

Ultrasensitive, Parity–Time-Symmetric Wireless Reactive and Resistive Sensors

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Abstract—We propose a new readout paradigm for enhancing the performance of wireless resistive and reactive sensors. Here, we consider a passive resistor–inductor–capacitor sensor that is inductively coupled to an active reader, with the equivalent circuit of the whole telemetry system obeying the space-time reflection symmetry or the parity–time (PT) symmetry. As inspired by PT-symmetric quantum systems, this circuit has a non-Hermitian effective Hamiltonian that commutes with the antilinear, combined $\mathcal{PT}$ operator, where $\mathcal{P}$ and $\mathcal{T}$ are parity-inversion and time-reversal operators. We demonstrate that the PT-symmetric wireless sensor system, when compared to conventional interrogation techniques using a passive coil antenna, may provide significantly improved quality factor (Q -factor), sensing resolution, and sensitivity in response to the sensor’s reactance or resistance variation. Our results may have an impact on various wireless sensing, detection, and imaging systems, particularly for emerging micromachined sensors, miniature implants, wearables, and Internet-of-Things applications.

Index Terms—Wireless sensors and actuators, LC sensors, non-invasive sensors, parity–time symmetry, sensor telemetry.

I. INTRODUCTION

MANY medical, industrial, and automotive applications require sensing of local physical or chemical quantities, where the wired connection between the sensor and the data acquisition system is not accessible. Representative examples include various bio-implants inside the human body (e.g. intraocular pressure sensors, intravascular pressure sensors, intracranial sensors, and tissue-characterization sensors [1]–[6]), pressure sensors on rotating components of vehicle, and sensing in harsh environments (e.g. corrosive media or high temperature [7], [8]). Telemetric sensing based on battery-free passive wireless sensors or radio-frequency identification (RFID) tags is perhaps one of the most viable ways to achieve the contactless and continuous measurement for the above mentioned applications. To date, a great

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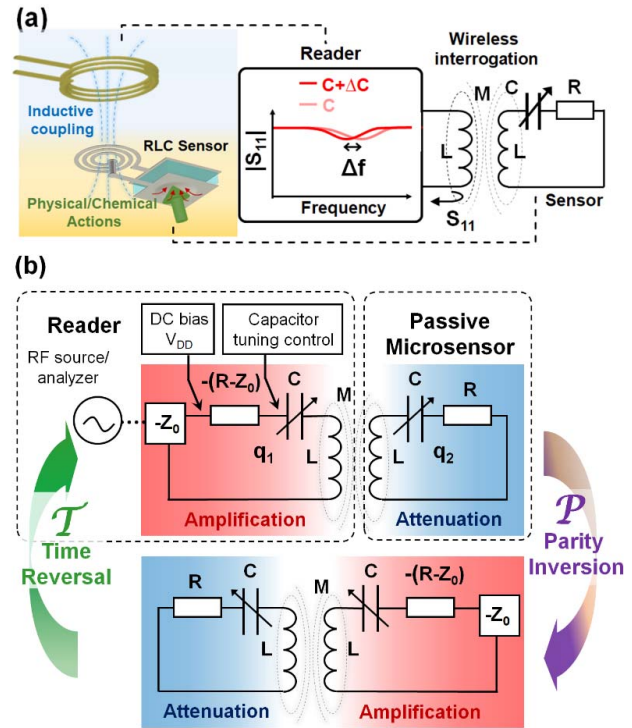


Fig. 1. (a) Schematics of a wireless passive RLC sensor, inductively coupled to a coil reader, and its equivalent circuit model. (b) Equivalent-circuit expression of the PT-symmetric wireless sensor system.

number of low-cost and low-profile wireless sensors have been proposed to measure miscellaneous quantities, such as temperature [8], [9], pressure [1], [7], [10]–[12], liquid volume [13], [14], humidity [15], [16], mechanical strain [17], and chemical reactions (e.g., chemresistive sensors). Most of these sensing devices are based on the passive RLC tank, where the quantity to be measured may change the effective resistance or effective capacitance/inductance of the sensor, resulting in the resonance frequency shift. Typically, a reader coil antenna is used to measure the frequency response of the wireless sensor through the inductive coupling, as illustrated in Fig. 1a.

