Enhancing transfer efficiency for metamaterial Wireless Power Transfer system through parity-time symmetry.

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요 약

The progress of WPT technology over the past decade proved its applicability for many applications ranging from powering IoT devices to charging cell phones. Previously, metamaterials (MTM) have been embedded into wireless power transfer system to extend the range of transmission. However, the system's narrow bandwidth remained a massive shortfall regarding the robustness and range of operation. In this work, we constructed a WPT system under parity-time symmetry (PT-symmetry) conditions in the near field domain. A comparison was presented between metamaterial embedded wireless power transmission system (MTM-WPT) and PT-symmetry metamaterial embedded wireless power system. (PT-MTM). It was shown that PT-MTM can achieve 3dB bandwidth 10MHz 3dB and could maintain an efficiency of 95%.

I. Introduction

Wireless power transfer (WPT) technology has greatly facilitated and improved human needs, from charging cell phones to powering medical implants [1]. Multiple approaches can be implemented to transfer power wirelessly, such as microwave, radio wave, induction coupling, and resonance coupling power transmission. The latter being the most dominant method of transmission due to its less complexity, higher efficiency, and safe non-radiant energy [2]. Incorporating metamaterials or high Q resonant structures with inductive wireless power systems has been proven to increase transfer distance and act as a waveguide to the transmitted waves [3].

Metamaterials (MTM) are artificially engineered materials to possess unusual electromagnetic (EM) properties, such as negative refraction and evanescent wave amplification. Metamaterials contribute to wireless power transmission through their evanescent wave amplification ability. As such, systems depend on focusing the power within a narrow resonance band frequency to achieve high efficiency, making it frail against frequency fluctuations with a transmission efficiency of lower than 60% [3].

Recently, Parity-time symmetry was introduced from Quantum physics as a solution to WPT systems instability towards fluctuation in operating frequency and coupling coefficients [3]. Parity-time symmetry emerges from non-Hermitian physics, which in short means that the system operates as a closed energy system even though there is energy inflow and outflow; if the system contains a gain rate that is equivalent to the loss rate.

It was shown previously [2] that WPT systems utilizing parity-time symmetry conditions can harness a near unity transmission efficiency. Suppose the gain rate is equivalent to the loss rate, and we have the same resonance frequency at both ends of the system under a specific coupling rate. In that case, the system will operate with two fundamental modes (operating frequencies) maintaining unity efficiency.

In this work, we demonstrate the effects of implementing PT- symmetry conditions on near-field WPT systems and present a comparison between (MTM-WPT) and (PT-MTM).

II. Design

Fig 1. (a) illustrates MTM-WPT, which consists of a transmitter (T_x), receiver (R_x) wideband antennas, and a four-turn spiral hexagonal resonator (4T-SR) (MTM) with resonant frequency ($f_0 = 12.9\ MHz$). It should be noted that the resonance frequency of (Tx, Rx) is different from that (of MTM). As shown in Fig. 1(b), $L_{1(tx,rx)}$ differs from L_0. While Fig 1. (c) describes (PT-MTM) of transmitter 4T-SR (MTM(T_x)) and (MTM(R_x)). All the components resonate at a single frequency f_0 as shown in Fig 1. (d), where L_0 and C_0 are common for all the system.

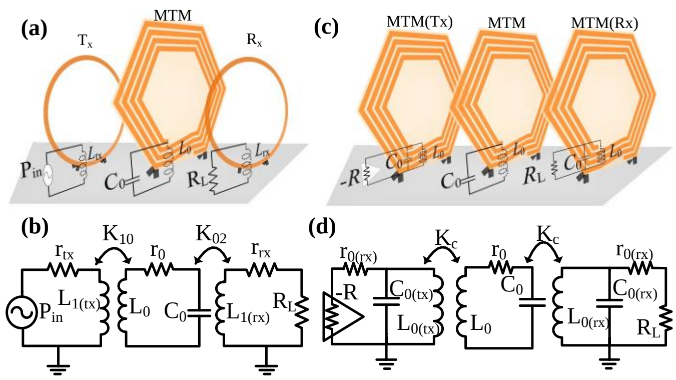

Fig 1. (a) Metamaterial embedded wireless power transmission system (MTM-WPT). (b) Enhanced Pt-time wireless power system. (PT-MTM). (b) and (d) are the circuit schematic of (a) and (c), respectively.

PT-symmetry can be implemented in WPT systems by introducing a gain element into the circuit equivalent to the loss element. As shown in Fig.1(d), it is denoted as (-R), which is equivalent to load resistance (R_L).

