A wearable metasurface for high efficiency, free-positioning omnidirectional wireless power transfer

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Abstract
We introduce a design principle of metasurfaces that can form any desired distribution of magnetic field for high-efficiency wireless power transfer centered at 200 kHz, which can be used to efficiently charge implanted medical devices. This metasurface can improve the power transfer efficiency for both single-user and multi-user cases by over tenfold compared to those without the metasurface. Our design enables a robust field distribution to the positions of the transmitting and receiving coils, as well as the geometric distortions of the metasurface itself, demonstrating its feasibility as a wearable device. With our design, the field distribution and subsequent power division among the multiple users can be readily controlled from equal distribution to any selective user(s). When incorporating a three-dimensional unit cell of the metasurface, we theoretically demonstrate an omnidirectional control of the field orientation to achieve a high-efficiency wireless power transfer for multiple users.

1. Introduction

An oscillating electromagnetic field can carry a large amount of energy. However, this power cannot be captured unless with a coupled resonator due to the non-radiating nature of the near field. Nicola Tesla first discovered the phenomenon of through-space power transfer in 1910s [1], yet the technology was not widely used in the 20th century because of its undesirable high voltage and limited applications. In 2007, a safer wireless power transfer (WPT) approach has been developed using magnetic induction of strongly coupled resonators [2]. Since then, WPT has increased applications in charging mobile devices such as phones [3–5], computers [4, 6], various sensors [7–9], and microimplants [10]. However, because of the fast divergence of the magnetic field in space, across-distance inductive WPT suffers from low efficiency and high field-leakage [11]. Even with strongly coupled resonators, the transmission efficiency cannot surpass 50% across two meters [2]. Moreover, the diverging magnetic field into the open space can potentially damage electronic devices, heat up metal objects, and become hazardous to people with implanted medical devices [11].

To improve the transmission efficiency and better confine the magnetic field, one common approach is to increase the number of transmitting coils (Tx coils) [3–6, 12–14]. Control algorithms, such as Magnetic multiple-input multiple-output (MIMO) [3], MultiSpot [4], hybrid directional and rotational WPT [13], and adaptive phased-array for WPT [14], will optimize the transmission efficiency by controlling the input power and driving phase of each Tx coil. To achieve these algorithms, each Tx coil requires an independent power source that has controllable output voltages and phase-shift. The high demands of power electronic
circuits for the Tx coils limit their numbers, typically below nine \([3, 4, 6, 12–14]\). As a result, even with the state-of-the-art control algorithms \([13]\), the efficiency is marginally improved by less than 10% compared to the original single Tx coil system. Another approach is to enhance the transmission with passive resonant coils \([15–20]\). Particularly, with a nonlinear resonant coil that has a variable resonance frequency depending on the coupling condition, the operational bandwidth is significantly increased, making the WPT system more robust \([19, 20]\). Despite the increase of efficiency, multiple resonators (i.e. repeaters) need to be placed in parallel between the Tx and receiving (Rx) coils, which greatly undermine the advantage and convenience of WPT. Moreover, the wide-spreading resonators increase the field leakage in space \([21]\), elevating the risks of damages caused by the high power magnetic field.

Metamaterials, as rising composite materials that aim to manipulate electromagnetic fields and waves, open a new path to this century-old puzzle. Metamaterials use an array of phase-tunable resonators to reshape the wavefront of radiative waves, and theoretically, can form any desired beam-form \([22–25]\). Metasurfaces, the 2D counterpart of metamaterials, demonstrate strong capabilities in redirecting and focusing radiative waves with a highly subwavelength thickness \([26–31]\). Analogous to the radiative metasurfaces, non-radiative magnetic metasurfaces have been proposed to enhance the magnetic field intensity for magnetic resonance imaging \([32–34]\) and WPT \([35–37]\). The magnetic metasurfaces consist of numerical passive inductive resonators that are coupled to the magnetic field and generate alternating currents. The currents can create an additional magnetic field and enhance the original field. However, the non-radiative magnetic field has a near-uniform phase distribution in space, and therefore, cannot be reshaped by phase-tuning resonators with the theory of radiative metasurfaces. Although references \([35–37]\) have demonstrated some degrees of controllability of the enhancement area through the on- and off-resonance states of the resonators, as there are only two states, it cannot accurately shape the field distribution in the desired manner, which limits the efficiency of WPT using such metasurfaces. With the dual-state design, even with 576 resonators, the efficiency enhancement cannot exceed 6.46-fold \([35]\). Moreover, this design cannot work for more complicated purposes other than enhancing the WPT efficiency.