Although, so far, many research efforts have been focused on the design and fabrication of miniature functional sensors, very limited effort has been made to develop a more robust and sensitive wireless readout technique. However, existing readout methods for passive wireless sensors still face several challenges. For instance, sensitivity and minimum detection

range of the miniature wireless sensors (e.g. integrated circuit piezoelectric or ICP sensors) usually suffer from the small resonance frequency shift and the low Q -factor, resulting from limited device dimensions, skin-effect and Eddy-current losses, and background absorption (e.g. human tissues and organs at high frequencies). In general, an effective resistance taking into account the total power dissipation must be introduced into the RLC tank, as shown in Fig. 1a. In this context, negative-resistance-based oscillators have been proposed for enhancing the resolution and the Q -factor of microwave-resonator sensors, of which the sharp transmission peak (S_{21}) is achieved with the effect of loss compensation [18]–[20].

In this work, we present a new wireless readout technique based on the concept of PT -symmetry, which may significantly enhance the sensitivity and the detection limit of transformer-based sensors. Figure 1b shows the equivalent circuit of the proposed PT -symmetric wireless sensor system, where the passive wireless functional sensor, modeled by an equivalent RLC tank circuit, is inductively coupled to an active $-RLC$ reader circuit. The whole telemetry system fulfills the spatial-inversion and time-reversal symmetry, so-called PT -symmetry [21]. In the following, we will theoretically and experimentally investigate the performance and critical operation conditions of the proposed PT -symmetric wireless sensors, which can provide loss compensation and optimal sensing performance.

II. PT -SYMMETRIC TELEMETRIC SENSOR SYSTEMS

The concept of PT -symmetry originates from the quantum mechanics, where a non-Hermitian Hamiltonian can have real eigenfrequencies, if the Schrödinger system is invariant under operations of spatial reflection $\mathcal{P}$ and time reversal $\mathcal{T}$ [21]. Thanks to formal similarities between Schrödinger and Helmholtz equations, PT -symmetry can be experimentally demonstrated in electromagnetic systems with balanced gain and loss [22]–[28], including transmission-line networks, coupled waveguides/cavities, and lumped-element circuits [29]–[34]. As illustrated in Fig. 1b, a PT -symmetric electronic circuit can be made by pairing the $-RLC$ and RLC tanks, correspondingly responsible for the amplification and attenuation of RF signal. When a RF source, such as a frequency synthesizer based on the negative-resistance device, excites this dimer circuit, a negative generator impedance $-Z_0$ must be included in the coupled-mode (closed-loop) analysis [35]. This is because while a resistor renders energy dissipation, a negative resistor implies an energy source. Therefore, for balancing the net gain and loss, a negative-resistance converter (NRC) with a resistance of $-(R-Z_0)[\Omega]$ must be used in the $-RLC$ tank (which is connected to the RF signal generator/analyzer representing $-Z_0$).

Applying Kirchhoff's laws to the circuit in Fig. 1b leads to the following set of equations:

$$\begin{aligned} \frac{d^2 q_1}{d\tau^2} &= -\frac{1}{1-\kappa^2} q_1 + \frac{\kappa}{1-\kappa^2} q_2 \\ &+ \frac{1}{\gamma(1-\kappa^2)} \dot{q}_1 + \frac{\kappa}{\gamma(1-\kappa^2)} \dot{q}_2 \end{aligned} \quad (1a)$$

