Arbitrary Wireless Energy Distribution within an Epsilon Near-zero Environment

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Efficient power distribution to multiple receivers with controlled amounts is critical for wireless communication and sensing systems. Previous efforts have attempted to improve power transfer efficiency through strong coupling and parity-time (PT) symmetry, providing attractive opportunities for flexible energy flow control. In this study, a novel method for achieving arbitrary power distribution is proposed and numerically demonstrated by leveraging the unique properties inside an epsilon near-zero (ENZ) environment. Specifically, it shows that the power from a single source can be transferred to multiple receivers inside an ENZ medium with negligible loss by modifying optical properties of receivers rather than introducing sophisticated active control modules. Importantly, full power transfer is independent of the size and shape of the ENZ medium, as well as the positions of the receivers and source. A realizable system is further designed with effective zero index at microwave frequencies to confirm the high efficiency of energy transfer. The innovative approach, employing photonic doping for advanced and efficient wireless power transfer, may shed light on the next generation of energy efficient communication/sensing systems with versatile control functionalities.

1. Introduction

Since Nikola Tesla first proposed the idea of wireless power transfer (WPT),[1] it has been playing a central role in both practical applications and fundamental research, especially in radio-frequency-related fields such as consumer electronics, medical devices and automotive applications.[2–5] As the demand for better efficiency and controllability increases, traditional WPT methods face compromises between efficiency, stability, and cost,[6,7] limiting their widespread adoption. Several solutions have been proposed to partially solve the aforementioned problem in recent years. Resonance based WPT is proposed to increase the coupling efficiency at mid-range distance between strongly coupled resonators.[8] PT-symmetric configurations provide robust to variations in coupling when distance is changed.[9–12] Self-oscillating WPT is beneficial for no additional tuning circuitry to realize robust operation.[13,14] Moreover, adding metamaterials of negative permeability in a WPT system is another way to improve energy transfer efficiency which is more compatible and miniaturized.[15–17] Some metamaterials techniques are more precious to control the transmission directions.[18,19] Epsilon near-zero index (ENZ) materials have gained immense momentum for decades, fertilizing many disciplines in photonics.[20–27] Among the intriguing phenomena associated with ENZ materials, supercoupling[28–30] stands out, enabling robust energy tunneling of electromagnetic waves against deformations of waveguides. Consequently, supercoupling has been proposed for various applications, such as waveguide interconnects,[31] cloaking,[32] nonlinear effect,[33] and quantum emission.[34] Besides, ENZ metamaterials have been reported...
to provide a limited efficiency improvement by amplification of near-field. However, the investigation of WPT inside ENZ materials remains elusive, leaving an open question regarding how the potential of ENZ can be fully explored for WPT.

Here, we propose a novel implementation of wireless power transfer with negligible loss inside ENZ environment, allowing for arbitrary power distribution. We reveal that the efficiency of power transfer remains near 100% for any arbitrary shape of an ENZ material, with minimal power leakage into open space, regardless of the distance between the emitter and the receiver. Notably, we unveil that the transfer efficiency at the receiver is determined by its own properties and is independent of the resonance of the emitter. We verify the above transmission properties through both an analytical model and full-wave simulations within an ideal ENZ material. The transmission properties are protected by the ENZ condition, independent of specific geometric parameters and immune to perturbations and inter-couplings that preserve the required ENZ condition. We further show that it is possible to distribute power among multiple receivers flexibly, using a passive approach that significantly reduces the complexity of the system. Our explorations may extend applications in the rapidly growing fields of WPT, opening up new opportunities for a wide range of electromagnetic systems that require robust and efficient functionalities.