In this paper, we propose a new theory of on-demand manipulation of the magnetic field with a tunable metasurface for WPT. The metasurface consists of a square array of strongly coupled resonators with continuously or quasi-continuously tunable compensation capacitors. By controlling the impedance of each resonator, the metasurface can re-distribute the magnetic field in any desired manner. We demonstrate its applications in reducing field leakage, improving WPT efficiency, and compensating variance in the coupling coefficients of multiple receivers at the frequency of 200 kHz, compatible with the most commonly used WPT standard—Qi \([38]\). Furthermore, we show that the metasurface is highly robust to physical distortions; thus, it can be made as a wearable device to continuously feed power, for example, to implanted medical devices. Using a 3D unit cell design, the metasurface shows controllability of not only the intensity but also the orientation of the non-radiative magnetic field. As the manipulations are made by a passive metasurface, one can achieve several advanced features, such as multi-user charging with controllable power divisions, compensation of non-uniform user couplings or loading conditions, and omnidirectional power transfer, with only a single Tx coil. This approach greatly reduces the cost and improves the capability of the WPT system.

2. Shaping current distributions with a tunable metasurface

As the schematics shown in figure 1, the metasurface is placed between the Tx coil and the Rx coil to enhance the transmission efficiency. The metasurface consists of resonators patterned in a square array. Each resonator is composed of a solenoid structure with finite turns and a tunable compensation capacitor. The magnetic field of a resonator carries an energy of \(E_{\text{res}} = \frac{1}{2} LI^2\), where \(L\) is the self-inductance of the resonator (assuming to be the same for all resonators). We choose the square root of the energy as a measure of the current of the resonator \(a = \sqrt{E_{\text{res}}}\).

Compared to the operational wavelength, which is around 1500 m at 200 kHz, the metasurface (around 10 cm in width) is highly sub-wavelength. Therefore, the radiation of the resonators is negligible. The resonators, with a periodicity much smaller than the wavelength, form a strongly coupled system through magnetic induction and can be described using the coupled-mode theory (CMT) \([2, 19]\)

\[
\frac{d}{dt} |A⟩ = (i\omega_0 - \Gamma - K) |A⟩ + |f⟩ ,
\]  

(1)
Figure 1. Schematics of the metasurface for WPT. The bottom illustrates the transmitting coil with a power source. The metasurface, formed by a square array (21-by-21) of resonators, is placed on top of the transmitting coil. Each resonator is composed of a tunable capacitor and a coil with 10 turns, 2 cm-radius, and periodicity of 2.2 cm in both the x and y directions. The partial overlap between the resonators is designed to increase their coupling (not shown in the schematics). The receiving coil is placed on top of the metasurface with a load resistance of \(5 \Omega\).

where \(|A\rangle = \begin{pmatrix} a_1 \\ \vdots \\ a_m \end{pmatrix}\) describes the current distribution on the metasurface. \(a_i\) is the square root of the energy associated with the \(i\)th resonator. The resonators are labeled row-by-row. \(\omega_0\) is the operational frequency of the WPT system, given by the oscillation frequency of Tx coil’s current. \(\Gamma\) is the decay rate matrix of the resonators, which describes how the resonators’ current in response to the driving voltage,

\[
\Gamma = \frac{1}{2i} \begin{pmatrix} Z_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & Z_m \end{pmatrix},
\]

where \(Z_n\) is the complex impedance of the \(n\)th resonator, \(Z_n = R_n + i\omega_0 L_n + \frac{1}{\omega_0 C_n}\).

\(R_n\) and \(C_n\) are the resistance and the tunable capacitance of the resonator. \(K = -i\omega_0^2 \begin{pmatrix} M_{11} & \cdots & M_{1m} \\ \vdots & \ddots & \vdots \\ M_{m1} & \cdots & M_{mm} \end{pmatrix}\) is the coupling matrix, where \(M_{in}\) is the mutual inductance between the \(i\)th and the \(n\)th resonators, given by Neumann’s formula

\[
M_{in} = \frac{\mu_0}{4\pi} \oint_{\partial \Omega_i} \oint_{\partial \Omega_n} \frac{1}{r_{in}} dl_i dl_n \quad i \neq n,[39].
\]

\(|f\rangle\) is the driving force from the magnetic field of the Tx coil, \(|f\rangle = \begin{pmatrix} F_1 \\ \vdots \\ F_m \end{pmatrix}\), where \(F_n = -i\omega_0^2 M_{nTx} a_{Tx}\). \(M_{nTx}\) is the mutual inductance between the Tx coil and the \(n\)th resonator, \(a_{Tx}\) describes the current of the Tx coil.

