logarithmic scale, the minima on each polariton branch deepen and appear visually sharper as δl is varied, which can

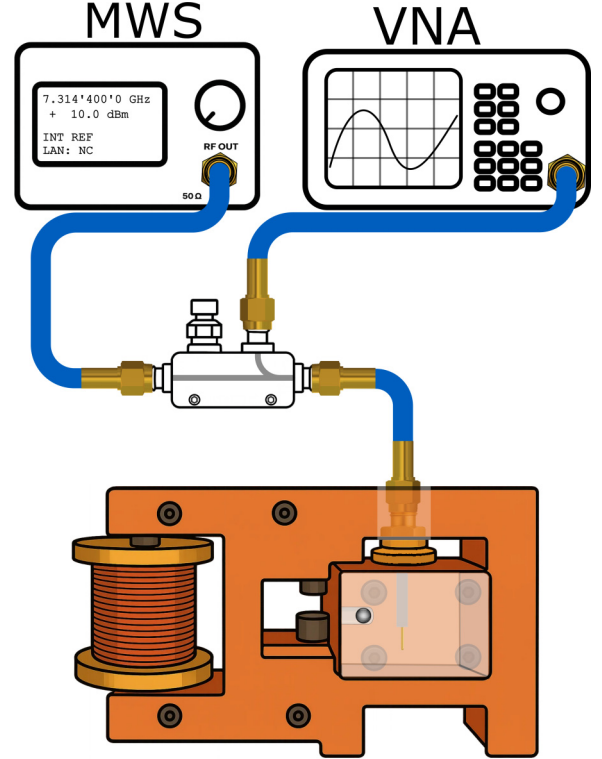


FIG. 4. Schematic of the cavity-magnomechanics experiment. A weak VNA probe monitors the reflection S_{11} , while an independent microwave source (MWS) is power-combined onto the same feedline to resonantly drive the upper-polariton mode.

suggest linewidth narrowing. The linear-scale spectra reveal that, at specific δl (hence κ_{ext}), the on-resonance reflection approaches zero—coherent perfect absorption—*without* reducing the polariton linewidths. Polariton widths are fixed by the *poles* of the hybrid susceptibility, whereas CPA concerns

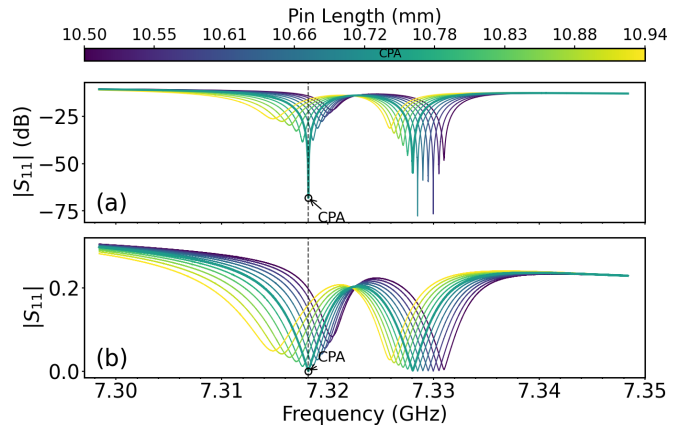


FIG. 5. Reflection spectra of a single-port cavity magnonics (Fig. 4) for several pin insertion length δl (equivalently, external dissipation rate κ_{ext}), shown in (a) logarithmic and (b) linear units. A two-polariton mode with deepest dip in the lower mode is bolded. The vertical dashed line marks CPA of the lower polariton (critical coupling, $\kappa_{\text{ext}} = \kappa_{\text{int}}$), where the on-resonance dip ideally vanishes.

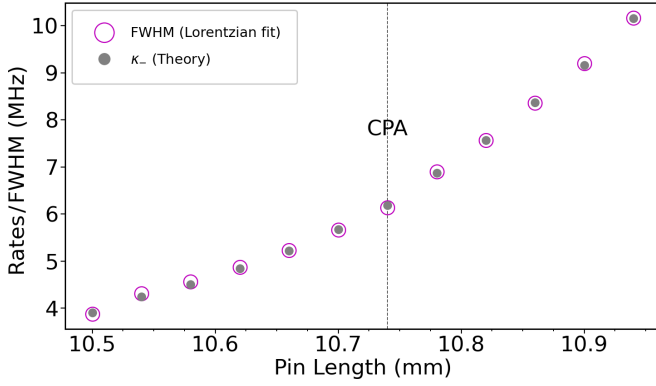


FIG. 6. Lower-polariton linewidth in cavity magnonics as a function of pin insertion length δl (equivalently, external dissipation rate κ_{ext}). FWHM from Lorentzian fits to the lower-polariton resonance in the experimental spectra (open purple circles) and theoretical prediction $\kappa_{-} = -2 \text{Im } \tilde{\omega}_{-}$ (filled gray circles). The vertical dashed line marks the CPA point; CPA does not reduce the linewidth.

the *zeros* of the reflection coefficient; hence, CPA does not, by itself, narrow the lines or reduce the decay rate.

