Mitigation of $B_1^+$ inhomogeneity for ultra-high-field magnetic resonance imaging: hybrid mode shaping with auxiliary EM potential

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The notion of mode shaping based on evanescent coupling has been successfully applied in various fields of optics, such as in the dispersion engineering of optical waveguides. Here, we show that the same concept provides an opportunity for the seemingly different field of ultra-high-field MRI, addressing transmit RF magnetic field ($B_1^+$) inhomogeneity. In this work, treating the human phantom as a resonator, we employ an evanescently coupled high-index cladding layer to study the effects of the auxiliary potential on shaping the $B_1^+$ field distribution inside the phantom. Controlling the strength and coupling of the auxiliary potential ultimately determining the hybridized mode, we successfully demonstrate the global 2D homogenization of axial $B_1^+$ for a simplified cylindrical phantom and for a more realistic phantom of spheroidal geometry. The mode-shaping potentials with a magnetic permeability or material loss are also tested to offer additional degrees of freedom in the selection of materials as well as in the manipulation of the $B_1^+$ distribution, opening up the possibility of $B_1^+$ homogenization for 3D MRI scanning.

Modal shaping with evanescent coupling has been employed as a proven technique in various applications of optics\textsuperscript{1–4}. For example, double-clad W-type fibers use a higher-index outer cladding layer in combination with a lower-index inner cladding layer to tailor the modal confinement and dispersion properties\textsuperscript{5–7}, which is not achievable from simple core-clad structures. A problem that is similar in nature also exists in different applications and carrier frequencies of magnetic resonance imaging (MRI) under the terminology of RF shimming or $B_1^+$ inhomogeneity mitigation. In the MRI system, the RF electromagnetic field $B_1^+$ is generated by the RF coil, tuned around the Larmor frequency $\omega_L$, which is set by and scales with the strength of the DC bias magnetic field ($B_0$). While the most commonly used MRI systems use a $B_0$ of 3 T (Tesla), the latest MRI devices employ a higher magnetic field, such as 7 T, to enhance the signal-to-noise ratio (SNR), spatial and temporal resolutions, and contrast\textsuperscript{8–11}.

Nonetheless, with the increase in bias $B_0$, the corresponding Larmor wavelength $\lambda_L$ for the $B_1^+$ RF field also decreases, causing $B_1^+$ inhomogeneity problems in MRI. In ultra-high-field (UHF) MRI over $B_0 = 7$ T, with the high permittivity of body tissue ($\varepsilon \sim 78$ at $\omega_L = 300$ MHz), the Larmor wavelength of the $B_1^+$ field in the body ($\lambda_L \sim 11$ cm) becomes comparable to or smaller than the size of the human body. This high permittivity body surrounded by air of much lower permittivity $\varepsilon = 1$ then constitutes an electromagnetic resonator operating at the Larmor RF frequency under the excitation of the MRI RF field $B_1^+$. This body resonator then inherently presents the typical field pattern of a few-mode resonator (e.g., bright in the central region, dark in the periphery)\textsuperscript{12,13}, and inhomogeneity in the $B_1^+$ field in MRI arises, which is detrimental to homogeneous retrieval of the intensity, SNR, and contrast in MRI applications\textsuperscript{14–17}.

Common approaches for mitigating or shimming this $B_1^+$ inhomogeneity are to use the capacity to alter the $B_1^+$ distribution with high-permittivity materials (HPM). Dielectric pads filled with water ($\varepsilon \sim 78$ at 300 MHz) placed in contact with the head have been used to improve the sensitivity of the signal in the peripheral region of the ROI (region of interest), especially in proximity to the high permittivity pads\textsuperscript{18}. Pads of mixtures of metal titanate and water have been employed to increase the permittivity of the pads so that they can be used in similar strategies\textsuperscript{19–24}. Structures with metallic inclusions, such as metasurfaces and hybridized meta atoms (HMAs),

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have also been reported to manipulate field profiles at subwavelength scales25,26. However, while successful in controlling the field distribution, most of the past efforts utilizing the local enhancement of $B_1^+$ in the vicinity of the pad structures, especially those in contact with the body, often resulted in deterioration of the global $B_1^+$ homogeneity over the ROI.