In the frequency domain, equation (1) can be simplified as

\[
(\Gamma + K) |A\rangle = |f\rangle.
\]

To reshape the magnetic field, we design the magnetic energy associated with all resonators, and thus, the current distribution on the metasurface. We set the targeted current distribution as \(|A_t\rangle = \begin{pmatrix} a'_1 \\ \vdots \\ a'_m \end{pmatrix}\). By solving equation (2), we get the required impedance of the resonators

\[
Z_n = \frac{2L F_n}{a'_n} + i\omega_0 \sum_{k=1}^{m} M_{nk} a'_k a'_n.
\]

For strongly coupled resonators, the second term in equation (3) dominates over the first term. Therefore, the impedance of the metasurface only needs to meet the following relationship

\[
\text{Im}(Z_n) = \omega_0 L - \frac{1}{\omega_0 C_n} = \frac{\omega_0 \sum_{k=1}^{m} M_{nk} a'_k}{a'_n}.
\]

We calculate the coupling between all resonators of the metasurface and the Tx coil using a semi-analytical approach (supplementary note I (https://stacks.iop.org/NJP/23/125003/mmedia)). We assume all resonators and the Tx coil have 10 turns and have a resistivity of 10 Ω/1000 ft (close to the resistivity of No. 20 American wire gauge (AWG 20) Litz wire under 200 kHz, with a diameter around...
3. Magnetic power density reshaped by the metasurface

We calculate the magnetic field distribution by considering the contribution of all the resonators and the Tx coil with the theoretical magnetic field distribution of a round current loop [40]. The magnetic power density is given by

\[ n_B = \frac{1}{2\mu_0} |B|^2. \]

We assume that the region-of-interest has a diameter of 5 periods, is offset by 3 periods in both the x and y directions and is located at 10 cm above the metasurface. Only 7.6% of the magnetic power generated by the Tx coil falls in the region-of-interest without the metasurface (figure 3(a)). In the approaches using repeater coils, as the repeater coils widely spread in space, the field leakage is usually larger than the single Tx coil case. In contrast, by shaping a Gaussian field distribution with the FWHM of 5 periods with the
metasurface, 57.1% of the magnetic power falls into the region-of-interest (figure 3(b)). Our results demonstrate that the metasurface can redirect the magnetic field and significantly enhance the transmitted power in the targeted region.

4. The single receiver case

Once a Rx coil is placed in the region-of-interest, it can capture power from the magnetic field. We use a Rx coil with a radius of 5 cm, 10 turns, and a resistivity of $32 \Omega/1000$ fts (close to the resistivity of No. 25 AWG Litz wire under 200 kHz with a diameter of around 0.455 mm), with a similar size of the embodied Rx coil in reference [41]. We choose a larger AWG number (thinner wires) because the resistance of the receiver does not significantly influence the transmission efficiency; in addition, a higher AWG number can reduce the weight and thickness of the charging device.

We consider the coupling between all the resonators, the Tx coil, and the Rx coil, and calculate the current using equation (2) as $|A| = (\Gamma + K)^{-1} |f|$. For the low-frequency WPT system with a sub-MHz operational frequency, the radiative loss is negligible, and the resistive loss dominates. The power consumed by the resistance of the Tx coil, the Rx coil, and the resonators is the lost power of the system, whereas that consumed by the load resistance is the useable power. Therefore, the efficiency can be expressed as

$$
\eta = \frac{I_{R_x}^2 R_L}{I_{R_x}^2 (R_L + R_{R_x}) + \sum_{i=1}^{M} I_{R_i}^2 R_i + I_{T_x}^2 R_{T_x}},
$$