B. Theoretical model

Now, we theoretically derive the reflection spectrum of a single-port cavity-magnonics system. We identify the conditions for zero reflection (CPA) and the spectral poles. Comparing these results with the analyzed experimental data extracted from Fig. 5, we confirm that CPA drives the on-resonance reflection to zero without reducing the linewidth. We consider a weak probe at frequency ω_p . The Hamiltonian is

$$\frac{H}{\hbar} = \omega_a \hat{a}^\dagger \hat{a} + \omega_m \hat{m}^\dagger \hat{m} + g_{ma} (\hat{a} \hat{m}^\dagger + \hat{a}^\dagger \hat{m}) + i\sqrt{\kappa_{\text{ext}}} \varepsilon_p (\hat{a}^\dagger e^{-i\omega_p t} - \hat{a} e^{i\omega_p t}), \quad (12)$$

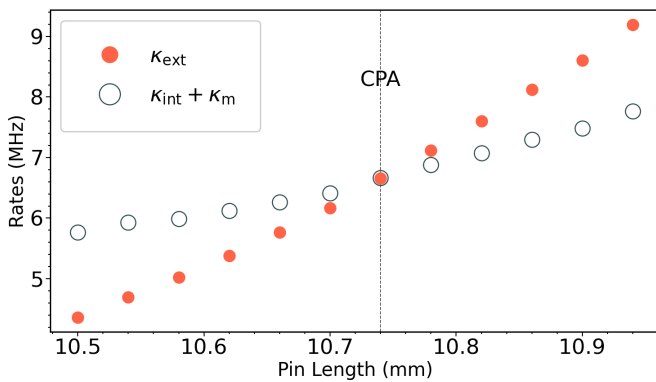


FIG. 7. Verification of the first CPA condition (critical coupling) in a cavity-magnon system, $\kappa_{\text{ext}} = \kappa_{\text{int}} + \kappa_m$, as a function of pin length δl (which tunes the external dissipation rate κ_{ext}). The condition is nearly satisfied at the CPA point, $\delta l \approx 10.740$ mm, where the on-resonance reflection approaches zero. These experimental data confirm the theoretical CPA condition, Eq. (17).

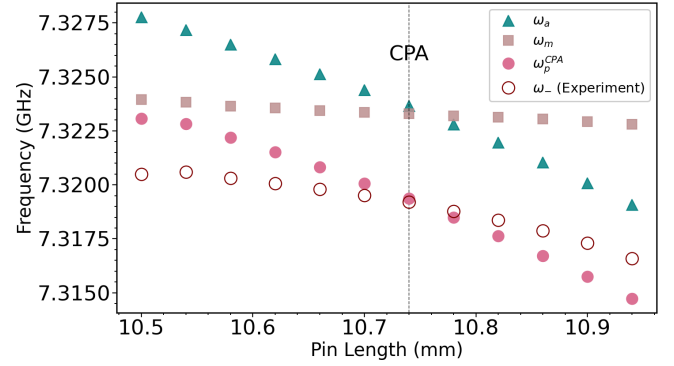


FIG. 8. Verification of the second CPA condition (resonance condition) in a cavity magnonic system, $\omega_p^{\text{CPA}} = \omega_a - \sqrt{g_{ma}^2 - (\kappa_m/2)^2}$, vs pin insertion length δl (which tunes the external dissipation rate κ_{ext}). Markers indicate the cavity (ω_a) and magnon (ω_m) frequencies, extracted by fitting data to the reflection spectrum, Eq. (16). Filled circles denote the frequency required for zero reflection (second CPA condition) at each δl , while open circles show the measured lower-polariton frequency for each δl . The vertical dashed line marks the δl at which CPA occurs. At resonance ($\omega_a = \omega_m$), CPA is realized when the polariton frequency reaches the CPA-predicted frequency ω_p^{CPA} .

with $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$ and κ_m . Neglecting noise,

$$\dot{\hat{a}} = -\left(\frac{\kappa_a}{2} + i\omega_a\right)\hat{a} - ig_{ma}\hat{m} + \sqrt{\kappa_{\text{ext}}} \varepsilon_p e^{-i\omega_p t}, \quad (13)$$

$$\dot{\hat{m}} = -\left(\frac{\kappa_m}{2} + i\omega_m\right)\hat{m} - ig_{ma}\hat{a}. \quad (14)$$

In frequency space,

$$a(\omega_p) = \frac{\sqrt{\kappa_{\text{ext}}} \left[\frac{\kappa_m}{2} + i(\omega_m - \omega_p) \right] \varepsilon_p}{\left[\frac{\kappa_m}{2} + i(\omega_m - \omega_p) \right] \left[\frac{\kappa_a}{2} + i(\omega_a - \omega_p) \right] + g_{ma}^2}. \quad (15)$$

With input-output theory, Eq. (5), the reflection spectrum is obtained as

$$S_{11}(\omega_p) = \frac{\left[\frac{\kappa_m}{2} + i(\omega_m - \omega_p) \right] \left[\frac{\kappa_{\text{int}} - \kappa_{\text{ext}}}{2} + i(\omega_a - \omega_p) \right] + g_{ma}^2}{\left[\frac{\kappa_m}{2} + i(\omega_m - \omega_p) \right] \left[\frac{\kappa_a}{2} + i(\omega_a - \omega_p) \right] + g_{ma}^2}. \quad (16)$$

