Extreme Metasurfaces Enable Targeted and Protected Wireless Energy Transfer

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Controlling the electromagnetic properties of materials beyond those achievable with natural substances has become a reality with the advent of metamaterials. The extreme properties that metamaterials provide offer an opportunity to manipulate and tailor electromagnetic waves in an arbitrary manner. Wireless energy transfer demands reliable and stable solutions for charging batteries of electronic devices with high efficiency and no effect on people, animals, plants, etc. Motivated by this challenging problem, a novel approach of using metamaterials with extreme parameters is suggested to enable targeted wireless energy transfer with reduced impact on biological tissues. Epsilon-near-zero (ENZ) and epsilon-and-mu-near-zero (EMNZ) metamaterials are designed and experimentally implemented, providing an energy transmission if and only if both the transmitter and the receiver are equipped with these metamaterials. The nonexistence of these extreme parameter metamaterials in nature protects the system from the presence of other objects with “ordinary” (effective) parameters causing neither noticeable change in operation nor any detrimental effect on foreign objects. The system behind the proposed approach can be realized in virtually any frequency band by appropriate scaling and suitable choice of material. This technology will find applications in targeted wireless energy transfer systems, especially where high power is needed, including electric vehicles.

1. Introduction

Metamaterials are artificially designed materials enabling material properties unachievable or barely found in nature. Many wisely designed metamaterials, consisting of identical or gradually changing cell arrays called artificial atoms or meta-atoms, were put forward, offering a wide range of unusual phenomena.[1–9] In particular, in electromagnetics and optics, metamaterials have enabled negative refractive index,[12,10] super-lenses,[11,12] cloaking,[13,14] nontrivial topological phases,[15–16] to name just a few. Although the use of bulk metamaterials is limited by their losses and complexity of manufacturing, especially in optics, their 2D counterparts—meta-surfaces—appear to be more loss-tolerant and feasible, often preserving the functionality of metamaterials, including control over the light propagation, reflection, and refraction.[17–31]

Since the unusual parameters of metamaterials virtually never occur in nature, this circumstance could be used for control or protection—a property that has not yet been explicitly used. One can think of a system that performs desired functionality in the “metamaterial mode”, but does not work otherwise. For example, in wireless power transfer (WPT), technology that enables charging the battery of portable and mobile devices without any additional plug-ins,[12,13] a challenging problem is yet to be resolved—targeted and safe transfer of strong alternating current field energy without affecting surrounding objects. Indeed, the harmfulness of strong high-frequency electric fields explains the almost exclusive use of magnetic coupling[34] in lieu of electrical capacitive coupling.[35] On the other hand, although the magnetic WPT systems are designed to provide a move-and-charge scenario,[33,36] they are limited to low-power systems due to harmful eddy currents heating metallic elements of, e.g., an electric vehicle.[37] Despite existing efficient low-power WPT solutions,[34,38,39] the technology still demands systems robust to dynamic operating conditions[40] and capable of targeted power transfer from a transmitter to randomly oriented and arranged receivers. If the WPT system worked only in the presence of a metamaterial with extreme parameters, then all surrounding objects would be protected by the absence of materials with such properties in nature, Figure 1a.

It is worth noting that other “active” methods of targeted WPT have been proposed, including time division multiple access,[40] multifrequency,[41] and phase-shifted control.[42] These methods rely on complicated active control circuits with enhanced power consumption. Another active approach of on-site wireless power generation,[43] while working only in the presence of the receiver circuit and consuming low energy in the passive mode, is very limited in its scalability and size. Moreover, several receivers would complicate these systems, making the existing approaches very challenging.

In this paper, we take a first step further and propose a novel approach of targeted WPT involving metasurfaces with extreme
parameters. The energy transmission occurs if and only if both the stacked transmitter and the receiver are equipped with these metasurfaces, making the transmission selective. Otherwise, the field does not penetrate or radiate out of the transmitter, excluding any interactions with external objects. We develop an epsilon-near-zero (ENZ) based multilayered structure illustrated in Figure 1. In this scenario, the energy transmission occurs only between two extreme metamaterials, and the nonexistence of these extreme materials in nature protects the system from the presence of “ordinary” objects. We design and experimentally realize zero-index metasurfaces with this functionality and demonstrate that the field does not penetrate through areas not covered by the upper metasurface slab providing targeted energy transfer. We show that the presence of foreign objects with “ordinary” parameters has no effect on the functionality of the WPT system.