In this paper, we apply the notion of optical mode shaping to UHF MRI systems and successfully achieve global 2D homogenization of the axial $B_1^+$ field. We treat the MRI system, composed of the body and an RF $B_1^+$ coil, as a waveguide operating at the Larmor wavelength and then employ a high permittivity cladding layer (auxiliary electromagnetic potential well) to tailor the mode shape inside the body through controlled evanescent mode coupling. For this, we control three key parameters of the RF $B_1^+$ waveguide: depth of the pad potential ($d_p$), width of the pad potential ($w_p$), and width of the potential barrier (air gap) between the body potential and the pad potential. From the results of a numerical analysis employing the simplified phantom of the brain, we then derive an optimal layout of the geometry and material parameters of the pad, which can be applied to the MRI systems in 2D scanning operations. Finally, we also examine the cases of pad potential with magnetic permeability or material loss to reveal additional degrees of freedom in the manipulation of the $B_1^+$ distribution, which can be used as a route for 3D MRI shimming.

Results

Concept of hybrid mode shaping with auxiliary EM potential. Considering the structure of MRI and the corresponding symmetries of the RF $B_1^+$ and DC $B_0$ fields, it is reasonable to approach the present solution as an electromagnetic boundary problem having dominant translational symmetry in the sagittal direction, with finite length. Since the uniformities of the $B_1^+$ field distribution in the radial and sagittal directions have a trade-off relation in a cylindrical phantom at a given Larmor frequency27, we focus here on axial 2D MRI scanning, which is widely used in clinical applications. To start, we first simplify the MRI system to maintain the $z$-translational symmetry by assuming a cylindrical phantom and a cylindrical pad to minimize the mode mixing between the radial ($r$), sagittal ($z$), and azimuthal ($\theta$) directions (Fig. 1a). In this setting, at a fixed sagittal ($z$-axis) height of the $B_1^+$ RF coil, phantom, and pad, the shaping of the mode is then determined by three control parameters: the depth of the auxiliary pad potential $d_p$, the width of the pad potential $w_p$, and the width of the potential barrier (air gap) $w_b$ (Fig. 1b). We further note that in view of evanescent coupling, it is clear that the control of $d_p$ and $w_p$ will govern the amplitude and width of the $B_1^+$ field in the pad, while the control of the potential barrier $w_b$ will determine the evanescent coupling and mode hybridization between the phantom and pad modes, achieving the resultant mode shaping in the target ROI.

To assess the effect of mode hybridization from the proposed evanescent mode coupling, full-wave electromagnetic numerical analyses are carried out by using an FEM-based simulation tool (COMSOL Multiphysics). As the source of $B_1^+$ field RF excitation, we assume an idealized coil consisting of 16 surface current sources (rectangular, 1 cm x 18 cm) equally spaced on a cylinder (radius 15 cm, height 18 cm). The currents on each source are sinusoidally driven with the same magnitude at a Larmor frequency of 300 MHz (corresponding to $B_0 = 7$ T) and are sequentially phase-shifted by $360°/16 \approx 22.5°$. It is noted that this sequential phase shift provides a homogeneous distribution of circularly polarized fields (i.e., $B_1^+$) with a coefficient of variation of less than 6%.
in the phantom loading region. The coil is surrounded by a cylindrical surface of the perfect electric conductor (PEC) with a radius of 17 cm and a height of 18 cm, modeling the shield of the coil for the MRI systems. To start, we also focus on the imaging of the head and employ a simplified head phantom, assuming a lossy dielectric cylinder (height of 18 cm, radius of 7 cm, relative permittivity of 74.2, conductivity of 0.87 S/m) made of an agar–agar gel. For the dielectric pad encircling the phantom, we also assume a high-permittivity material and cylindrical geometry, to emphasize, not in contact but evanescently coupled to the head phantom through the potential barrier of the air gap. These shielded coil, cylindrical pad, and phantom constitute a coaxial structure, as shown in Fig. 1a,b, with air gaps in between.

Figure 1c shows the excited modes without or with the presence of pad potential: the yellow and the blue curve correspond to the $B_1^+$ field amplitude with the phantom only and the pad only, respectively, while the red curve shows that of the two potentials together, forming a hybridized mode exhibiting a flattened mode profile in the ROI of the head ($z=0$). Depending on the relative strength of the phantom and pad potentials with gaps in between, each potential dominates the overall mode profile in the MRI system, perturbed by the other potential. It is also critical to note that for a pad potential of sufficiently high permittivity, higher than that of the phantom, the behavior of the coupled mode is dominated by the pad potential and not greatly perturbed by the geometry or permittivity distribution of the phantom.