(6)

where $R_L$ is the load resistance of the Rx coil, $I_{R_x}$ and $R_{R_x}$ are the current and resistance of the Rx coil; $I_{R_i}$ and $R_i$ are the current and resistance of the $i$th resonator; $I_{T_x}$ and $R_{T_x}$ are the current and resistance of the Tx coil. Figure 4(a) shows the calculated efficiency as a function of the distance between the Rx coil and the metasurface. We assume the Rx coil is under perfect compensation (imaginary part of its impedance equals zero). An optimal efficiency does not occur immediately after the metasurface but at a certain distance, which we refer to as an optimal point. It is expected that as the Rx coil moves further away, the magnetic field decays, and thus the efficiency decays. Such decay is unavoidable from a non-radiative field. On the other hand, as the Rx coil moves closer towards the metasurface beyond the optimal point, the strong non-uniform coupling from the Rx coil disrupts the current distribution on the metasurface, forming a sub-optimal field-shaping at the region-of-interest (figures 4(b) and (c)). We use cross-correlation between the targeted current distribution and the resulting current distribution as a measure of the field-shaping quality. The correlation is defined as

$$
corr(A_r, A_t) = \frac{|\langle A_r | A_t \rangle|}{\sqrt{\langle A_r | A_r \rangle \langle A_t | A_t \rangle}},
$$

(7)

where $A_r$ and $A_t$ represent the resulting and targeted current distribution on the metasurface. As shown in figure 4(a), the cross-correlation drops to the left of the optimal point, which results in a decrease in the efficiency. For each metasurface design and targeted current distribution, there exists a unique optimal point of the Rx coil’s relative position to the metasurface. We define the Rx coil-metasurface distance for...
optimal efficiency as the working distance of the metasurface. The working distance is at about 7.5 cm for a Gaussian distribution with the FWHM of 5 periods; the working distance is tunable with the FWHM.

We calculate the enhanced efficiency with different FWHM of the targeted Gaussian distributions. As shown in figure 5(a), a larger FWHM leads to a shorter working distance and a slower decay rate to the right of the optimal point. Moreover, as shown in figure 5(b), with a Rx coil-metasurface distance of 10 cm, the larger FWHM also leads to a slightly lower enhancement in efficiency but a much broader operational bandwidth. The 3 dB bandwidth is 3.69 kHz for the distribution with a FWHM of 5 periods and 5.04 kHz for the one with a FWHM of 10 periods. One should choose the FWHM of the targeted current distribution according to the designed working distance and the operational bandwidth.

5. The multi-receiver case

In most WPT applications, multiple devices need to be charged at the same time. To boost the transmission with multiple receivers, we can use the metasurface to shape multiple targeted distributions to the locations of each receiver. Most interestingly, by controlling the intensity of the fields, we can control the ratio of the power delivered to each device and compensate for an unbalanced coupling condition. In the following, we discuss two scenarios: (1) uniformly coupled Rx coils and (2) non-uniformly coupled Rx coils, as shown in figures 6(a) and (b), respectively. In both cases, the three receivers are in parallel with the metasurface. The uniformly coupled Rx coils are all placed at a height of 10 cm above the metasurface, and the non-uniformly coupled Rx coils are placed at 7 cm, 12 cm, and 17 cm above the metasurface, respectively. The heights of all Rx coils are above the optimal distance; therefore, no significant distortion to the current distribution will be induced by the Rx coils.

For uniformly coupled devices, the WPT efficiency to each device can be evenly increased by 6.74-fold using three targeted Gaussian distributions with the same intensities (figure 6(c)). All receivers have the same Rx coil with a radius of 5 cm and a load resistance of 5 Ω. We can control the ratio of power feeding into each device using the intensity ratio of the Gaussian distribution. As the receiving power is proportional to the magnetic flux captured by the Rx coil, the power ratio is approximately the square of the intensity ratio. For example, a targeted intensity ratio of 0:0.4:1 corresponds to a targeted power ratio of 0:0.4²:1². While preserving the overall efficiency, the power of each device can be tuned from 2.08% to 50.64% of the total input power. Table 1 shows the numerical results for this scenario.
Figure 5. Influence of the FWHM of the targeted Gaussian distribution on the working distance and the operational bandwidth. (a) The WPT efficiency as a function of Rx coil-metasurface distance. The Rx coil is placed at the same relative position with respect to the Tx coil with and without the metasurface. (b) The WPT efficiency as a function of the operational frequency with a fixed Rx coil-metasurface distance of 10 cm. All targeted distributions are centered.