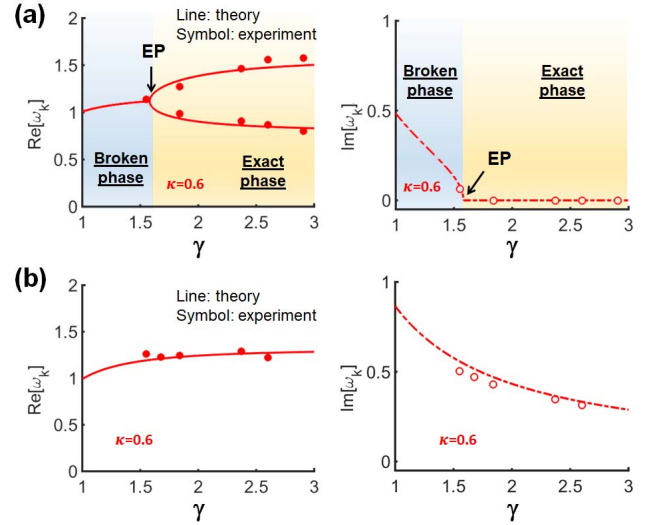


Fig. 2. (a) Real (left) and imaginary (right) eigenfrequency versus the non-Hermiticity parameter γ for the PT -symmetric circuit in Fig. 1b. (b) is similar to (a), but for measurement results obtained by the micro-coil reader shown in Fig. 1a. Here, eigenfrequencies are in units of ω_0 .

$$\begin{aligned} \frac{d^2 q_2}{d\tau^2} &= \frac{\kappa}{1-\kappa^2} q_1 - \frac{1}{1-\kappa^2} q_2 \\ &- \frac{\kappa}{\gamma(1-\kappa^2)} \dot{q}_1 - \frac{1}{\gamma(1-\kappa^2)} \dot{q}_2, \end{aligned} \quad (1b)$$

where q_1 (q_2) corresponds to the charge stored on the capacitor in the amplifying (attenuating) tank, $\tau \equiv \omega_0 t$, the natural frequency of an RLC tank $\omega_0 = 1/\sqrt{LC}$, the dimensionless gain-loss parameter or the non-Hermiticity parameter $\gamma = R^{-1}\sqrt{L/C}$, $\kappa = M/L$ is the coupling strength between the $-RLC$ and RLC tanks, M is the mutual inductance, and $0 \leq \kappa \leq 1$; here all frequencies are measured in units of ω_0 . We find that Eq. (1) remains unchanged under the combined $\mathcal{P}$ ($q_1 \leftrightarrow q_2$) and $\mathcal{T}$ ($t \leftrightarrow -t$) transformations. Further, Eq. (1) can be written in the Liouvillian formalism as [36]:

$$\begin{aligned} \frac{d\Phi}{d\tau} &= \mathcal{L}\Phi; \\ \mathcal{L} &= \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{1}{1-\kappa^2} & \frac{\kappa}{1-\kappa^2} & \frac{1}{\gamma(1-\kappa^2)} & \frac{\kappa}{\gamma(1-\kappa^2)} \\ \frac{\kappa}{1-\kappa^2} & -\frac{1}{1-\kappa^2} & -\frac{\kappa}{\gamma(1-\kappa^2)} & -\frac{1}{\gamma(1-\kappa^2)} \end{pmatrix}, \end{aligned} \quad (2)$$

where $\Phi \equiv (q_1, q_2, \dot{q}_1, \dot{q}_2)^T$. An effective Hamiltonian can be defined as $H_{\text{eff}} = i\mathcal{L}$, which takes a non-Hermitian form and is symmetric with respect to generalized PT transformations:

$$\mathcal{P} = \begin{pmatrix} \sigma_x & 0 \\ 0 & \sigma_x \end{pmatrix}, \quad \mathcal{T} = \begin{pmatrix} \mathbf{I} & 0 \\ 0 & -\mathbf{I} \end{pmatrix} \mathcal{K}, \quad (3)$$

σ_x is the Pauli matrix, $\mathbf{I}$ is an 2×2 identity matrix, and $\mathcal{K}$ conducts the operation of complex conjugation. H_{eff} commutes with PT , namely $[PT, H_{\text{eff}}] = 0$, which implies that H_{eff} and PT share the same set of eigenstates.