CPA at the polariton frequencies (split branch). For the resonant case $\omega_a = \omega_m \equiv \omega_0$, CPA corresponds to *zeros of the numerator* of Eq. (16). Seeking split-frequency zeros at

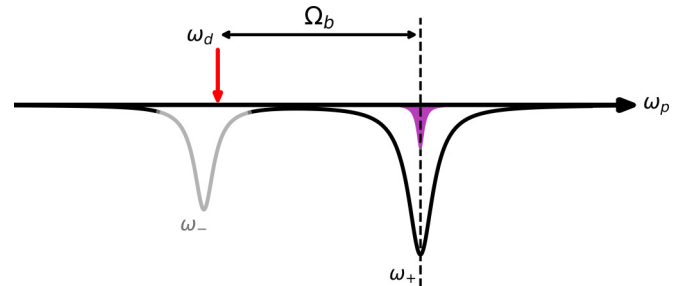


FIG. 9. Frequency schematic based on the measurement. The red arrow marks the MWS drive at ω_d , which excites the upper-polariton mode at ω_+ (dashed line). The lower polariton ω_- is shown in gray. Ω_b denotes the mechanical frequency, and ω_p is the probe frequency axis.

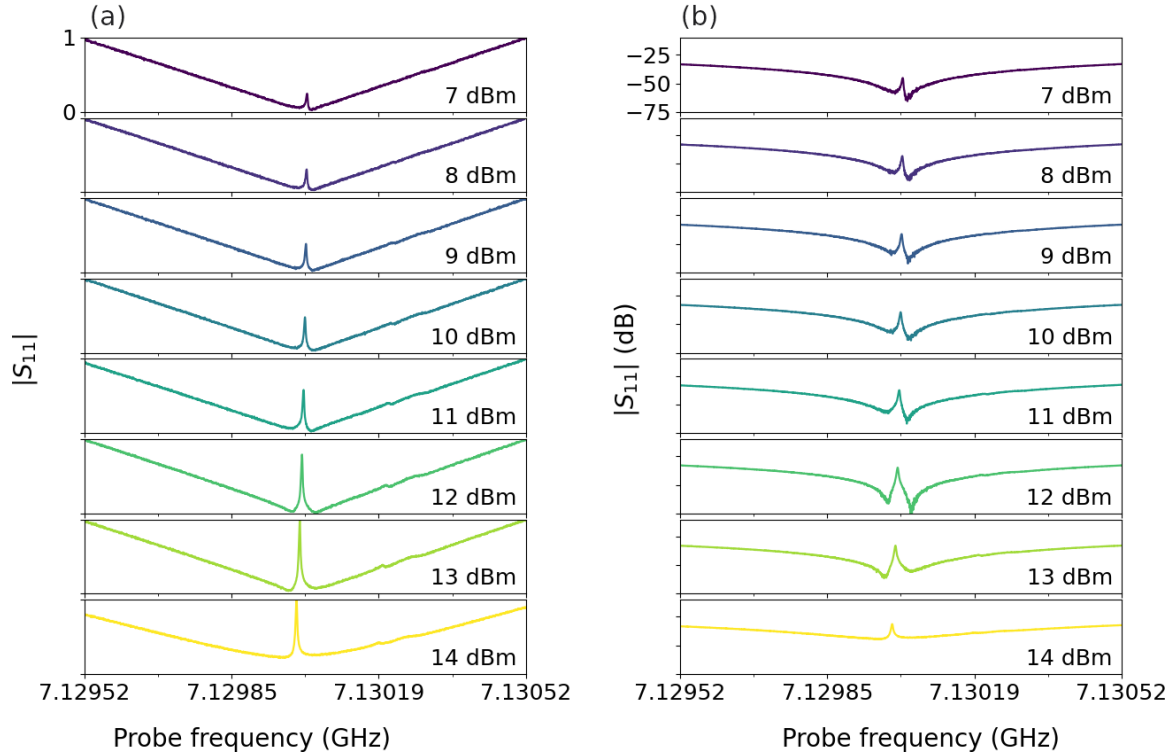


FIG. 10. Reflection spectra $|S_{11}|$ of the upper polariton vs probe frequency for drive powers 7–14 dBm, shown over a 1 MHz span. The cavity is driven with a strong tone red-detuned by $\Omega_b/2\pi = 15.6$ MHz (low-frequency/left side) from the upper polariton, so MMIT appears on its red shoulder while the polariton is tuned to CPA. Because changing the drive power shifts the polariton frequency, we retune the bias magnetic field B_0 at each power to keep the mechanical mode at the CPA point (i.e., maintain $\Delta_+ = \Omega_b$). (a) linear scale; (b) logarithmic. The near-zero minimum at CPA can mimic a doublet in logarithmic, but the linear-scale data show a single mode with a transparency window, not a genuine splitting.

