Frequency Selective Surface (FSS) Radiofrequency Shield of Solenoid Coil for Low-Field Portable MRI

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Abstract

A lightweight cylindrical Frequency Selective Surface (FSS) using high-pass inductive mesh grid is proposed as a radiofrequency (RF) shield for solenoid coils at 2.84 MHz working in a portable MRI system with a transversal B0-field averaged at 67 mT. Using a solenoid coil of 60 mm diameter as an example, the proposed FSS shield shows good shielding effectiveness at different wall-to-wall distances between the coil and the shield (5-25 mm). It also shows less compromise in B1-sensitivity when compared to the coil with a copper shield. The effects of the FSS shield were examined numerically and validated experimentally. When the wall-to-wall distance is 5 mm, the solenoid coil with the proposed FSS shield is compact, lightweight, and shows B1-sensitivity of more than 50% higher than the copper counterparts with comparable shielding effectiveness. Compared to an unshielded coil, it shows a wider bandwidth which benefits the excitation of an MRI system that has less homogeneous fields and a smaller inductance which indicates less trapping of energy and thus can enable different pulse sequence programming by taking this approach. This study shows that an FSS shield with inductive mesh grids around a solenoid coil is a promising approach for compact shielding without a big shielding box. It will contribute to the compactness of a portable MRI system.
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Abstract—In this paper, lightweight cylindrical Frequency Selective Surface (FSS) using high-pass inductive mesh grid is proposed as a radiofrequency (RF) shield for solenoid coils at 2.84 MHz working in a portable MRI system with a transversal $B_0$-field averaged at 67 mT. Using a solenoid coil of 60 mm diameter as an example, the proposed FSS shield shows good shielding effectiveness at different wall-to-wall distances between the coil and the shield (5-25 mm). It also shows less compromise in $B_1$-sensitivity when compared to the coil with a copper shield. The effects of the FSS shield were examined numerically and validated experimentally. When the wall-to-wall distance is 5 mm, the solenoid coil with the proposed FSS shield is compact, lightweight, and shows $B_1$-sensitivity of more than 50% higher than the copper counterparts with comparable shielding effectiveness. Compared to an unshielded coil, it shows a wider bandwidth which benefits the excitation of an MRI system that has less homogeneous fields and a smaller inductance which indicates less trapping of energy and thus can enable different pulse sequence programming by taking this approach. This study shows that an FSS shield with inductive mesh grids around a solenoid coil is a promising approach for compact shielding without a big shielding box. It will contribute to the compactness of a portable MRI system. The study can be extended to other types of FSS for compact shielding for other RF coils.

Keywords—RF shield, MRI, Frequency Selective Surface, FSS, inductive mesh grid, portable MRI

I. INTRODUCTION

MRI is an extensively used diagnostic imaging modality showing good soft tissue contrast with non-ionizing radiation. The conventional MRI scanners with high $B_0$-field strength (> 1 T) are limited by high cost (purchase and maintenance), bulkiness, and high power consumption. Over the last few years, there has been resumed interest among researchers and industries in developing low-field MRI technology [1]–[9] to provide portable and cost-effective MRI scanners overcoming the above disadvantages of a conventional MRI. Halbach magnet array is widely used in portable MRI scanners which produces transversal static $B_0$ with homogeneous magnetic field [6] or built-in linear gradient [5] or non-linear gradient [1], [3]. Those with built-in gradient fields reduce the required number of gradient coils and hence lesser the hardware complexity with lowered power consumption. In such portable systems [10], [11], solenoid coils producing axial $B_1$-field are commonly used.

RF shielding is necessary to reduce interference for MRI signals. A shielding room enclosing the entire MRI scanner including the main magnet, gradient and RF coils is a common shielding approach [12]. However, taking this approach, the room needs to be renovated, which adds to the bulkiness and cost of a conventional system. For the portable MRI systems recently reported [1], [2], [5], [6], a shielding box is usually used to enclose the dedicated magnet. Although a shielding box is much smaller compared to a shielding room that favors the portability of the system, it still takes up space and adds weight.