We begin with a rigorous analytical analysis of the electromagnetic wave tunneling effect in two systems with extreme parameters: two-layered ENZ-dielectric heterostructure and three-layered ENZ-dielectric-ENZ heterostructure illustrated in Figures 1b,c, respectively. This analysis will guide our design strategy to realize targeted WPT based on zero-index metamaterials. Both structures are illuminated by a plane wave with transverse magnetic (TM) polarization while the magnetic field is parallel to the structure interfaces. The incident wave angle manifests itself as a narrow perfect transmission resonance in the spectrum around the plasma frequency of 2.45 GHz, Figure 1e. In the tunneling mode, the 3L-structure allows the electromagnetic wave of a proper frequency and angle of incidence to tunnel from the first ENZ layer through the dielectric to the second ENZ layer. This tunneling depends on the effective permittivity of the 3L-structure and only possible in the presence of both ENZ layers. This mode appears at the intersection

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

**Figure 1.** Illustration of the concept of extreme material-enabled targeted and protected wireless energy transfer. a) Concept of wireless energy transfer targeted and protected by metamaterials with extreme parameters: the transmission occurs only between two extreme metamaterials, and the nonexistence of these extreme materials in nature protects the system from the presence of “ordinary” objects. Schematic view of b) transversely homogenous ENZ-dielectric and c) ENZ-dielectric-ENZ structures under TM-polarized plane wave illuminations. Calculated transmittance of the d) ENZ-dielectric structure and e) ENZ-dielectric-ENZ structure. The permittivity of the dielectric is \( \varepsilon_0 \) is the free-space permittivity, and \( \mu_0 \) is the free-space permeability. The plasma frequency is \( f_p = 2.45 \text{ GHz} \). The dashed white line in (e) follows the narrow perfect transmission resonance. The red cross in (e) denotes a BIC state.

We calculate the transmittance through the systems for different incidence angles of the plane wave.

The ENZ-dielectric structure (from now on, 2L-structure) containing one ENZ layer (Figure 1b) under TM-polarized excitation reveals angle-dependent and dispersive transmission except for the plasma frequency, where it vanishes, Figure 1d. The vanishing of transmission at the plasma frequency is explained by diverging TM wave impedance along the z-direction in ENZ. The transmission response, associated with extremely high values of the resonance Q-factor, is unique states that facilitate a sharp resonant response, associated with extremely high values of the resonance Q-factor. Figure 1d. BICs are unique states that facilitate a sharp resonant response, associated with extremely high values of the resonance Q-factor.

Adding the second ENZ layer (from now on, 3L-structure), as shown in Figure 1c, enables the field tunneling mode that manifests itself as a narrow perfect transmission resonance in the spectrum around the plasma frequency of 2.45 GHz, Figure 1e. In the tunneling mode, the 3L-structure allows the electromagnetic wave of a proper frequency and angle of incidence to tunnel from the first ENZ layer through the dielectric to the second ENZ layer. This tunneling depends on the effective permittivity of the 3L-structure and only possible in the presence of both ENZ layers. This mode appears at the intersection
of the Fabry–Perot mode of the dielectric layer and the ENZ resonances in the claddings. In ref. [45], this mode was found to be associated with the so-called Berreman mode mainly studied in metal-dielectric multilayers [48–50] and primarily explained through the effective medium theory [51,52]. This mode in spectrum makes the structure perfectly transparent, providing wave tunneling through the heterostructure for all incident angles. The tunneling mode is also obtained for an incident transverse electric (TE)-polarized wave in a mu-near-zero (MNZ) configuration (Section S1, Supporting Information). However, the application of the tunneling effect to enable a targeted wireless energy transfer has not been studied so far. Thus, we study the most attractive case for tunneling mode existence such as the epsilon-and-mu-near-zero metamaterials (EMNZ) (Section S3, Supporting Information), and investigate it experimentally for targeted energy transfer.