$\omega_p^{\text{CPA}} = \omega_0 \pm \Delta$, with $\Delta \neq 0$, and separating real/imaginary parts yields

$$\kappa_{\text{ext}} = \kappa_{\text{int}} + \kappa_m, \quad (17)$$

$$\Delta = \sqrt{g_{ma}^2 - \frac{\kappa_m^2}{4}}, \quad (18)$$

which, respectively, can be considered as the critical coupling and resonance conditions of the cavity magnonics. Thus, for $g_{ma} > \kappa_m/2$, perfect absorption occurs at the two polariton frequencies when the external coupling equals the total internal loss of the hybrid.

Poles and linewidths. The poles [roots of the denominator of Eq. (16)] are

$$\tilde{\omega}_{\pm} = \omega_{\pm} - i\frac{\kappa_{\pm}}{2} = \frac{\omega_a + \omega_m}{2} - \frac{i}{4}(\kappa_a + \kappa_m) \pm \frac{1}{2}\sqrt{\left[(\omega_a - \omega_m) - \frac{i}{2}(\kappa_a - \kappa_m)\right]^2 + 4g_{ma}^2}. \quad (19)$$

The observable half-widths are $\kappa_{\pm}/2 = -\text{Im} \tilde{\omega}_{\pm}$, so the FWHM equals $\kappa_{\pm}$ and is fixed the *denominator*. Satisfying Eqs. (17) and (18) (zeros of the numerator) drives $|S_{11}|$ to zero at specific frequencies but does not move the poles or narrow the polariton linewidths.

For further analysis, we focus on the lower polariton (a two-polariton mode with deepest dip in the lower mode is bolded in Fig. 5). Figure 6 summarizes the FWHM extracted

from Lorentzian fit to the lower polariton mode and compares it with the prediction from Eq. (19) using parameters obtained from simultaneous fits to both branches. The agreement confirms that the linewidth/decay rate is not reduced under CPA.

To experimentally check both CPA conditions, Eqs. (17) and (18), Fig. 7 shows the rates extracted from fits: At the CPA point, the critical-coupling relation $\kappa_{\text{ext}} = \kappa_{\text{int}} + \kappa_m$ [Eq. (17)] is satisfied. Complementarily, Fig. 8 tests the frequency condition: For $\omega_a \simeq \omega_m \equiv \omega_0$, the CPA zeros occur at $\omega_p^{\text{CPA}} = \omega_0 \pm \Delta$ with $\Delta = \sqrt{g_{ma}^2 - (\kappa_m/2)^2}$ [Eq. (18)]; the measured lower-polariton frequency follows this prediction at the observed CPA point.

IV. CAVITY MAGNOMECHANICS UNDER THE CPA CONDITION

In this section, we investigate magnomechanical interactions in the presence of CPA. By driving either the cavity or the magnon mode, a hybrid cavity-magnon polariton is excited, whose magnetostrictive response mediates an effective magnon-phonon interaction. In the dispersive regime, this interaction is directly analogous to the radiation-pressure coupling in cavity optomechanics and gives rise to magnomechanically induced transparency (MMIT) [19,20]. The optomechanical analog of electromagnetically induced transparency [32], called magnomechanically induced transparency/absorption in magnomechanical systems, arises from