Using a copper-shield to enclose an RF coil is another common approach for RF shielding in MRI. It was used for birdcage coils or transverse electromagnetic (TEM) RF coils in conventional MRI systems [13], and for solenoid coils in portable MRI systems [5], [14]. In this approach, the copper-shield is in close proximity to the coil. It reflects the magnetic field from the coil and the reflected fields interfere with those from the coils. It is desired to design the coil and the shield to have constructive interference in the field of view (FoV), i.e., an increase in $B_1$ sensitivity. However, destructive interference can happen, which reduces the $B_1$-sensitivity [15]. In Ref.[16], it was reported that a cylindrical copper-shield is preferred to be distant to the coil for a high SNR at $B_0 \leq 7$ T while SNR peaks are observed at 9.4 T and higher fields at the cylindrical waveguide modes.

Besides a copper-shield, an artificial magnetic shield (AMS) can be designed to provide enhancement of $B_1$ sensitivity. In Ref.[17], AMS based on a corrugated structure was proposed to provide portable and cost-effective MRI scanners overcoming the above disadvantages of a conventional MRI. Halbach magnet array is widely used in portable MRI scanners which produces transversal static $B_0$ with homogeneous magnetic field [6] or built-in linear gradient [5] or non-linear gradient [1], [3]. Those with built-in gradient fields reduce the required number of gradient coils and hence lesser the hardware complexity with lowered power consumption. In such portable systems [10], [11], solenoid coils producing axial $B_1$-field are commonly used.

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inside the coil while the main disadvantage is the additional power consumption added to the system and the resultant heat dissipation. This may not be a preferred approach for a portable MRI system which requires low power consumption for portability.

Recently, machine learning was applied to mitigate noise in an MRI system. To remove the shielding box, for a head dedicated MRI system, a deep-learning-based electromagnetic interference (EMI) cancellation method was proposed [9]. The proposed technique requires a network of strategically placed sensing coils to collect EMI signals to train a convolution neural network (CNN) to predict noise. The generalization of this approach need to be further tested.

On the other hand, frequency selective surfaces (FSS) [22] using inductive mesh grids [23]–[25], capacitive patches [26] and their combination [27] are widely used for EMI shielding in many areas such as communication devices [28], windows in buildings [29], radomes [30], and wearable devices [31]. The inductive mesh grid FSS with conformal shape has been considered for effective mantle cloaking applications [32]–[34]. However, the above applications are mostly focused in the microwave and millimeter wave frequency bands.

Recently, a shielding box constructed using steel chicken wires which can accommodate the system along with two persons was proposed for a prepolarized low-field MRI system which has a Larmour frequency of 180 KHz [35]. The chicken wire consists of inductive mesh grid structures. In the experiment when a saddle coil was used, a noise reduction of 10 dB was shown when chicken wires were used which is comparable to the case when solid aluminium shield was used (a 15 dB reduction). However, such enlarged shielding is not favourable for portability. Furthermore, FSS that is used as RF coil shield in close proximity is yet to be explored.

In this paper, lightweight cylindrical FSS using high-pass inductive mesh grid is proposed as a close RF shield for solenoid coils at 2.84 MHz working in a portable MRI system with a transversal B₀-field averaged at 67 mT.

II. DESIGN OF FSS SHIELDING FOR SOLENOID COILS

A high-pass FSS-shield consisting of inductive mesh grids was designed for a solenoid coil working at 2.84 MHz that can work in a portable MRI with a transversal B₀-field averaged at 67 mT [3]. Figure 1(A) and (B) show a 3D and top view of the proposed shield with a solenoid. The proposed FSS-shield is a cylindrical surface that is co-axial with the solenoid coil and consists of connected square meshes as unit-cells. The unit-cell is shown in the insert in Figure 1(A).

The high-pass FSS-shield with inductive mesh grids was designed to have a cutoff frequency, f_c, for external incident waves. The cutoff is required to be higher than 2.84 MHz. It is the cutoff frequency of the dominant mode of the cylindrical FSS-shield, f_c = min(f_{11}^{TEρ}, f_{11}^{TEz}) where f_{11}^{TEρ} and f_{11}^{TEz} are the cutoff frequencies of the dominant modes for the TE_ρ and TE_z waves, respectively. The TE_ρ and TE_z waves propagate on the xy-plane and in the z-direction, respectively, and are coupled into the cylinder. They are illustrated in Figure 1(D) and (E), respectively. The detailed equations and their derivations of f_{mn}^{TEρ} and f_{mn}^{TEz} are presented in Appendix A.