By utilizing coupled-mode theory for characterizing WPT systems [4], we can obtain the operating frequency (ω) by solving for the eigenvalues of equation (1). Here ω_0 is the resonance frequency of MTM ($\omega_0 = 1/\sqrt{L_0 C_0}$), κ is the coupling rate ($\omega_0 K/2$). g and γ are the gain rate and the loss, respectively. Our PT-symmetric system, ($g = \gamma = (R^{-1}\sqrt{L_0/C_0}$). As shown in equation (2), the system obtains two real fundamental modes if $\kappa \geq \gamma$. The coupling coefficient corresponding to $\kappa = \gamma$ is called critical coupling coefficient K_C. For our system parameters shown in (Fig 1) with values in Table 1 (ignoring(r_0 (intrinsic resistance)) the critical coupling is K_C =0.63.

$$\frac{d}{dt}\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} j\omega_0 + g & -j\kappa & 0 \\ -j\kappa & j\omega_0 & -j\kappa \\ 0 & -j\kappa & j\omega_0 - \gamma \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \quad (1)$$

$$\omega = \omega_0 \pm \sqrt{\kappa - \gamma} \quad (2)$$

Table 1. Design parameters.

L_1	L_0	C_0	R_L=R
86 nH	0.68 uH	224 pF	50 Ω

The gain unit of PT-MTM was characterized as the input impedance of the vector network analyzer (VNA). As the input impedance matched the output impedance of the VNA and power flows from port 1 to port 2. Therefore, port 1(port2) resembles -50Ω (50Ω).

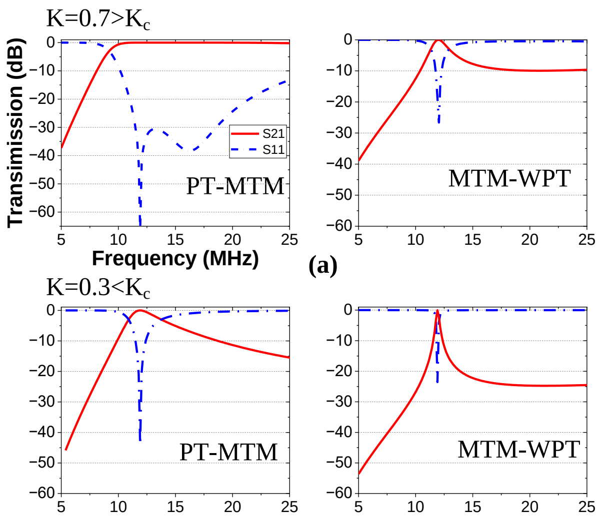

Fig 2. Simulation results S-parameters of the two WPT systems. (a) and (b) for coupling coefficient $K = 0.7$ and $K = 0.3$, respectively.

Fig 2. shows the simulation results of both systems in two conditions, $K = 0.7 > K_C$ and $K = 0.3 < K_C$. PT-MTM system can achieve more than 95% efficiency for a bandwidth of 30 MHz and a 3dB bandwidth of 10MHz. In contrast, MTM-WPT has only 1.7 MHz. That means the PT-MTM system is more robust against frequency fluctuations. Also, PT-MTM shows higher bandwidth than MTM-WPT when $K < K_C$, with 4MHz 3dBbandwidth while MTM-WPTT with only 0.27 MHz. Experimental results in Fig.3 match that of Fig.2 when $K > K_C = 0.7$.

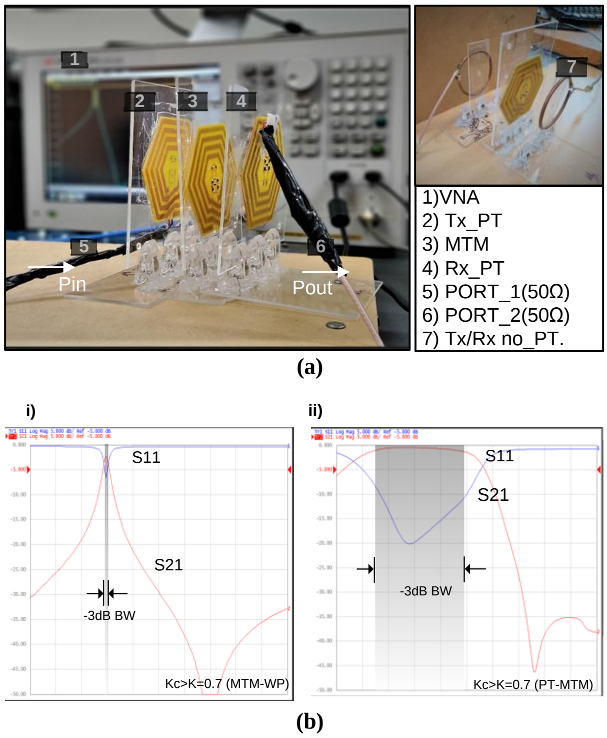

Fig 3. (a) Experimental setup. (b) Experimental (VNA) results S-parameters i) (MTM-WPTT) ii) (PT-MTM) coupling coefficient (K) =0.7

Ⅲ. Conclusion

This work designed a near-field WPT system operating in the MHz domain. Hexagonal 4T-SR metamaterial was embedded into the system to improve transmission efficiency and extend the transmission range. Then, parity time symmetry conditions were applied to increase the system's robustness. It was shown that PT-MTM increases 3dB bandwidth by 98.5 MHz and could maintain an efficiency of 95% for 10 MHz bandwidth.

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