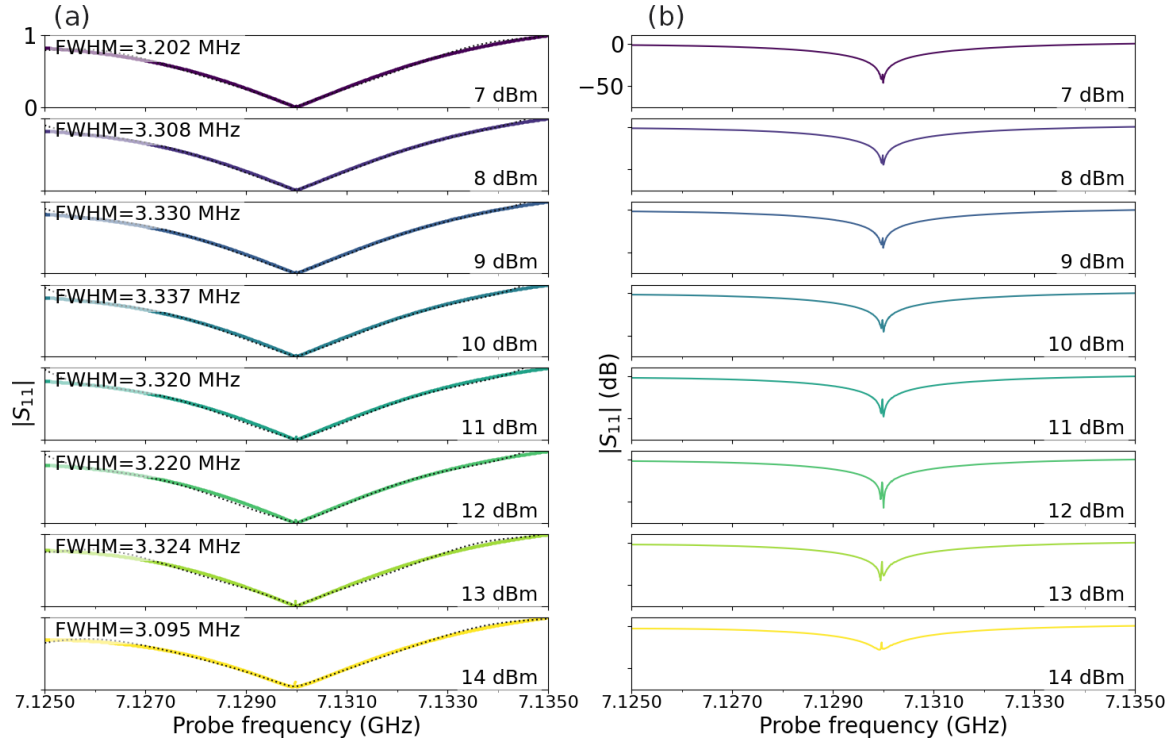


FIG. 11. Reflection spectra $|S_{11}|$ of the upper polariton vs probe frequency for drive powers 7–14 dBm, shown over a 10 MHz span. The cavity is driven with a strong tone red-detuned from the upper polariton by $\Delta_+/2\pi = \Omega_b/2\pi = 15.6$ MHz, so MMIT appears on its red shoulder while the polariton is tuned to CPA. Because the drive power shifts the polariton frequency, the bias field B_0 is retuned at each power to maintain the CPA operating point. (a) Linear magnitude; dotted curves are fits, and the extracted FWHM for each trace is annotated (all ≈ 3.3 MHz). (b) Logarithmic magnitude. The wider 10 MHz window, which captures the full width of the upper polariton, shows a single resonance with a weak transparency feature [more apparent in panel (b)]—no genuine normal-mode splitting. CPA deepens the dip but does not narrow the linewidth; the FWHM remains essentially constant across drive powers.

coherent interference between a weak probe field and the anti-Stokes (Stokes) scattering generated by a strong red-(blue-)detuned control field via mechanical motion. This interference produces a narrow transparency window or absorption dip in the probe transmission near the polariton resonance, with a linewidth determined by the mechanical dissipation rate [19]. In our experiment, we excite the polariton by driving the microwave cavity with a strong microwave source (Fig. 4).

We operate with the drive *red-detuned* from the upper polariton by $\Delta_+/2\pi = \Omega_b/2\pi = 15.6$ MHz, where we define $\Delta_+ \equiv \omega_+ - \omega_d$ (with ω_d the drive frequency and ω_+ the upper-polariton frequency) and Ω_b as the mechanical-mode frequency. This places the probe on the low-frequency side of the upper polariton, so that MMIT appears on its red shoulder (Fig. 9). Throughout, the polariton is tuned to satisfy the CPA condition. Representative amplitude reflection spectra ($|S_{11}|$) of the upper polariton, in both linear and logarithmic scales, are shown in Figs. 10 and 11 for drive powers from 7 to 12 dBm. The two panels use different frequency spans—1 MHz in Fig. 10 and 10 MHz in Fig. 11. As expected under CPA, the on-resonance reflection at the bottom of the polariton approaches zero. While logarithmic plots over a narrow span can give the impression of a splitting (as concluded in Ref. [26] and as can be seen at 12 dBm drive in Fig. 10(b), based solely on logarithmic representations), the *linear*-scale, Fig. 10(a), spectra clearly exhibit MMIT *without* any

genuine splitting. CPA deepens the polariton dip; under drive, the resulting sharp minimum can resemble a doublet on a logarithmic scale. However, the wider-span linear response (Fig. 11), which captures the full width of the upper-polariton mode, clearly indicates a single mode. If a genuine splitting were present, it would also appear in this figure.

Figure 12 presents a contour plot of $|S_{11}|$ versus drive power and probe frequency. Again, logarithmic views may suggest an apparent splitting near CPA, whereas the corresponding linear-scale data show MMIT without any sign of mode splitting. Thus, the interpretation in Ref. [26] is not acceptable: CPA does not cause linewidth reduction leading to true normal-mode splitting; the apparent features arise from plotting logarithmically and from the sharpened CPA dip.

We further measured the response while increasing the drive power *without* adjusting the bias magnetic field. In this case, power-induced shifts of the magnon frequency move the polariton due to magnon Kerr nonlinearity [19,33], so that CPA is not maintained at all drive powers. The logarithmic spectra in Fig. 13 can resemble polaromechanical normal-mode splitting, yet the linear-scale traces do not exhibit true splitting. The apparent “splitting” near 9.5–9.7 dBm coincides with sharper dips when CPA is satisfied.