We also observe the accidental BIC state [53] appearing in the spectrum as an unboundedly narrowing transmission and reflection line marked by the red cross in Figure 1c. A true BIC with infinite radiative Q-factor and vanishing resonance width can exist only in ideal lossless infinite structures or for extreme values of parameters [54–57] as in the considering case. In the 3L-structure, this anomaly scattering state appears when the Fabri–Perot mode of the dielectric spacer layer coincides with the ENZ resonances of the ENZ layers; hence the dielectric mode becomes trapped [58]. In what follows, we design and realize the extreme-parameter metasurfaces and demonstrate theoretically and experimentally the tunneling effect for targeted wireless energy transfer. However, the study of the accidental BIC is out of the scope of the current paper.

Now we investigate the tunneling effect in the finite 2L and 3L-structure, Figure 2a,b. The first ENZ layer (from now on, a layer) and dielectric are now square sheets of size \(a_1 = 100 \text{ cm}\). The second square ENZ layer (from now on, a slab) is of \(a_2 = 70 \text{ cm}\). Other parameters are the same as in Figure 1. In Figure 2c, we compare the transmittance of 3L- and 2L-structures versus frequency for the incident wave angle of \(\theta = 30^\circ\). The transmittance of 3L-structure versus frequency for other incident wave angles is discussed in Section S2 (Supporting Information). One can observe the transmittance of 0.4 for 3L-structure and a minor frequency deviation with respect to the infinite case due to the finite size of the structure. We normalized transmittance \(T_{3L}/T_{2L} \approx 8\) at the plasma frequency. The power flow through 3L- and 2L-structures are simulated and shown in Figure 2d. Remarkably, in 3L-structure, the energy of the electromagnetic field indeed propagates majorly through the slab. However, the field does not pass the 2L-structure, as revealed by simulations, Figure 2d. To elucidate the effect of size, Figure 2e shows the transmittance versus frequency normalized to the case of no ENZ slab. The enhancement gradually increases for \(a_2 > 50 \text{ cm}\) and reaches 25 for \(a_2 = 100 \text{ cm}\). Figure 2f shows the power flow integrated over the surface at 4 cm above the ENZ slab and normalized to the case of no slab. The maximum integral power enhancement of 25 is observed, proving that the energy mostly goes through the ENZ slab.

Figure 2. Tunneling in a finite structure. Schematic view of the finite a) ENZ-dielectric (2L-structure) and b) ENZ-dielectric-ENZ structures (3L-structure) under TM-polarized plane wave illuminations. The second ENZ (slab) is smaller than the first one (layer). c) Transmittance of the 2L and 3L-structures numerically obtained for the incident wave angle of 30°. d) Simulated power flow through the structures in panels (a) and (b) at plasma frequency. e) Transmittance of the 3L-structure normalized to the one of 2L-structure versus frequency and ENZ slab side size \(a_2\). f) Integrated power flow over the surface in x-y plane 4 cm above the ENZ slab and normalized to the same without a slab.
To demonstrate that the tunneling effect is targeted we perform the simulations of the finite 3L-structure with different locations of the ENZ slab. An arbitrary displacement of the ENZ slab over the dielectric surface reveals that the tunneling effect follows the slab, Figure 3a. For example, Figure 3b,c illustrates the intense field obtained inside the ENZ slab for two very different positions of the slab. The strong enhancement of the electric field compared to the incident field (≈ 400 times) over the area of the ENZ slab proves that all tunneled energy concentrates within the ENZ slab. The tunneling effect, being enabled by the slab with extreme parameters, finds its way through this layer whenever it is located. Thus, by changing the position of the ENZ slab, one can easily guide the energy tunneling route making a targeted WPT system. Moreover, two ENZ slabs enable the energy tunnel through both slabs, Figure 3d. In order to demonstrate that for this effect to occur, the slab must be made of ENZ material, a substance that virtually never meets in nature, we substituted the ENZ slab by a high permittivity dielectric of the same size, Figure 3e,f. As one can see from the simulated electric field distribution, the dielectric slab demonstrates no tunneling effect.