2. Theory of Full Energy Transfer in the ENZ Limit

To describe how ENZ materials can lead to a robust and highly efficient transfer scheme, we consider a general scenario, which is schematically depicted in Figure 1a, in which a source resonator and a receiver resonator are immersed in a 2D ENZ body of an arbitrary shape, identified as S-rod and R-rod, respectively. To simplify the analysis, we model the source as a magnetic dipole along the z direction in a dielectric medium, and use a lossy medium to simulate the receiver. We solve the problem by using the doping theory, which is originally developed for adjusting the permeability of materials with near zero permittivity. We find that one of the unique features of ENZ medium - the uniform distribution of magnetic field, persists when the source and receiver are immersed in the ENZ material (see details in Supporting Information). Interestingly, the magnetic field is solely determined by the shape and dielectric parameter of the medium, and is independent of positions of S-rod and R-rod. This position-independence indicates that the coupling strength between rods is invariant at difference distances, and it leads to invariant power transfer even when the distance between them changes inside the ENZ medium. This property provides a platform to achieve highly efficient wireless energy transfer.

Now, we will demonstrate how to obtain distance-independent transfer of energy between the source and receiver. We begin with the calculation of the power that is leaked into air and the field on the boundary of S-rod and R-rod for the different shape of ENZ in (a,b), respectively. The x and y axis represent the real and image part of the permittivity, respectively. e,f) Transmission spectrum for \( \text{Im} (\varepsilon_2) = 0.0016 \) for the configuration in (a,b). The ‘trans’ represents theory and ‘Sim’ represents simulation.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Illustration of the robust and highly efficient transfer inside ENZ materials. (a,b) Sketch of the geometry configuration: a 2D arbitrary shape of ENZ material. Inside the ENZ, the ideal source and receiver are presented by two circles with different permittivity \( \varepsilon_1 \) and \( \varepsilon_2 \) respectively (radius \( r \). The magnetic dipole along z-axis is placed at the center of S-rod to excite the wave. (c,d) Dependence of transmission on the permittivity of R-rod for the different shape of ENZ in (a,b), respectively. The x and y axis represent the real and image part of the permittivity, respectively. (e,f) Transmission spectrum for \( \text{Im} (\varepsilon_2) = 0.0016 \) for the configuration in (a,b). The ‘trans’ represents theory and ‘Sim’ represents simulation.

In Figure 1, the transmission properties are protected by the ENZ condition, independent of specific geometric parameters and immune to perturbations and inter-couplings that preserve the required ENZ condition. We further show that it is possible to distribute power among multiple receivers flexibly, using a passive approach that significantly reduces the complexity of the system. Our explorations may extend applications in the rapidly growing fields of WPT, opening up new opportunities for a wide range of electromagnetic systems that require robust and efficient functionalities.
the working wavelength in free space. With this configuration the field can be solved analytically based on the Helmholtz equation. Direct calculation of the magnetic field inside the R-rod yields 

\[ \psi_{\text{loss}}(t) = J_0(k_r r) / J_0(k_r R_{\text{rod}}) \]

where \( J_0 \) and \( k_r \) represent the cylindrical Bessel function of order \( n \) and the wave number in \( e_2 \), respectively. The power transfer into the R-rod is given as

\[
P_{\text{transfer}} = \text{Re} \left[ \frac{\pi r^2}{io\varepsilon} \frac{k J_0(k_r r)}{J_0(k_r R_{\text{rod}})} [Hz]^2 \right]
\]

Similarly, outside the ENZ region, the distribution of field is given by \( \psi_{\text{out}}(t) = H_0(k_r r) / H_0(k_r R_{\text{rod}}) \), where \( H_0 \) represents the cylindrical Hankel function of order \( n \). The energy loss in the air is thus expressed as

\[
P_{\text{loss}} = \text{Re} \left[ \frac{\pi R_{\text{ENZ}}}{io\varepsilon} \frac{k_0 H_1(k_r R_{\text{ENZ}})}{H_0(k_r R_{\text{ENZ}})} [Hz]^2 \right]
\]

From Equation (1), resonant behavior occurs at \( J_0(k_r r) = 0 \) when \( k_r \) is real, corresponding to a lossless dielectric rod. However, when the dielectric rod becomes lossy, \( J_0(k_r r) \) would have no zeros. Nonetheless, the resonance still occurs at the original lossless dielectric parameter. Under the condition of resonance, the field inside R-rod is much stronger than at other locations, indicating that \( P_{\text{loss}} \) is much smaller than \( P_{\text{transfer}} \), allowing for near unity energy transfer.