Finally, Fig. 14 shows a contour plot of the reflection spectra versus drive power and probe frequency for the same protocol (increasing drive power without retuning the magnon). As in Fig. 13, logarithmic plots can suggest

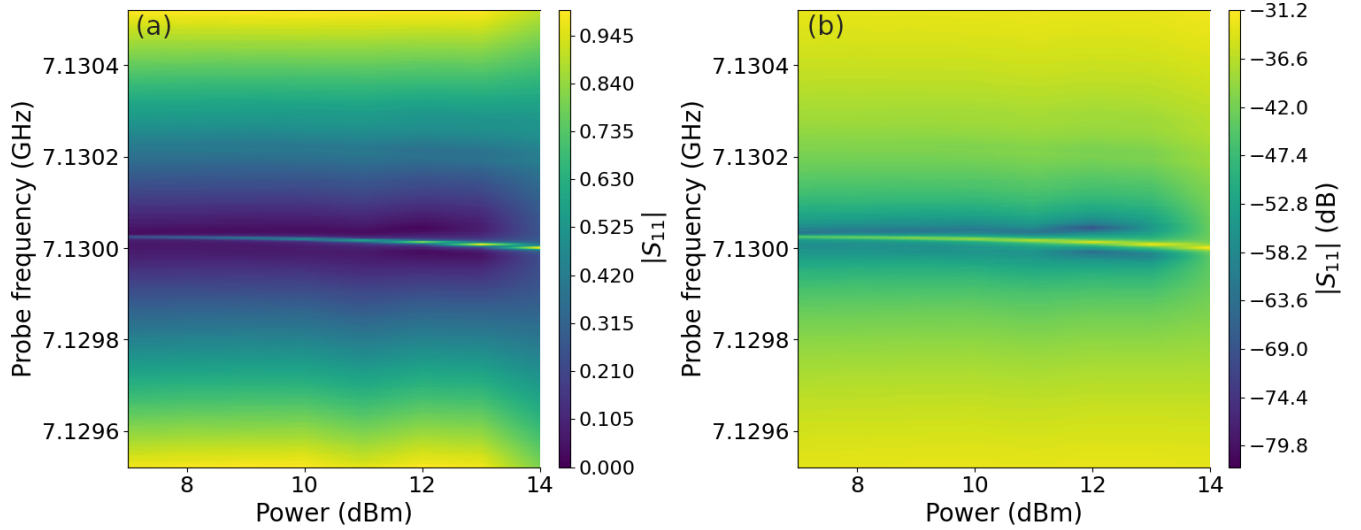


FIG. 12. Contour plots of the upper-polariton reflection $|S_{11}|$ vs probe frequency and drive power (7–14 dBm). The cavity is driven red-detuned by $\Omega_b/2\pi = 15.6$ MHz (low-frequency side) with the polariton tuned to CPA. (a) Linear magnitude; (b) logarithmic. The narrow ridge marks MMIT at CPA; no genuine normal-mode splitting (the logarithmic “doublet” is a plotting artifact).

splitting at CPA, but the linear-scale data reveal no genuine normal-mode doublet. Together with the discussion above on CPA, these observations emphasize that CPA does not imply linewidth/decay rate suppression: Claims of splitting require corroboration from both linear and logarithmic spectra over a sufficiently wide frequency range. Here, the linear-scale results in Fig. 14 show no evidence of true splitting.

V. CONCLUSION

We have revisited how CPA affects spectral widths in single-port cavities and cavity-magnon hybrids, combining input-output theory with experiments displayed in both linear and logarithmic units. The key outcome is that CPA creates a *zero* of the reflection amplitude without shifting the *poles* that set the linewidth: The FWHM is governed by the total decay