In this study, a solenoid with a diameter of 60 mm (shown in Figure 1(C)) is used to show the feasibility and effectiveness of the proposed shielding design. Busbar wires (18 AWG tinned copper, with a diameter of 1 mm) are used to construct the FSS-shield for the experiments. With the available wires, the mesh grid was constructed with an a of 10 mm and w of 1 mm. The solenoid coil used in this study has 18 turns, a pitch of
4 mm, and thus a height, \( H_{\text{coil}} \) of 72 mm. The copper wire with a diameter of 1 mm was used. The height of the FSS-shield, \( H_{\text{shield}} \), was set to 200 mm, which is much longer than the coil. It was placed at a wall-to-wall proximity distance (denoted as \( d \)) of 5-25 mm away from the coil, i.e., corresponding to a shield radius (\( R_{\text{shield}} \)) of 70-110 mm, as shown in Figure 1(B). The corresponding cutoff frequencies are 2.39 GHz - 1.55 GHz which is good for shielding the solenoid working at 2.84 MHZ.

III. INDUCTANCE OF THE FSS-SHIELDED SOLENOID COIL

The inductance of an RF coil [36] is an important parameter that quantifies how much it traps energy after excitation pulses. In the presence of the proposed FSS-shield, it is affected due to the mutual coupling between the coil and the shield. A solenoid with the proposed FSS-shield can be modeled using the equivalent circuit as shown in Figure 2. The effective inductance of the FSS-shielded solenoid, \( L_{\text{eff}} \), can be obtained from the circuit in Figure 2(A) using Eq. (1) below,

\[
L_{\text{eff}} = (L_1 - L_M) + \frac{L_M}{L_{22}} (L_{22} - L_M)
\]

where \( L_1, L_2, \) and \( L_M \), are the self-inductance of the solenoid, self-inductance of the FSS-shield, and the mutual inductance between them, respectively. For the self-inductance of a solenoid coil, \( L_1 \), it can be calculated using the Neumann’s curve integral formula [37].

The self-inductance of the FSS-shield and the mutual inductance between the coil and the shield, \( L_2 \) and \( L_M \), are decided by the induced currents in the shield. Figure 2(B)-(D) shows an illustration of the induced currents in the proposed FSS-shield due to the solenoid coil. The eddy currents induced in the shield are primarily induced in the circumferential loops nearby the solenoid which are highlighted in red, and those in the loops away from the solenoid or those induced in the orthogonal vertical gratings can be assumed to be negligible. Therefore, \( L_2 \) can be calculated using Eq. (2) by summing up the self-inductance, \( L_0 \) of each circumferential loop nearby the solenoid and the mutual inductance, \( M_{ij} \), between each pair of such loops in the FSS-shield that are not adjacent [38],

\[
L_2 = N_{\text{FSS}} L_0 + \sum_{j=1}^{N_{\text{FSS}}} \sum_{i=1}^{N_{\text{FSS}}} M_{ij}, (i \neq j)
\]

where \( N_{\text{FSS}} \) is the number of circumferential loops (nearby the solenoid) whose z-position lies within the height of the solenoid coil, given in Eq. (3) below,

\[
N_{\text{FSS}} = \frac{H_{\text{coil}}}{a} + 1
\]

The mutual inductance between the coil and the FSS-shield, \( L_M \), can be calculated from the sum of mutual inductance between the loop in the solenoid coil and that in the FSS-shield (shown in Figure 2(C)) using Eq. (4).

\[
L_M = \sum_{j=1}^{N_{\text{coil}}} \sum_{i=1}^{N_{\text{FSS}}} M_{ij}
\]

In Eq. (2), \( L_0 \) can be calculated from the self-inductance of a circular loop [39]. In both Eq. (2) and (4), \( M_{ij} \) can be calculated from the mutual-inductance between two circular loops [40].

IV. SIMULATION & EXPERIMENT

Simulations were performed by frequency sweeping to validate the cutoff frequencies of the proposed cylindrical FSS acting as high-pass filters. The cylindrical FSS with the considered unit-cell dimensions of two extreme cases, \( D_{\text{shield}}=70 \) mm, 110 mm were simulated when excited with normal \( \text{TE}_\rho \) and \( \text{TE}_z \) incident plane waves. The frequency domain solver in CST microwave studio was used. In the above simulations, the magnetic, electric, and open boundary conditions were set up along the corresponding H-, E- and k-direction as shown in Figure 1(D) and (E). The cutoff frequencies of the dominant modes were extracted from the simulated \( S_{11} \) and compared to the analytical model obtained using Eq. (12).