After the substitution of time-harmonic charge distributions $q_n = A_n e^{i\omega\tau}$, eigenfrequencies for this PT -symmetric circuitry can be obtained from the eigenvalue equation, $(H_{\text{eff}} - \omega_k \mathbf{I})\Phi_k = 0$ and $k = 1, 2, 3, 4$, as functions of the non-Hermiticity parameter γ and the coupling strength κ :

$$\omega_{1,2,3,4} = \pm \sqrt{\frac{2\gamma^2 - 1 \pm \sqrt{1 - 4\gamma^2 + 4\gamma^4 \kappa^2}}{2\gamma^2(1 - \kappa^2)}}, \quad (4)$$

Although there are four normal modes, there is redundancy and only two distinct modes are necessarily considered because positive and negative eigenfrequencies of equal magnitude are essentially identical. The complex eigenfrequencies evolve with γ , showing three distinct regimes of behavior. As can be seen in Fig. 2a, the eigenfrequencies undergo a bifurcation process and branch out into the complex plane at the exceptional point (or the spontaneous PT -symmetry breaking point):

$$\gamma_{EP} = \frac{1}{\kappa} \sqrt{\frac{1 + \sqrt{1 - \kappa^2}}{2}}. \quad (5)$$

In the parametric region $\gamma \in [\gamma_{EP}, \infty]$, eigenfrequencies are purely real ($\gamma \in \mathbb{R}$) and $PT\Phi_k = \Phi_k$ such that the PT -symmetry is *exact*. Moreover, if one seeks only purely real solutions, there is redundancy because positive and negative eigenfrequencies of equal magnitude are essentially identical. The motion in this exact PT -symmetric phase is oscillatory at the two (purely real) eigenfrequencies. At the exceptional point γ_{EP} , eigenfrequencies undergo a bifurcation process and branch out into the complex plane, and thus the PT -symmetry is spontaneously broken. The region $\gamma \in [\gamma_c, \gamma_{EP}]$ is known as the broken PT -symmetric phase, where eigenfrequencies become two complex conjugate pairs ($\gamma \in \mathbb{C}$). In this region, $PT\Phi_k \neq \Phi_k$ and the PT -symmetry is broken. Another crossing between the pairs of degenerate frequencies (and another branching) occurs at the lower critical point:

$$\gamma_c = \frac{1}{\kappa} \sqrt{\frac{1 - \sqrt{1 - \kappa^2}}{2}}. \quad (6)$$

In the sub-critical region $\gamma \in [0, \gamma_c]$, ω_k become purely imaginary and, therefore, the modes have no oscillatory part and simply blow up or decay away exponentially, corresponding to the over-damped/amplified mode. Finally, we note that in the loss (gain)-less scenario ($\gamma \rightarrow \infty$), two frequency pairs are given by $\omega_{1,2,3,4} = \pm 1/\sqrt{1 \pm \kappa}$. These modes are associated with a pair of double-degenerate frequencies $\omega_k = \pm 1$ for a single isolated LC tank with $\kappa = 0$.