Figure 6. Targeted current distribution for the multi-user case with different coupling conditions. (a) The uniform coupling case. All the three Rx coils are placed in parallel with the metasurface, and with the same distance $h_1$, $h_2$, and $h_3 = 10$ cm. The $x$–$y$ coordinate of the Rx coils are $[-3$ periods, 3 periods], [3 periods, 3 periods], and [0, −3 periods] respectively. (b) For equal power distribution among the three receivers, the targeted current includes three Gaussian distributions with equal intensities, FWHM of 5 periods, and $x$–$y$ central locations same as the three Rx coils. (c) The non-uniform coupling case. The three Rx coils are placed at $h_1 = 7$ cm, $h_2 = 12$ cm, and $h_3 = 17$ cm above the metasurface. (d) For equal power distributions, to compensate the non-uniform coupling, the intensities of the three Gaussian distributions are chosen as 0.186:0.366:1.

Table 1. Three receivers with a uniform coupling. By varying the intensity ratio among the three Gaussian distributions, we can control the power among the users. The receiving power of each receiver can various from 2.08% to 50.64% of the input power with negligible changes in the total efficiency. The Rx coils are placed at the same relative positions with respect to the Tx coil with and without the metasurface.

| Case          | Receiver 1 power | Receiver 2 power | Receiver 3 power | Total efficiency |
|---------------|------------------|------------------|------------------|-----------------|
| 0 (no metasurface) | 3.11%            | 3.11%            | 3.78%            | 10%             |
| 1:1:1         | 23.23%           | 23.23%           | 20.93%           | 67.39%          |
| 0:1:1         | 1.94%            | 31.61%           | 31.73%           | 65.28%          |
| 0:1:0.4       | 2.08%            | 50.64%           | 11.47%           | 64.19%          |

On the other hand, when multiple devices are not uniformly coupled to the metasurface (e.g. they are placed at different heights above the metasurface), the unbalanced coupling conditions will result in an
unequal power division. Figure 6(b) illustrates three non-uniformly coupled receivers. Rx 3 has the weakest coupling coefficient, while Rx 1 has the strongest coupling coefficient due to their different heights above the metasurface. Without the metasurface, the load with Rx 3 will receive relatively more power (5.02%), while the one with Rx 1 will barely receive any power (1.36%). To balance the power among the three receivers, we design a stronger current distribution toward the device with a weaker coupling as shown in figure 6(d). After such compensation, the power distribution among receivers becomes more uniform (14.20:14.19:14.23) or (1.0007:1:1.002) by choosing a targeted intensity ratio of 0.186:0.366:1 among the three Gaussian distributions. More evenly distributed power can be achieved by optimizing the ratios between the targeted peak intensities of the Gaussian distributions (Table 2).

### Table 2. Three receivers with non-uniform coupling. The metasurface can compensate the power density at the specific location to achieve a similar receiving power. The no-compensation case uses a targeted intensity ratio of 1:1:1, and the with-compensation case uses a ratio of 0.186:0.366:1. The Rx coils are placed at the same relative positions with respect to the Tx coil with and without the metasurface.

| Case                              | Receiver 1 power | Receiver 2 power | Receiver 3 power |
|-----------------------------------|------------------|------------------|------------------|
| Without metasurface               | 5.02%            | 2.35%            | 1.36%            |
| No compensation                   | 50.40%           | 13.46%           | 4.10%            |
| With compensation                 | 14.20%           | 14.19%           | 14.23%           |

Figure 7. Influence of geometrical distortion of the metasurface. (a) Schematics of the planar metasurface. (b) Current distribution on the metasurface. (c) Magnetic power density at 10 cm above a planar metasurface. (d) The metasurface is bent by 60 degrees. Its impedance distribution is not changed. (e) The current distribution on the metasurface. (f) The magnetic power density distribution at 10 cm above the metasurface (on a curved surface) remains mostly unchanged. The targeted current distribution is the same as figures 3(b) and 4.

6. The capability of the metasurface as a wearable device

When the metasurface is designed as a wearable device to provide power to the implanted medical devices, the geometrical distortion can potentially result in a change of the current distribution and thus changes in the magnetic field. In equation (2), the coupling coefficients between the neighboring resonators are dominant in the coupling matrix. The coupling coefficient quickly attenuates to less than 10% of its value.
between the neighboring resonators within 2 periods. Therefore, the current distribution largely depends on the coupling between the neighboring resonators. As the resonators are relatively small compared to the size of the metasurface, the relative position between the neighboring resonators is insensitive to the overall distortion. As shown in figure 7, even when the metasurface is bent by 60 degrees (figure 7(d)), without any adjustments to the impedance distribution, compared to the current and magnetic power density of a planar metasurface (figures 7(b) and (c)), the changes are negligible (figures 7(e) and (f)).