Further simulations were conducted to examine the shielding effectiveness and \( B_1 \) sensitivity enhancement of the proposed FSS-shield. The setups shown in Figure 1(A)-(B) at \( d=5 \) mm, 15 mm and 25 mm with a wide-band noise source centered at 2.84 MHz were simulated using frequency domain solver in CST microwave studio. Open boundary conditions were considered. For comparison, copper-shielded solenoids with the same dimensions and an un-shielded solenoid were simulated. The \( B_1 \) fields within a 3D cylindrical FoV with a diameter of 37 mm and a length of 40 mm were examined.

For validation, the copper- and FSS-shielded solenoids were examined in two extreme cases when \( D_{\text{shield}}=70 \) mm and 110 mm...
were constructed. For the solenoids, 18AWG solid copper wires were used. The photographs of the built coils are shown in Figure 3. They were matched at 2.84 MHz. Their B1-sensitivity map were measured in the considered FoV on the xy-plane at z = 0 via S21. Figure 4(A) shows the measurement setup where the shielded solenoid and a pickup loop (8 mm in diameter) were connected to Port 1 and Port 2 of a vector network analyzer (Rhode & Schwarz ZVH8) and the S21 parameters were obtained to indirectly show the B1 sensitivity of the coil under measurement.

Further validation of the shielding effectiveness and the B1 sensitivity enhancement were conducted using MRI scans in an in-house-build MRI system shown in Figure 4(B). The system has a rotatable Halbach array (average field strength of 67 mT and a field pattern with non-linear gradients) for signal encoding and imaging [3]. The FSS-shielded, copper-shielded, and unshielded solenoids were used as transceive coils. The phantom consisting of an array of bottles filled with CuSO4 solution as shown in Figure 4(C) and a single pulse with a pulse width of 26 µs and an amplitude of -10 dB was used. FID signals were acquired when different coils were used.

V. Results

The cutoff frequencies of the proposed cylindrical FSS, \( f_c \), s, were determined for the two extreme cases of the considered \( R_{\text{shield}} \) (35 mm and 55 mm). The analytical model in Appendix B shows that \( f_c = f_{11}^{TE} = f_{11}^{TM} \) for an infinitely thin shield. The analytical and simulated \( f_c \) were 2.39 GHz and 2.38 GHz, respectively when \( R_{\text{shield}} = 35 \) mm. Whereas, they were 1.55 GHz and 1.54 GHz, respectively when \( R_{\text{shield}} = 55 \) mm. They are much larger than the considered operating frequency of 2.84 MHz (\( f_c \gg f \)). Therefore, the cylindrical FSS-shields of the considered dimensions can effectively act as high-pass filters.

The shielding effectiveness of the proposed FSS-shield was investigated by examining the induced B1-field in the FoV when there is a noise source outside the coil. Figure 5 shows the simulated induced B1-field distributions at 2.84 MHz on the xy-planes at \( z = 0, 10, 20 \) mm within the considered FoV for the copper- and FSS-shielded solenoid coils when they are exposed to the wide-band noise source (with an excitation current of 1000 A and centered at 2.84 MHz). The results of the unshielded case is included as a reference. The average induced B1-field strength is labeled in each sub-plot. For the FSS-shielded cases at \( d = 5 \) mm, the noise sources with both the \( H_z \) and \( H_y \) polarizations were considered, and for the other cases, only the \( H_z \) polarization was considered. For the copper-shielded cases, only the \( H_z \) polarization was considered because a noise source with a \( H_y \) polarization is not likely to generate noise to B1-fields.