**Optimization process.** While some clinical imaging prefer $B_1^+$ profiles brighter in the central region of the ROI, a flattened mode profile is preferred in conventional, 2D MRI scanning. Here, focusing on the 2D homogenization of $B_1^+$ over the transverse plane, in terms of the control parameter set ($d_p$, $w_p$, $w_b$), we look into the following figures of merit (FOMs): (1) $B_1^+$ maximum-to-minimum ratio (MmR) over the axial plane ($r, \theta$) signifying the degree of 2D flattening; (2) the position of the $B_1^+$ node in the radial direction ($r_{node}$) representing the redistribution of the $B_1^+$ fields; and (3) the contour of $B_1^+$ at the plane ($r, z$) showing homogenization over the $z$ direction.

Figure 2 shows the effect of the pad potential-well depth $d_p$ on the mode profile of the phantom. When the pad potential is shallower than that of the phantom ($\varepsilon_p < 80$) (Fig. 2a,b), the effect of the pad on the mode shaping is not significant, with the deeper and wider potential of the phantom dominating the coupled system. On the other hand, with a pad permittivity $\varepsilon_p > 200$ (Fig. 2h,i), the $B_1^+$ field is strongly confined in the pad, inhibiting its coupling to the phantom. At fixed $w_p = 2$ cm and $w_p = 2$ cm, with $\varepsilon_p = 180$, the lowest axial MmR of 1.2 is obtained, far lower than the MmR of 4.3 for the phantom-only case ($\varepsilon_p = 1$).

Figure 3 shows the effect of the pad width $w_p$ at various $\varepsilon_p$. As expected, the depth and width of the potential operate in a complementary manner providing almost the same pattern of modes and MmR values, e.g., for sets

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**Figure 2.** Effects of the pad permittivity $\varepsilon_p$ (pad potential depth) on the mode shaping. Normalized field amplitude in the sagittal plane ($\theta = 0$). Contour lines represent the $B_1^+/B_1^+$ center values of 1 (red), 1/2 (yellow), and 1/4 (blue). The region of interest, i.e., the cylinder phantom, is marked with a black rectangle. The pad is marked by the black-dashed rectangles. The width of the air-gap potential barrier $w_b$ is set at 2 cm. The width of the pad potential well $w_p$ is set at $2 \text{ cm}$. [Diagram of Figure 2 showing different modes for various $\varepsilon_p$ values]
(\(\varepsilon_p, \omega_p\)) = (140, 3 cm), (180, 2 cm), and (300, 1 cm), implying an extra degree of freedom in the selection of pad materials (Fig. 3b). It is also noted that the lowest MmR is achieved when the node positions are farthest from the center, signifying the redistribution of the \(B_1^+\) fields in the radial direction for the shimming.

Figure 4 shows the effects of the air-gap barrier width \(w_b\) on the mode shaping. It is noted that \(w_b = 0\) refers to a pad in contact with the phantom, and \(w_b > 0\) corresponds to the evanescently coupled potential case. By controlling \(w_b\), it is possible to adjust the strength of the evanescent coupling from the high-permittivity pad while retaining the general shape of the pad mode. From this added degree of freedom, we find that a nonzero \(w_b\) consistently provides much better homogeneity than the contact pad (\(w_b = 0\)), which has been demonstrated previously\(^{18,20,21,28,29}\). An MmR value of 1.2 is obtained, far lower than that in the case of the contact pad (MmR > \(\sim \) 2.6). Furthermore, we note that the stability of our solution against a range of \(w_b\) values implies the robustness of our evanescent mode-shaping solution to the shape or displacement of the used phantom. In the optimization process, only three factors (effectively two) need to be considered for homogenization, which is less complex than the pad optimization scheme in other studies\(^{30,31}\).

**Effect of the phantom geometry and other material parameters of the pad.** By replacing the cylindrical phantom with a more realistic one of prolate spheroid geometry (semiaxis of 7 cm along the x-direction, 7 cm along the y-direction, and 9 cm along the z-direction), we continue the optimization of the pad geometry for 2D scanning MRI. It is found that the \(B_1^+\) mode profile is not critically sensitive to the geometry of the tested phantoms unless the size of a phantom changes dramatically. Especially when the pad mode dominates the overall system with a high pad-permittivity value, the geometry of the phantom is perturbative only to the overall system behavior. Considering that the homogeneity of the \(B_1^+\) field over a sliced plane affects the performance of the 2D scanning MRI system, we focus on the in-slice \(B_1^+\) uniformities of the system. Figure 5 shows MmR values and mode profiles along different z-cut planes without and with the mode-shaping pad. It is noted that the two nodes of \(B_1^+\) at \(z \sim +/− 2\) cm are the signatures of the Fabry–Perot resonance modes of the high-permittivity pad along the z-direction. Overall, the max/min ratio of \(B_1^+\) in a transverse plane is kept less than 2 throughout the phantom. Specifically, with the cylindrical pad, a large reduction (max of 57%) of the MmR is observed in the central region (\(z = − 4\) to 4 cm) of the spheroid phantom, where \(B_1^+\) field focusing is usually observed without the application of an evanescently coupled pad.