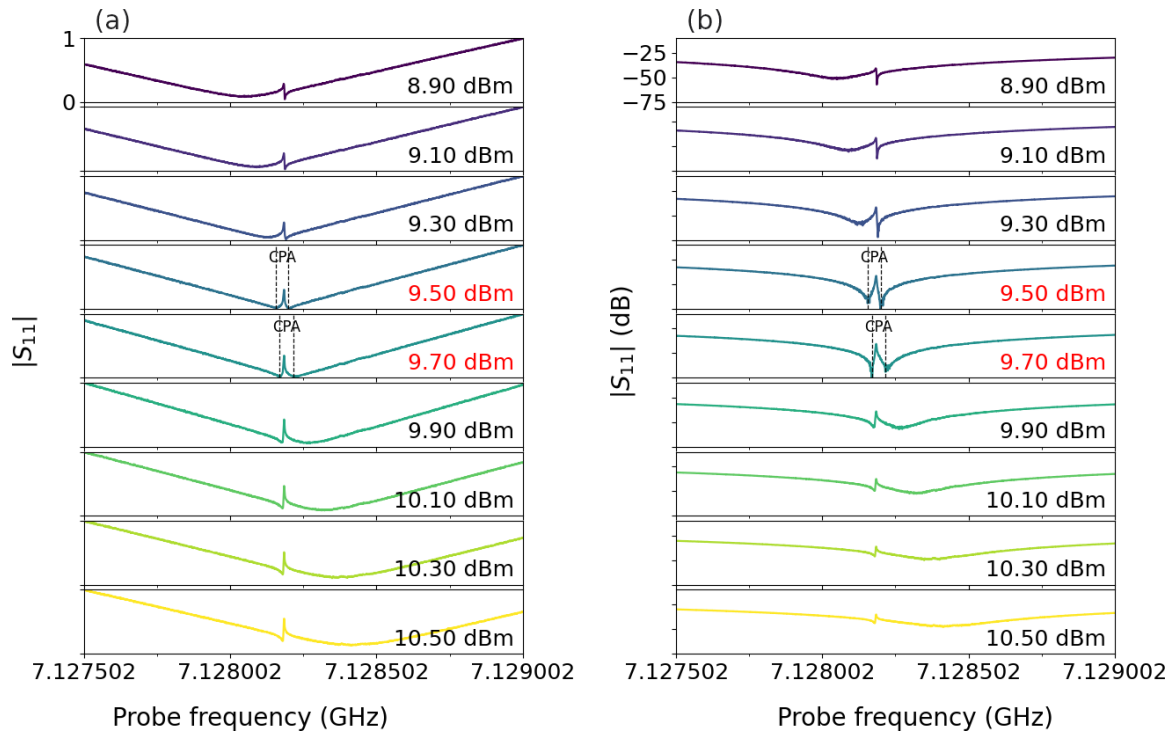


FIG. 13. Reflection spectra $|S_{11}|$ of the upper polariton vs probe frequency for drive powers 8.90–10.50 dBm. With the bias field fixed, increasing power shifts the polariton; CPA is reached only near 9.5 and 9.7 dBm, where the dip sharpens. (a) linear magnitude; (b) logarithmic. Near CPA the logarithmic traces can resemble a doublet, but the linear-scale spectra show a single resonance with an MMIT feature—no true normal-mode splitting.

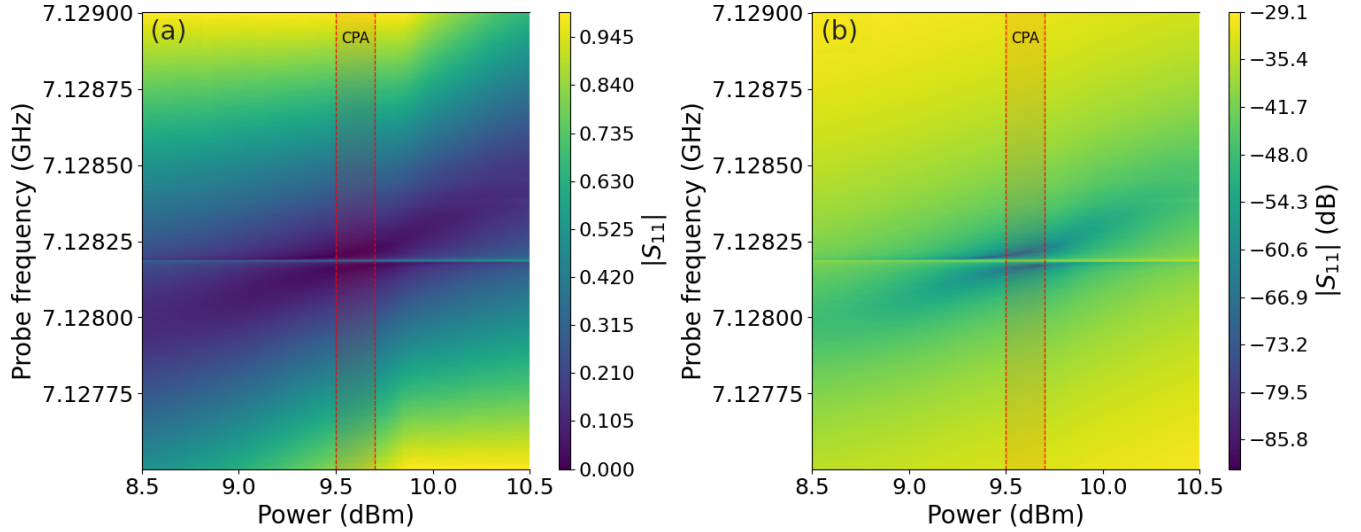


FIG. 14. Contour plots of the upper-polariton reflection $|S_{11}|$ vs probe frequency and drive power with the bias field fixed. (a) linear magnitude; (b) logarithmic. The shaded region between the red dashed lines indicates near-zero reflection, corresponding to the onset of CPA, reached only near 9.5–9.7 dBm.

rate $\kappa_a = \kappa_{\text{int}} + \kappa_{\text{ext}}$ (or, in the hybrid case, by the polariton poles) and is *not* reduced at CPA. Visual “sharpening” seen in logarithmic plots over narrow spans reflects amplitude zeros, not linewidth narrowing or decay rate suppression.

We further studied *magnomechanical* interactions under the CPA condition. In this regime, logarithmic spectra can display sharp dips that mimic a doublet; however, linear-scale data over a wider span reveal a single polariton with a transparency feature (MMIT), not genuine polaromechanical normal-mode splitting.