Figures 3a and 3b show the frequency responses of reflection (Γ), as functions of γ and the normalized frequency $\omega [\omega_0]$, for the conventional wireless sensor system [1]–[17] (which uses a coil antenna with inductance L to interrogate the passive sensor [Fig. 1a]), and the PT -symmetric one (which consists of a $-RLC$ tank to communicate with the same sensor [Fig. 1b]); here, we assume that the coupling strength $\kappa = 0.6$ and the input impedance of the RF source (e.g. a vector network analyzer or VNA) $Z_0 = 0.33R$. We find that resonant reflection dips in Fig. 3b are in consistent with the eigenfrequency analysis in Fig. 2a: (1) if $\gamma < \gamma_c$, there

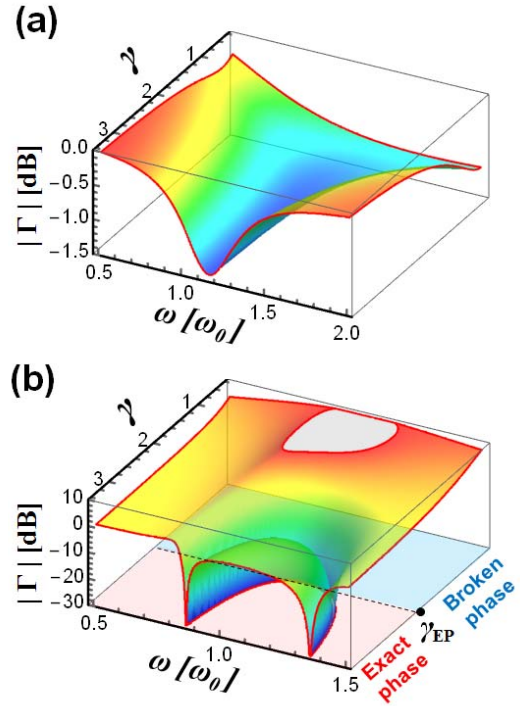


Fig. 3. Contours of reflection coefficient, as a function of the normalized operating frequency and the non-Hermiticity parameter, for the circuit of (a) the conventional wireless sensor system [Fig. 1(a)] and (b) the PT -symmetric one [Fig. 1(b)]; here the coupling strength $\kappa = 0.6$ and the input impedance of the RF source $Z_0 = 0.33 R$.

is no clear resonant peak, but a purely amplification or decay phenomenon; (2) if $\gamma \in [\gamma_c, \gamma_{EP}]$, a broadband resonance is obtained, as the system operates in the broken PT -symmetry phase; (3) if $\gamma > \gamma_{EP}$, the exact PT -symmetry phase yields two real eigenfrequencies, resulting in sharp reflection dips. Comparing the conventional fully-passive wireless sensing scheme and the PT one, it is seen that the proposed approach may offer superior sensitivity in terms of resonance frequency shift due to perturbations in γ , modulation depth, and spectral resolution; here, γ is a function of the sensor's effective resistance, capacitance, and inductance that could be tuned by physical or chemical parameters to be sensed.

III. IMPLEMENTATION AND CHARACTERIZATION OF WIRELESS CAPACITIVE SENSORS

To validate the theoretical results in Section II, we have built a PT -symmetric RF circuit that resembles practical wireless sensor systems. For example, many medical and industrial pressure sensors are based on the capacitance change due to the mechanical deflection or the variation of dielectric constant [8], [10]. In order to mimic a passive wireless capacitive sensor, we have made an onboard series RLC tank [Fig. 1a], consisting of a variable capacitor (BBY40: $C = 2\text{--}32$ pF), a resistor (MNR02JR-0402: $R = 150 \pm 0.5\%$ Ω), and a microstrip coil ($L = 0.3$ μH) [37]. To suit the PT -symmetric circuit topology in Fig. 1b, the reader may need to be equipped with a negative resistor $-R$, which can be realized by a NRC that pulls in power to the circuit, rather than dissipating it like a resistor. Hence, the active reader is a $-RLC$ tank that has