We implement the 2L and 3L-structures introduced above using aluminum metasurfaces with the unit cell design illustrated in Figure 4a. The metasurface unit cell has a square shape to take an advantage of both polarizations. We extract the effective permittivity and permeability of the metasurface using the well-known retrieval method[59,60] (see more details in Supplementary Materials, Section S3). The results of the extraction are presented in Figure S3d,e (Supporting Information). The designed metasurface possesses an ENZ response in the frequency range of 1–3 GHz, with the plasma frequency at about 1.83 GHz. The metasurface design provides virtually constant permeability of $\mu = 0.07+i0.002$ in this range. Both effective parameters exhibit a Lorentz-type resonance at the frequency of $f = 3.3$ GHz. Thus, the proposed metasurface acts as an EMNZ media over the frequency band of 1–3 GHz. To reduce the loss factor in the dielectric, we use either air (in simulations) or microwave foam (in experiments) with permittivity of $\varepsilon = 1$

To validate the tunneling effect, we calculate the wave transmittance through the 2L- and 3L-structures based on EMNZ metasurfaces (see more details in Section S3, Supporting Information). The top sub-figure of Figure 4b compares the transmittance through the 2L structure and 3L-structure. In contrast to the previous scenario, we do have air instead of the dielectric layer, and the transmission reaches unity at the frequency of $f = 1.83$ GHz for the 2L structure. At this frequency, the effective wave impedance $Z_{EMNZ} = \sqrt{\mu_{EMNZ} / \varepsilon_{EMNZ}} = 1$ is matched with the air. For the 3L structure (or in presence of the second EMNZ), we observe the enhancement of the transmittance as high as $T_{3L}/T_{2L} \approx 4$ at the frequencies of 1.56 GHz and 2.13 GHz, Figure 4b. It means that the tunneling effect occurs at these frequencies when the second EMNZ layer appears. However, the important question is the dependence of the tunneling effect from the separation between the EMNZ layers in 3L-structure. The bottom subfigure of Figure 4b shows the calculated transmittance through the 3L-structure as a function of the gap d. One can see that for all the separations under study the transmittance is near unity, and the electromagnetic energy passes the structure regardless of the gap size between the metasurfaces. However, one needs to point out a slight frequency deviation with maximal transmittance for different

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**Figure 3.** Targeted power transfer in the finite structure. a) Finite 3L-structure with shifted ENZ slab. The ENZ slab size is $a_2 = 40$ cm. Other parameters are the same as in Figure 2. b,c) Calculated E-field distribution of the finite 3L-structure for different locations of the ENZ slab. d) Calculated E-field distribution for the presence of two ENZ slabs. e) Finite structure with ENZ slab replaced by a lossless dielectric with permittivity $\varepsilon = 80$ of the same size as the ENZ slab. f) Calculated E-field distribution of the 3L-structure with dielectric slab showing vanishing transmission.
gap size (more details in Section S3, Supporting Information). This frequency deviation is similar to the frequency splitting phenomenon in classical WPT systems, where the coupling between the transmitter and receiver coils becomes higher than the critical coupling. As a result, the system's transmission coefficient over the frequency splits into two peaks. Therefore, it can be solved at the engineering level with the solutions that have been proposed for the frequency splitting phenomenon. The transmittance of the 2L- and 3L-structures for the TE- and TM-polarized waves as a function of the incident angle and frequency are shown in Figure 4c-f. The comparison of panels (d) and (f) with panels (c) and (e) reveals that the presence of the second EMNZ layer leads to two narrow bandwidth enhancements in the transmission (indicated by dashed white lines in panels (d) and (f)). The formation of these tunneling modes is attributed to the strong coupling effect and analyzed by coupled modes approach (see Methods). Remarkably, the appearance of these modes makes the structure transparent for almost all incident angles except the angle associated with BICs.

The 2L- and 3L-structure prototypes were fabricated and experimentally investigated. The structures under study are excited by a horn antenna to mimic a plane wave of different polarization. We measured the transmittance through the 2L- and 3L-structures and the near magnetic field distributions over the EMNZ slab (see Methods and Supporting Information for more details). We directly visualized the power flow using a receiver loaded with a light-emitting diode (LED). We first demonstrate the targeted WPT in the EMNZ-air-EMNZ structure using a wideband loop receiver above the EMNZ metasurface slab (see the details in Section S4, Supporting Information). The current induced in the loop antenna was rectified and delivered to the LED at the frequency of 1.56 GHz only for the 3L-structure. The placement of the foreign objects next to the EMNZ slab of the 3L-structure excited at the frequency of 1.56 GHz did not change the properties of the system and the LED was ON. When receiving loop with the LED is placed in another place without the slab, the LED is OFF, indicating no energy transfer. This experiment confirms that the energy tunnels via the 3L-structure and the foreign objects do not influence on it. To further elucidate on the transmission enhancement, we measure transmittances of the 2L and 3L structures and compare them in Figure 5b (we refer to Figure S6c in Section S3 of Supplementary Materials for simulated results). We observe the enhancement in the transmittance as high as $T_{3L}/T_{2L} \approx 3$ and $T_{3L}/T_{2L} \approx 10$ at the frequencies of 1.56 GHz and 1.96 GHz, respectively. Although the results are in excellent agreement with the numerical results for both infinite (Figure 4) and finite structures (Figure S6), we also observe the appearance of several minor modes in the frequency range of 1.6–1.9 GHz, caused by the meta-atom’s eigenmodes and their strong interlayer interactions.