Practically, linewidths and mode structure should be inferred from linear-scale fits or from the pole locations of the response, with logarithmic plots used for dynamic range only when accompanied by linear-scale spectra. These results correct the misconception that CPA provides a route to linewidth suppression or polaromechanical normal-mode splitting in the linear, weak-probe regime, and establish robust guidelines for analysis and presentation in cavity magnonics and related platforms.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: WIGNER TIME DELAY AND LINEWIDTH

Motivated by the procedure used in Ref. [26] to assess decay-rate suppression under CPA, we discuss here a related pitfall in the interpretation of linewidth or decay-rate reduction. In particular, we examine whether the Wigner time delay (WTD) [34] can be considered as an indicator of reduced decay rates. By considering a single-port bare microwave cavity, we show both theoretically and experimentally that the WTD is directly related to the phase response of the reflection spectrum. Specifically, the real part of the WTD corresponds to the frequency derivative of the reflection phase and therefore characterizes the group delay (or group velocity), which is inherently frequency dependent. As such, WTD should not be interpreted as a direct measure of the photon lifetime or decay rate of the cavity mode. While genuine suppression of the cavity decay rate would indeed affect the WTD, there exists a distinct and experimentally relevant situation—namely, critical coupling ($\kappa_{\text{int}} = \kappa_{\text{ext}}$), corresponding to CPA—in which the WTD diverges despite the cavity linewidth/decay rate remaining finite.

The general definition of the Wigner time delay is given by [34]

$$\tau(\omega) = \frac{\psi_{\text{in}}^\dagger Q(\omega) \psi_{\text{in}}}{\psi_{\text{in}}^\dagger S^\dagger(\omega) S(\omega) \psi_{\text{in}}}, \quad (\text{A1})$$

where $Q(\omega) \equiv -iS^\dagger(\omega)\partial_\omega S(\omega)$. For a single-port bare microwave cavity, $S(\omega) = r(\omega)$ is the complex reflection coefficient, and $\psi_{\text{in}} = \varepsilon_p$ denotes the real amplitude of the probe field. Substituting into Eq. (A1), the WTD reduces to

$$\tau(\omega) = -i \frac{r^*(\omega) \partial_\omega r(\omega)}{|r(\omega)|^2}. \quad (\text{A2})$$

Writing the reflection coefficient as $r(\omega) = A(\omega)e^{i\phi(\omega)}$, with $A(\omega)$ and $\phi(\omega)$, respectively, representing the amplitude and

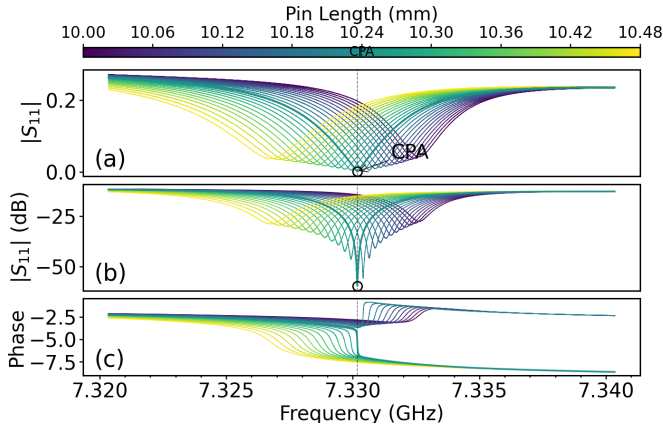


FIG. 15. Reflection spectra of the single-port bare microwave cavity. (a) Magnitude of the reflection coefficient $|S_{11}|$ plotted on a linear scale, (b) the same data plotted on a logarithmic (dB) scale, and (c) the corresponding phase of the reflection coefficient. The color scale indicates the pin length used to tune the external coupling, with CPA highlighted.

phase of the reflection spectra, the WTD can be expressed as

$$\tau(\omega) = \partial_{\omega}\phi(\omega) - i\frac{1}{A(\omega)}\partial_{\omega}A(\omega). \quad (\text{A3})$$

This form makes clear that the real part of the WTD is given by the frequency derivative of the phase, i.e., the group delay, which varies with frequency.

For the reflection spectrum of a single-port bare microwave cavity [Eq. (6)], the WTD evaluated at resonance ($\omega = \omega_a$) is

$$\tau(\omega_a) = \frac{4\kappa_{\text{ext}}}{(\kappa_{\text{ext}} + \kappa_{\text{int}})(\kappa_{\text{ext}} - \kappa_{\text{int}})}. \quad (\text{A4})$$

This expression shows that the group delay diverges under two distinct conditions: (1) when the total decay rate vanishes, $\kappa_{\text{ext}} + \kappa_{\text{int}} \rightarrow 0$, and (2) when the system is critically coupled, $\kappa_{\text{ext}} = \kappa_{\text{int}}$, corresponding to CPA. The latter case is particularly important, as it demonstrates that a divergent WTD can occur even when the cavity decay rate remains finite.

Figure 15 shows the amplitude and phase of the reflection spectrum of a single-port bare microwave cavity. Panels (a) and (b) display the magnitude of the reflection spectra on linear and logarithmic scales, respectively, while panel (c) shows the corresponding phase response. Although the cavity decay rate—given by the linewidth of the amplitude response—is finite and frequency independent, the group delay at resonance diverges under the CPA condition.

This large group delay originates from destructive interference at the external coupling port, which drives the reflected amplitude toward zero. It is therefore an interference effect and is not related to the photon lifetime inside the cavity, which is determined by the cavity linewidth and remains unchanged at CPA.

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