For the given geometric parameters shown in Figure 1a, the influence of complex permittivity of R-rod on the energy transmission is illustrated by Figure 1c, which shows the transmission plotted against the real (x-axis) and imaginary (y-axis) parts of \( e_2 \), respectively. As we predicted, nearly complete transmission occurs at resonance (\( e_2 = 9.843 + 0.0016i \)). It is important to note that the resonance persists within a narrow range around the designed parameters. As a result, the efficiency of energy transfer is more than 80% in the relatively large range for the real part of the permittivity. However, far from the resonance condition, the efficiency drops significantly. We validate our results via numerical simulations based on Comsol Multiphysics with a fixed imaginary part of permittivity (\( \varepsilon_{\text{inc}} = 0.0016 \)). The numerical results, as shown in Figure 1c, agree well with the analytical studies.

Because the ratio of energy transfer is determined by the energy leakage into air, we next investigate the influence of size and shape of ENZ while keeping the resonance of the R-rod fixed. Equation (2) shows that \( P_{\text{loss}} \) has no resonance behavior. Thus, near-unity energy transfer cannot be destroyed by varying the size of the ENZ region. In addition, the value of \( P_{\text{loss}} \) decreases with the increase of \( R_{\text{ENZ}} \), leading to transmission even closer to unity for a larger ENZ region. Importantly, this high efficiency is robust against arbitrary shapes of ENZ materials.

3. Results and Discussion

To better visualize the power transfer inside ENZ materials, we study the power flow between the S-rod and R-rod inside the ENZ region. Previous studies show that power flow inside ENZ is analogous to ideal fluid, meaning that power flow is robust against the defects by smoothly bending around defects of arbitrary geometries. However, in our case, the receiver (R-rod) is not lossless and therefore it serves as the sink of power inside. Under the ideal energy transmission condition as shown in Figure 2a, the power flux lines converge into the R-rod and there is negligible fringe of power flux lines into the free space. We also simulate another configuration with randomly positioned R-rod and S-rod, which exhibits similar behavior, as shown in Figure 2b. Although close to the boundary of ENZ region, there is still little energy loss in the air, which indicates the full energy transfer from S-rod to R-rod. The uniform magnetic field distribution is observed inside the ENZ region, which plays an important role in realizing the full transmission. While the magnetic field in free space may be larger than the field in the ENZ region, it is significantly smaller than the field within the receivers. This marked difference is a result of the resonance behavior, which enhances the field within the receiver and ensures efficient energy transmission. As comparison, we break the ENZ condition (increasing \( \varepsilon_{\text{inc}} \) to 0.01) and show the power flow in Figure 2c. A part of energy is coupled outside and the uniformity of the magnetic field in ENZ vanishes. When the receiver approaches the boundary, more energy escape to the free space (as shown in Figure 2d, leading...
Figure 2. Investigation of the power transfer on dependence of ENZ condition. a, b) Normalized magnetic field and streamlines of the power in ENZ condition ($\varepsilon_{\text{enz}} = 0.0001$) for two configurations of randomly positioned S-rod and R-rod. c, d) Normalized magnetic field and streamlines of the power in ENZ-broken condition for two randomly distributed configuration of S-rod and R-rod at $\varepsilon_{\text{enz}} = 0.01$. e) The transmission with varying position of R-rod under ENZ and ENZ-broken condition, respectively. f) Normalized magnetic field and streamlines of the power in lossy-ENZ condition.

to the efficiency degradation. The transfer efficiency in different positions is shown in Figure 2e. The x-axis is the position of R-rod along the y-direction. The corresponding transmission have verified the high efficiency for arbitrary position in ENZ region when ENZ condition preserves well. However, when the ENZ condition is broken, both advantages of position-independence and high efficiency are lost. Similarly, the loss of ENZ also breaks the uniform magnetic field, which is shown in Figure 2f.