In Figure 5, when the noise source is in \( H_z \) polarization as shown in Figure 5(A)-(B), (D)-(G), the shielded cases show lower induced B1 compared to the unshielded one. Comparing the cases of the FSS-shielded coils (\( H_z \) polarized noise) in Figure 5(B), (E), and (G) to the unshielded one in Figure 5(H), the former shows a reduction of the average induced B1-field strength (i.e., the equivalent noise in the FoV) by about 79%, 89%, and 91% relative to the latter when \( d = 5, 15, \ldots \)
and, 25 mm, respectively. When the FSS-shield is further away from the coil, the lower the induced $B_1$-field is and the better the shielding is. Comparing the cases of copper-shielded coils in Figure 5(A), (D), and (F) to the unshielded solenoid coil in Figure 5(H), all the copper-shielded coils show a reduction of the induced field of at least 99.8% compared to the unshielded case. The trends of the induced $B_1$-field versus $d$ of these three cases are plotted in Figure 5(I). As shown, the shielding effectiveness of the FSS-shield is lesser than the copper counterpart, by about 20% when $d$ is 5 and about 8% when $d$ is 25 mm. Although the shielding effectiveness of FSS in close proximity to the coil is slightly lesser than the copper-shield, it still provides at least 80% noise attenuation when compared to the unshielded solenoid. Moreover, when the polarization of the noise is changed to $H_y$ where the induced $B_1$-field is supposed to be negligible, however, as shown in Figure 5(C), at $d=5$ mm, the induced $B_1$-field is small and comparable to the copper-shielded counterpart at the central slide while it increases considerably at the slides towards the ends of the FoV. This implies a higher vulnerability of the FSS-shield due to the mesh grids.

Besides the shielding effectiveness, furthermore, the effect of the proposed shielding on the $B_1$ sensitivity of the coil was investigated. The simulated $B_1$-field distributions at 2.84 MHz on the $xy$-planes within the considered FoV for the cases of the copper-, FSS-shielded, and unshielded solenoid coils are shown in Figure 6. The average $B_1$-field strength ($B_{1^{avg}}$) and inhomogeneity (IH) obtained from the root mean square deviation ($\sigma_{RMS}$) of the field are labeled in each sub-plot. IH was estimated using Eq.(5) below,

$$\text{IH} = \frac{\sigma_{RMS}}{B_{1^{avg}}} \times 100\%$$  \hspace{1cm} (5)

As shown in Figure 6, comparing the shielded cases to the unshielded cases, fields in the shielded cases are compromised in terms of field strength and comparable in terms of inhomogeneity. Comparing the $B_1$-field distributions of the FSS-shielded coils in Figure 6(B), (D), and (F) to those of their copper-shielded counterparts in Figure 6(A), (C), and (E), the former are higher than the latter by about 40%, 6%, and 2.5% at $d=5$, 15, 25 mm, respectively. The least compromise of $B_1$-sensitivity in the FSS-shielded coil is observed when $d$ is in close proximity to the coil. It compromises considerably less when the FSS-shield is away, going beyond $d=5$ mm. The proposed FSS-shield compromises less in field sensitivity compared to the copper-shield while the effect of the shield...
Fig. 6. (A)-(G), Simulated $B_1^\text{avg}$-field distribution on the $xy-$planes at $z = 0, 10, 20$ mm when the input port is excited at $2.84 \text{MHz}$ using $1 \text{ A}$ current source in the copper-, FSS- and un-shielded coils with a proximal distance, $d$ of (A)-(B), 5mm, (C)-(D), 15mm, and (E)-(F), 25mm, respectively. (H), 1D-plot of $B_1^\text{avg}$ obtained in the 3D cylindrical FoV for the considered cases with varying proximal distance, $d$.

becomes similar when the field is away from the coil. The trends of the average $B_1^\text{avg}$-field of the shielded coils versus $d$ of the shielded cases as well as those of the unshielded cases are plotted in Figure 6(H). When the shield is in the closest proximity, the coil shows the least compromise in sensitivity among all the cases.

The effect on $B_1^\text{avg}$-sensitivity of the proposed FSS-shield and that of the copper-shield are further analyzed by examining the following shielding: 1) shield with vertical gratings with a periodicity $a=10$ mm (having end loops to mimic current paths in the FSS-shield), 2) and 3) shield with circular loops (having a vertical connection to mimic the current paths in the FSS-shield) with a periodicity of $a=10$ mm and 5 mm, and $d=5$ mm. The 3D views of the coils are shown in Row 1 in Figure 7. A naked solenoid (shown in Figure 7(A)) and the copper-shielded solenoid are included in the comparison.