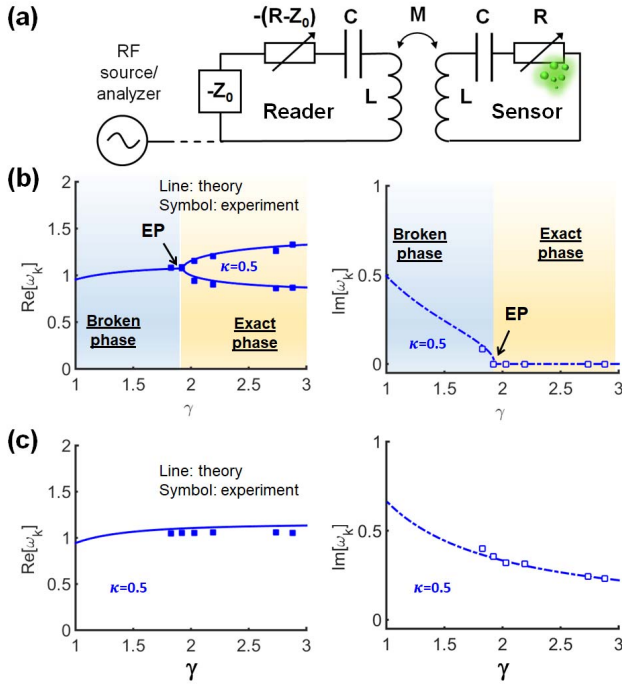


Fig. 6. (a) Schematics of the *PT*-symmetric wireless resistive sensor system. (b) Real (left) and imaginary (right) eigenfrequency versus the non-Hermiticity parameter γ for the *PT*-symmetric circuit in (a). The resistance of the pseudo *RLC* sensor is varied from 190 Ω to 300 Ω , corresponding to the change of γ from 2.8 to 1.9. (c) is similar to (b), but for measurement results obtained by the micro-coil reader shown in Fig. 1a. Here, eigenfrequencies are in units of ω_0 .

eigenfrequency results in a broad (low- Q) resonance (not shown here for saving some space) and low sensitivity to perturbations of γ .

IV. IMPLEMENTATION AND CHARACTERIZATION OF WIRELESS RESISTIVE SENSORS

Recently, there has been substantial investigation and research in wireless (bio-)chemical sensors based on the chemiresistor (i.e., chemically-tuned variable resistor). Particularly, nanomaterials (e.g., graphene [47], [48]) has been a recent thrust in micro/nano-sensor development. However, due to the large electrical resistance of chemiresistor, these resistive sensors typically exhibit low Q -factor and imperceptible resonance frequency shift. In this work, we also apply the concept of *PT*-symmetric telemetry to improve the sensing performance of wireless resistive sensors. In this scenario, a variable resistor is connected in series with a capacitor and an inductor, forming a passive *RLC* tank. The sensor is inductively coupled to an active reader based on a $-RLC$ tank, as shown in Fig. 6a. For the proof-of-concept demonstration, we used an onboard *RLC* tank with a variable resistor to simulate the resistance variation caused by, for example, chemical reactions in a chemiresistor. The series *RLC* tank is built by a microstrip coil ($L \approx 0.6 \mu\text{H}$), a capacitor (BBY40: $C \approx 2 \text{ pF}$), and a variable resistor (MNR02JR-0402: $R = 150 \sim 300 \pm 0.5\% \Omega$). The active reader is similar to the one used in Section III, of which the effective negative resistance is tuned by the external DC bias. When the