In view of the refractive index, the magnetic permeability of the pad should work as an equivalent potential for the \(B_1^+\) RF field in the same way as the electric permittivity discussed earlier. In Fig. 6a–c, as an additional degree of freedom in the design of the \(B_1^+\) shimming pad, we present cases of magnetic pads (\(\mu_p = 2, \varepsilon_p = 135\)), (\(\mu_p = 4, \varepsilon_p = 98\)), and (\(\mu_p = 6, \varepsilon_p = 78\)), such as those based on metamaterials, providing a similar \(B_1^+\) RF field pattern to that of nonmagnetic pads (\(\mu_p = 1, \varepsilon_p = 180\)). In Fig. 6d–f, we also show the effect of pad loss (or the imaginary part of the permittivity, \(\sigma_p\)) on the mode shaping. For a non-negligible damping of \(\sigma_p > 0.01\), the z-directional Fabry–Perot resonance in the pad is suppressed, decreasing the contrast or inhomogeneity of the \(B_1^+\) field in the z-direction. Together, these results offer strategies for the selection of materials, and the pad-based 3D shimming of the \(B_1^+\) RF field.
Discussion
To summarize, we propose the concept of $B_1^+$ field mode shaping in the notion of evanescent coupling of an auxiliary potential to address the issue of transmit RF ($B_1^+$) inhomogeneity in UHF MRI. Specifically, treating the head-air-HPM (high-permittivity materials) MRI system as an RF waveguide excited by an external electromagnetic source, we systematically optimize the material and geometrical parameters of the HPM and evanescent coupling for $B_1^+$ shimming and prove its validity against the conventional contact-pad structure. It is revealed that the mode shape and homogeneity inside the phantom are determined by two key factors: the mode shape inside the pad potential and the hybridization strength between the phantom and pad potentials. The mode shape inside the pad potential is dictated by the electric permittivity of the pad ($\varepsilon_p$), the width of the pad ($w_p$), the magnetic permeability of the pad ($\mu_p$), and the loss of the pad ($\sigma_p$). The hybridization strength is controlled by the width of the air potential ($w_b$), working as a potential barrier between the phantom and pad potentials. With the strong boundary condition derived from the high permittivity of the pad ($\varepsilon_{pad} > \varepsilon_{phantom}$), we achieve a robust, global homogenization of axial $B_1^+$ throughout the ROI with negligible dependence on the geometry of the phantom. With a simplified phantom of spheroidal geometry, the max-to-min ratio of $B_1^+$ was kept < 2 over the whole region, being applicable to 2D MRI scanning. With the use of additional parameters, such as a noncylindrical pad geometry, an anisotropic HPM material and a metasurface HPM, further extension of our proposal should be possible for higher-level $B_1^+$ mode control in UHF MRI.

Figure 4. Effects of the air-gap potential barrier width $w_b$ on the mode. (a) Potential distribution in the radial direction. (b) Max/min ratio obtained for various $w_b$ values at the central plane of the system ($z = 0$). (c–f) Mode profile in the sagittal plane ($\theta = 0$). $\varepsilon_p = 180$, and $w_p = 2$ cm.
Figure 5. $B_1^+$ homogenization tested with a spheroidal phantom (long axis = 9 cm, short axis = 7 cm). For the pad, $\varepsilon_p = 188, w_b = 2$ cm, and $w_p = 2$ cm. (a) Mode profile in the sagittal view. (b) Max/min ratio at different axial slices ($z$-positions). (c) Axial images along the $z$-direction.

Figure 6. Effect of the magnetic permeability and the loss of the pad. (a-c) Mode profile for a magnetic pad of $\mu_p = 2, 4, 6$. (d-f) Effects of pad loss ($\sigma_p = 0.01, 0.2, 0.5$) on the mode shaping. $\varepsilon_p = 180$. For all cases, $w_b = 2$ cm, and $w_p = 2$ cm.
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Author contributions

M.P. developed the ideas, performed the theoretical analyses and numerical calculations. H.N. reviewed data analysis and physical interpretation of the results. N.P. proposed the application of mode shaping to MRI B1+ field shimming, and encouraged M.P. to investigate the additional degrees of freedom in the selection of mode-shaping pad materials while supervising the findings of this work. All authors discussed the results and contributed to the final manuscript.

Competing interests

The authors declare no competing interests.

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