7. Omni-directional metasurfaces with 3D unit cells

The planar unit cell geometry works well for generating the magnetic field in the $z$ direction, which is suitable for Rx coils placed in parallel with the metasurface. However, in a practical scenario, the axes of a wearable metasurface may be bound by the body shape of a patient, and the Rx coil of an implanted medical device may not be necessarily in parallel with the metasurface but with a tilt angle $\theta$. The receiving power from a tilted Rx coil will drop in the order of $\cos^2(\theta)$. For example, if the receiver is titled by 54.7 degrees with respect to the normal vector of [1, 1, 1] as shown in figure 8(b), its receiving power will drop by $\sim 66.7\%$ with a planar metasurface (figure 8(a)).

To solve this problem, we redesign the planar resonators into 3D resonators, which consist of coils in the $x$, $y$, and $z$ directions with different numbers of turns. As shown in figure 8(b), we use three coils with different directions connected in series with a compensation capacitor to construct a 3D resonator. Among the three coils within the resonator, there is a dominant coil with the most number of turns in one direction and the other two coils in the other directions, which create coupling to its orthogonal resonators. For example, the $x$-resonator (i.e. $x$-res, indicated in red in figure 8(b)) has 10 turns in the $x$ direction, 2 turns in the $y$ direction, and 2 turns in the $z$ direction. The planar metasurface, we use a radius of 2 cm and resistivity of 10 $\Omega$/1000 ft for all the coils within each resonator. Three 3D resonators, with the $x$-, $y$-, and $z$-dominant direction respectively, are placed in a group with a separation of 1 mm to ensure strong
coupling. The groups are placed in a square array with a periodicity of 2.2 cm, forming an omnidirectional metasurface with 1323 3D resonators \((21 \times 21 \times 3)\).

The magnetic field vector is defined as the ratio of current of the \(x\)-, \(y\)-, and \(z\)-resonators [13]. By shaping the magnetic field vector, we can control its direction (figure 8(b), subplots), and therefore optimize the efficiency for a receiver with any random orientations.

In figures 8(b) and (c), the targeted current has a Gaussian distribution with a FWHM of 5 periods, a central location of \([3 \text{ periods}, 3 \text{ periods}]\) in the \(x\)–\(y\) coordinate, and with the magnetic field vector pointing towards the \([1, 1, 1]\) direction. In other words, the targeted intensities of the \(x\)-, \(y\)-, and \(z\)-resonators are the same. Therefore, the receiving power of a Rx coil facing \([1, 1, 1]\) will be optimized. As all the resonators are strongly coupled, current in any distribution of the resonators can be formed. First, we calculate the coupling between all the 1323 3D resonators with Neumann’s formula considering coils in all directions. Then, we solve the impedance distribution with equation (4) and the resulting current distribution with equation (2). The impedance distributions for the \(x\)-, \(y\)-, and \(z\)-resonators are shown in figure 8(c), and the current distributions are shown in figure 8(d), where the metasurface is placed in parallel with the Tx coil at 20 cm above. The ratio among the maximum current is approximately 1:1:2, which differs from the targeted current of 1:1:1. It is because the driving field generated by the parallel-placed Tx coil is mainly in the \(z\) direction; the strong mismatch between the targeted current distribution and the driving field results in the error in the magnetic field vector, caused by the first term in equation (3) that has been ignored in our calculation. Nevertheless, the Gaussian current distributions are well-shaped for the targeted orientations. The error in the magnetic field vector can be mitigated by increasing the \(x\)- and \(y\)-components of the targeted field vector.

8. Conclusion

Here, we theoretically demonstrate a tunable metasurface for controlling the non-radiative magnetic fields. The metasurface can generate a desired magnetic field distribution by tuning the impedance of each resonator. We investigate its capabilities as a wearable device, aiming to wirelessly charge implanted medical devices operating at 200 kHz with an enhanced efficiency. We design the impedance distribution of the resonators that can achieve any desired current distribution. It is worth noting that for strongly coupled resonators, the impedance distribution is independent of the excitation field from the Tx coil. Therefore, we can design the impedance distribution using the periodicity and size of the resonators composing the metasurface. This metasurface enables WPT with improved efficiency, controllable power division among multiple users, and omnidirectional power transfer. Further, as the coupling of the metasurface is mainly formed between the neighboring resonators of the metasurface, the current distribution is robust to geometric distortions of the metasurface, allowing the metasurface to be used as a wearable device.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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