Finally, we measure the near magnetic field distribution in the $x$–$y$ plane 10 cm over the 3L-structure for different locations of the EMNZ slab (see Section S4, Supporting Information). As illustrated in Figure 5c–e, the magnetic field is strongly
concentrated in the area of the EMNZ slab. The measured field distribution of the single EMNZ metasurface presented in Figure 5f reveals a vanishing magnetic field everywhere in the absence of the EMNZ slab.

We have demonstrated a novel approach of targeted WPT involving metasurfaces with extreme parameters. The approach uses two extreme-parameter metamaterials and allows energy transmission if and only if two metamaterials are stacked together. We have experimentally realized this approach with EMNZ-air-EMNZ metastructures and demonstrated that the field does not penetrate through areas not covered by the smaller extreme metasurfaces. This suggests a targeted energy transfer enabled and protected by the extreme parameter metamaterials—wherever we place the metamaterial slab, it enables energy tunneling and concentration. Currently, the proposed design of the WPT system utilizes a plane wave excitation to demonstrate the tunneling effect. However, in practice, a point-like excitation of the extreme parameter metamaterials must be developed taking into account the optimization of the system’s transmittance for a desired frequency band, size of the transmitter/receiver, and distance between them. We believe that this technology can be applied in targeted wireless energy transfer systems, especially where high power is needed, including charging electric vehicles.[64] This implies that the parking spot can be covered with one layer of the extreme metasurface and the second layer is placed directly on the vehicle.

2. Methods

2.1. Transfer Matrix Formalism

For given parameters of extreme materials and dielectric \( \varepsilon_{\text{ENZ}}, \mu_{\text{MNZ}}, \) and \( \varepsilon \), we define the transfer (T-) matrix for the complete layered structure,\(^{[65]}\)

\[
\hat{T}_d = \hat{T}_m \otimes \hat{T}_s \otimes \hat{T}_m. \tag{1}
\]

Here \( \hat{T}_m \) and \( \hat{T}_s \) are T-matrices for the extreme materials and dielectric layer, respectively

\[
\hat{T}_i = \hat{D}_i \otimes \hat{P}_i \otimes \hat{D}_i
\]

where matrices \( \hat{D}_i \) describe propagation across the boundary between layers \( i \) and \( j \), and the matrix \( \hat{P}_i \) accounts for propagation through the particular layer \( i \). For the TE-polarization (s) and TM-polarization (p), these matrices can be expressed in the form

\[
\hat{D}_i^{(s)} = \frac{1}{2} \begin{bmatrix}
1 + \eta_{i,s} & 1 - \eta_{i,s} \\
1 - \eta_{i,s} & 1 + \eta_{i,s}
\end{bmatrix}
\]

\[
\hat{P}_i = \begin{bmatrix}
\exp(-ik'_i d') & 0 \\
0 & \exp(i k'_i d')
\end{bmatrix}
\]

where \( \eta_i = k''_i / k'_i \), \( \varepsilon_i = \varepsilon_i / k'_i k''_i \), \( k'_i \) is the out-plane wave number in the particular layer \( i \), \( d' \) is the thickness of the

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Figure 5. Experimental demonstration of the targeted power transfer. a) LED demonstration of the targeted power transfer in the EMNZ-air-EMNZ metastructure. The lower EMNZ metasurface is 81 × 81 cm² (18 × 18 cells) in all experiments. The distance between two EMNZ metasurfaces is \( d = 80 \) mm. The LED demonstration experiment is conducted for the metasurface slab of 22.5 × 22.5 cm² (5 × 5 cells) size. b) Measured transmittance of the 2L- and 3L-structures (two 18 × 18 cells metasurfaces). c–e) Measured magnetic field of the 3L-structure in the \( x-y \) plane at 10 cm over the EMNZ slab of 40.5 × 40.5 cm² (9 × 9 cells) for different positions: c) at the center, d) at the edge, and e) at the corner. f) Measured magnetic field of the EMNZ-air structure in the \( x-y \) plane at 10 cm over. Fields are normalized to the maximum in panel (c) in all cases.
layer \(i\). With the T-matrix of the whole structure \(\hat{T}_i = \begin{bmatrix} T_{i1} & T_{i2} \\ T_{21} & T_{22} \end{bmatrix}\), we can calculate the reflectance \(R\) and transmittance \(T\) spectra for the multilayer structure, \(R = |T_{21}/T_{11}|^2, T = |1/T_{11}|^2\).