With an increasing number of devices working simultaneously in a wireless network, it is important to be able to charge the local devices at equal proportion or at any desired proportions by WPT. Here, we show that ENZ provides a solution to distribute the energy at will, regardless of locations of the devices. Again, this salient feature can be attributed to the uniform magnetic field inside the ENZ region, which decouples the receivers from each other. To demonstrate equal energy distribution into multiple receivers, we place four identical receivers at arbitrary positions in the ENZ region, as shown in Figure 3a. The proportion of the energy each receiver acquires is plotted in Figure 3b. The uniform power distribution is manifested as the equal number of flux lines flowing into each receiver. The energy leakage into air is only 1.6%. This passive method for wireless power distribution would be much more energy-saving than the active methods. For distributing different powers to different receivers, one can simply manipulate the resonance frequencies of the receivers such that the receivers on resonance would acquire more energy. Because under the circumstance that ENZ region decouples the receivers from each other, from Equation (1) we calculate the energy different receivers get. The energy is dependent on the permittivity and radius of the receivers instead of the source and the position. By careful design of the relative size of each receiver, we can get the target energy distribution which is also position independent. The detailed steps is in Section S3 (Supporting Information). In the presence of the ENZ region that effectively decouples the receivers from each other, from Equation (1), we can calculate the energy distribution acquired by each receiver. Notably, this distribution is dependent on the permittivity and radius of the receivers rather than the source or their positions. Detailed steps for this process are provided in Section S3 (Supporting Information). To illustrate this, we design a system with three receivers and the targeted power proportions are 50:30:20. The locations of the three different receivers, are shown in Figure 3c and the corresponding realized energy distribution is in Figure 3d. Interestingly, although $R_3$ is the furthest, it acquires about half of the energy. $R_1$ acquires 29% of energy due to the slight deviation from the resonance condition, despite its proximity to the source.

Here, a simple structure consisting of two paralleled metallic circular plates is employed as the ENZ system, as shown in Figure 4a. It has been well established that the propagation of a TE mode at its cutoff frequency in this structure is equivalent to wave propagation inside a material with effective zero permittivity.[28–30] Therefore, any electromagnetic wave propagating in such a structure is decoupled from the environment. This property is key for the wireless power transfer, as it allows for the distribution of energy without the need for physical contact. The separation of the two metallic plates in the z-axis is $H = \lambda_0/2$ corresponding to the cutoff frequency of TE$_1$.
The decrease of efficiency for $\text{ENZ}$ configuration is shown in Figure 4b. It is shown that, in contrast to the ENZ condition, the efficiency drops rapidly with the increase of distance. Figure 4c,d illustrates the distribution of the magnetic field in the center plane ($z=H/2$) for the configurations corresponding to points A and B in Figure 4b, respectively. In Figure 4c, the key signature of wave propagation inside ENZ is preserved, i.e., the magnetic field is uniform in phase and amplitude across the structure. In contrast, in Figure 4d, the nonuniform magnetic field confirms the breakdown of ENZ condition despite the very small deviation of the operating frequency. The efficiency of power transfer can be further enhanced by enclosing the ENZ environment with a PEC (perfect electric conductor) shell, thus eliminating leakage power into the air. However, this approach may not only increase costs but also block external signals. In practical applications, particularly for long-range, or far-field wireless power transfer (WPT), the open environment proposed here may be preferable.

4. Conclusion

In conclusion, we have proposed to use ENZ media for achieving efficient wireless power transfer, offering a flexible, robust, and distance-independent energy distribution. We demonstrate a nearly perfect power transmission when the receiver resonates at the operating frequency inside the ENZ region. The power distribution can be fully controlled by the shape and optical property of receivers, independent of the parameters of the emitter. Furthermore, the power transfer is ENZ protected, regardless of specific geometric and optical parameters, and immune to perturbations. This stands in sharp contrast to other methods reported previously.[8–19] However, these advantages are conferred by the unique properties of the ENZ region, which add additional complexity to the environment.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

S.Z. and C.L. designed research; Q.Y. and S.Z. performed research; Q.Y., Y.W, J.S., C.L., and S.Z. analyzed data; Q.Y., C.L., and S.Z. wrote the paper. All authors discussed the results.
Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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