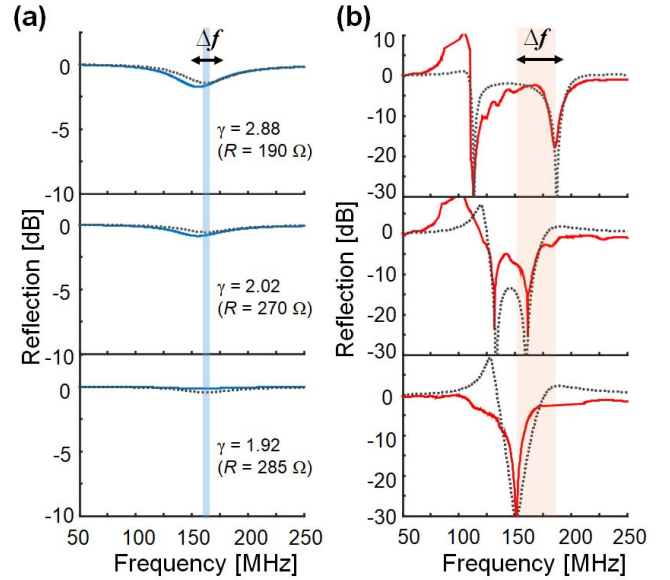


Fig. 7. Measured reflection coefficient for a (pseudo) *RLC* sensor with effective capacitance $C = 2 \text{ pF}$ and effective inductance $L = 600 \text{ nH}$, which is wirelessly read by (a) the conventional coil-antenna reader shown in Fig. 1a, and (b) the active reader ($-RLC$ tank in Fig. 6b). The effective resistance R of the pseudo *RLC* sensor is varied from 190 Ω to 285 Ω .

active reader ($-RLC$ tank) is used to wirelessly interrogate the pseudo resistive sensor (*RLC* tank), the *PT*-symmetric telemetry system can be achieved, with its equivalent circuit shown in Fig. 6a.

Figure 6b presents the theoretical (solid lines) and experimental (dots) results for the complex eigenfrequency as a function of the non-Hermiticity parameter γ , which is varied by adjusting the effective resistance of the *RLC* tank sensor. Here, we find a good agreement between experimental and simulation results. Similar to the case of *PT*-symmetric wireless capacitive sensor [Fig. 2], there exists two distinct regimes of behavior divided by the exceptional point. As can be seen in Fig. 6b, around the exceptional point, the real eigenfrequencies become ultrasensitive to perturbation of the sensor's effective resistance. Figure 6c is similar to Fig. 6b, but for the fully-passive wireless sensing scheme using a simple microcoil reader. In this case, the eigenfrequency is complex-valued and insensitive to the change in γ (or R of the sensor).

Figures 7a and 7b present evolutions of the reflection spectrum for the fully-passive and *PT*-symmetric wireless sensor systems in Fig. 6, respectively. In both cases, measurements results (solid lines) are in good agreement with theory (dashed lines). As can be seen in Fig. 7, in the *PT*-symmetric telemetry system, the real eigenfrequencies give rise to sharp and high- Q reflection dips, even though the sensor's effective resistance is large. However, the passive micro-coil reader only achieves a weak resonance with a broad linewidth. Again, our measurement results demonstrate that a wireless sensor system engineered into the *PT*-symmetric dimer can provide superior sensitivity and detectivity, as it achieves not only higher spectral resolution and greater modulation depth, but also more sensitive frequency responses associated with the bifurcation

effect near the exceptional point. Fundamentally different from conventional loss-compensation resonator circuit, where $-R$ and R components are in direct contact [18]–[20], [41], [42], in our *PT*-symmetric telemetry system, the balanced gain and loss are wirelessly interacted, thus offering a promising route for improving the performance of the wireless reactive and resistive sensors (e.g., without the need of active component and power source in the sensor). Most importantly, the *PT*-synthetic circuit topology can significantly enhance the sensitivity in terms of the resonance frequency shift under reactive and resistive perturbations.

V. FUNDAMENTAL LIMIT OF SENSITIVITY

In this section, we will study the fundamental limit of sensitivity of *PT*-symmetric telemetric sensors. Of particular interest is the strong coupling regime. In an extreme case, if $\kappa = 1$, the critical and exceptional points have the same value: $\gamma_c = \gamma_{EP} = 1/\sqrt{2}$, and the degenerate eigenfrequencies become $\pm i\infty$, owing to the overlap between these two points. As κ approaches (but less than) unity and $\gamma \gg \gamma_{EP}$, the four eigenfrequencies expressed in units of ω_0 are:

$$\omega_{1,2,3,4} \simeq \pm \frac{1}{\sqrt{1 \pm \kappa}}, \quad (8)$$

which merge at the exceptional point:

$$\omega_{EP} = \pm \frac{1}{4\sqrt{1 - \kappa^2}}. \quad (9)$$

When the exceptional point is taken as a reference, the possible bifurcation range is given by:

$$\Delta\omega_+ \in \left[0, (1 - \kappa)^{-1/2} - (1 - \kappa^2)^{-1/4}\right]; \quad (10a)$$

$$\Delta\omega_- \in \left[(1 + \kappa)^{-1/2} - (1 - \kappa^2)^{-1/4}, 0\right], \quad (10b)$$

where $\Delta\omega_+$ and $\Delta\omega_-$ are variations in the upper and lower branches of eigenfrequencies. From Eq. (10), one can readily understand that if the coupling strength approaches one, $\Delta\omega_+$ and $\Delta\omega_-$ tend to: $\Delta\omega_+ \in [0, \infty]$ and $\Delta\omega_- \in [-\infty, 0]$. In this case, largely bifurcating eigenfrequencies are obtained around the exceptional point, implying that even a small perturbation of γ could lead to considerably shifted resonance frequencies. It is worth mentioning that the bifurcating rate of eigenfrequencies, related to the sensitivity of wireless *RLC* sensor, increases with increasing the coupling strength (not shown here). However, the coupling strength (or the mutual inductance between two coils) has its own limit. In practice, for two tightly coupled planar coils, it is difficult to achieve a large κ that is close to one.

In another extreme case, if $\kappa = 0$, the critical and exceptional points are: $\gamma_c = 1/2$ and $\gamma_{EP} \rightarrow \infty$, which are far apart from each other. In the weak coupling regime (i.e., $\kappa \ll 1$), if $\gamma \gg \gamma_c$, the four eigenfrequencies expressed in units of ω_0 can be derived as:

$$\omega_{1,2,3,4} \simeq \pm 1 \pm \frac{\kappa}{2} \sqrt{1 - \frac{1}{(\kappa\gamma)^2}}. \quad (11)$$

If $\gamma \gg \gamma_{EP}$, the four eigenfrequencies become:

$$\omega_{1,2,3,4} \simeq \pm 1 \pm \frac{\kappa}{2}, \quad (12)$$

which degenerate into $\omega_{EP} \simeq \pm 1$ at the exceptional point. Hence, when taking the exceptional point as a reference, the maximum range of the eigenfrequency shift is given by:

$$\Delta\omega_+ \in [0, \kappa/2]; \quad (13a)$$

$$\Delta\omega_- \in [-\kappa/2, 0]. \quad (13b)$$

If $\kappa \ll 1$, the bifurcation effect is rather weak and thus low sensitivity is obtained. Based on the above discussions, we can conclude that the sensitivity is proportional to the coupling strength. If the coupling strength approaches the singular point ($\kappa = 1$), at which γ_c and γ_{EP} overlap, the effect of sensitivity enhancement due to the bifurcation effect is particularly obvious.

VI. CONCLUSIONS

We have put forward the concept and practical designs of the *PT*-symmetric telemetry system for enhancing the sensitivity and detection limit of *RLC*-based passive wireless sensors. Specifically, the equivalent circuit of this wireless sensor system is tailored to fulfill the spatial-inversion and time-reversal symmetry, so-called *PT*-symmetry. We have first theoretically studied different *PT* phases and critical conditions for obtaining the optimal sensing performance. Then, we have experimentally demonstrated the possibility of using the *PT*-symmetry concept to wirelessly read the (lossy) capacitive and resistive sensors, with high spectral resolution and high sensitivity. The proposed wireless sensing technique is potentially revolutionary, as it may be beneficial to a plurality of environmental, infrastructural, wearable, and implantable wireless sensors, as well as emerging applications in the fields of RFIDs and IoTs.

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