2.2. Mode Coupling Description

The appearance of two resonant transmissions in the spectrum is explained by the strong coupling of modes of the two EMNZ layers. The modes are characterized by the corresponding complex eigenfrequencies \(\omega_{1,2} = -i\omega_{1,2}/2Q_{1,2}\) where \(\omega_{1,2}\) is the real frequency of the modes and \(Q_{1,2} = \omega_{1,2}/2\Delta\omega_{1,2}\) is their quality factor defined by the spectral bandwidth \(\Delta\omega_{1,2}\). The effective interaction Hamiltonian \(\hat{H}_{\text{int}}\) of the two modes considered as two oscillators with the coupling strength \(g\) yields

\[
\hat{H} = \begin{pmatrix}
\omega_1 - i\omega_1/2Q_1 & g \\
g & \omega_2 - i\omega_2/2Q_2
\end{pmatrix}
\]

The coupling strength depends on the mode overlap, and for the close spacing \(d\) it is real-valued. The diagonalization of this Hamiltonian yields the new eigenfrequencies of dressed modes,

\[
\omega_{1,2} = (\omega_1 + \omega_2)/2 - i(\Delta\omega_1 + \Delta\omega_2)/2 \pm \sqrt{(\Delta\omega_1 + \Delta\omega_2)^2/4 + \delta^2},
\]

where \(\delta = \omega_1 - \omega_2\) is the detuning. In our case of identical metasurfaces, the mode splitting (Rabi splitting) is \(\Omega = 2g\). The transmittance spectrum (solid blue curve) in Figure 4b reveals the Rabi splitting \(\Omega = 0.58\) GHz, corresponding to the coupling strength \(g = 0.29\) GHz. Since \(g > (\Delta\omega_1 + \Delta\omega_2)/2\), the modes are strongly coupled.

2.3. Numerical Simulations

The simulations in Figures 1–4, and Figure S1–S6 (Supporting Information) were performed using CST Microwave Studio 2020. All simulations used extremely fine mesh-cell settings, determined by adaptive meshing results. All the parameters used in the CST simulations were close to experimentally realized systems. The simulations were performed using a frequency-domain solver.

The S-parameter-based method is used to retrieve the effective material parameters of the single-layer Metasurface (Section S3, Supporting Information). Considering the normal incident wave, we first calculated effective refractive index \(n\) and wave impedance \(Z\) of the metasurface from the S-parameters. Then permittivity \(\varepsilon\) and permeability \(\mu\) were calculated from calculated effective refractive index \(n\) and wave impedance \(Z\).

2.4. Metamaterial Fabrication

Several EMNZ metasurface prototypes with the sizes of 81 \(\times\) 81 cm\(^2\) (18 \(\times\) 18 cells), 40.5 \(\times\) 40.5 cm\(^2\) (9 \(\times\) 9 cells), and 22.5 \(\times\) 22.5 cm\(^2\) (5 \(\times\) 5 cells) were fabricated using laser cutting method from aluminum characterized by the conductivity of 3.56 \(\times\) 10\(^7\) S m\(^{-1}\). The slots width is 1 \(\pm\) 0.05 mm.

3. Experimental Section

The transmittance of the wave irradiated by a horn antenna through the 2L- and 3L-structures was measured indirectly through near-field measurements.\(^{[6]}\) The photo of the experimental setup and detailed discussion can be found in Section S4 (Supporting Information). The near-field mapping of the magnetic field was done to measure the magnetic near-field distribution for EMNZ-air and EMNZ-air-EMNZ structures with a small second EMNZ. The experiments with a LED as the light source are described in Section S4 (Supporting Information).

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.

Data Availability Statement

Research data are not shared.

Keywords

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