All the solenoids were simulated and their $B_1^\text{avg}$-field distributions on the central $xy-$plane ($z = 0$ mm) at $2.84 \text{MHz}$ are shown in Row 2 in Figure 7. The average $B_1^\text{avg}$-field and field inhomogeneity are labeled at each sub-plot. In Figure 7(A2) and (B2), comparing the case with a shield formed by cylindrically arranged vertical gratings to the unshielded one, it is observed that the $B_1^\text{avg}$ distributions are similar. This is because the vertical wires in the shield are orthogonal to the current running in the solenoid coil, so are the flux in the solenoid and the loops formed by the vertical wires and the end loops, which lead to minimum coupling between the shield and the coil. For the cases with stacked circular loops, comparing the case with a periodicity of 10 mm (Figure 7(C2)) and the case with $a = 5$ mm (Figure 7(D2)) to the unshielded solenoid in Figure 7(A2), it shows that the $B_1^\text{avg}$-field strength of both the shielded coils with stacked circular loops substantially decreases and the field inhomogeneity is slightly improved compared to that of the unshielded one. Moreover, comparing the case with $a=10$ mm to that with $a=5$ mm, it shows that the $B_1^\text{avg}$-field strength is reduced by 15% in the latter when the loops are denser compared to the former. It drops further then the loops are extremely dense, i.e., the case where they are all connected and form a copper-shield. The reduction of $B_1^\text{avg}$-field is caused by the opposing eddy currents induced in the shielding loops which results in a decrease in the $B_1$-field, i.e., a negative mutual coupling between the loops and the coil. As $a$ increases and the loops become sparser, the negative mutual coupling becomes less and the $B_1$-field decreases less. This explains the reason that the FSS-shielded solenoid has less compromise in $B_1^\text{avg}$-sensitivity compared to the copper-shielded one because the FSS-shield can be considered as a shield that consists of sparser loops compared to a copper one which has extremely dense loops.

The shielding effectiveness of the above cases are further examined. Simulations of the solenoids with wideband noises were conducted and the induced $B_1^\text{avg}$-field distributions in the
FoV were recorded for the study. The induced $B_1$-field distributions when there was a $H_z$-polarized and $H_y$-polarized noise source are shown in Row 3 and 4 in Figure 7, respectively. The average $B_1$-field in each case is labeled in each sub-figure. Comparing the naked coils in Figure 7(A3) and (A4), the $H_z$-polarized noise has much more penetration into the coil than the $H_y$-polarized noise. For the $H_z$-polarized noise, as shown in Row 3 of Figure 7, the vertical gratings (Figure 7(B3)) do not offer effective shielding while the loops do ((Figure 7(C3) and (D3)). The reason is that the loops have induced currents that slow the change of flux in the cylinder thus lowering the induced currents in the solenoid and the induced $B_1$-field while the vertical gratings are in parallel with the magnetic fields of the noise and do not offer similar effects. Comparing Figure 7(C3) (D3), and (E3), it shows that the shielding is more effective when the loops are denser. For the $H_y$-polarized noise, as shown in Row 4 of Figure 7, the vertical gratings (Figure 7(C4)) offer effective shielding, which is because the induced currents in the loops formed by the gratings and the end loops cancel partially the flux entering the solenoid. The loops provide relatively lesser effective shielding as shown in Figure 7(C4) and (D4) until they are fully connected to form a copper-shield as shown in Figure 7(E4). This is because they are in parallel with the magnetic fields of the noise.

Considering both the shielding effectiveness and the effects on the $B_1$-field sensitivity, when the shield is at the closest proximity to the solenoid coil, the FSS-shielded coil has the least compromise in $B_1$-sensitivity in all cases with acceptable shielding effectiveness, $\sim 80\%$ noise-attenuation. This favors the low-field portable MRI systems that have a low signal-to-noise ratio (SNR) due to a low field and a limited bore size.

Figure 8 shows a comparison between the simulated and measured results for validation. In Figure 8, Row 1 shows the normalized simulated $B_1$-field distribution and Row 2 shows the normalized measured $S_{21}$ that represent the $B_1$-sensitivity.
on the $xy$-plane ($z = 0$) within the defined FoV for the cases of copper- (Column 1 and 3) and FSS-shielded solenoid coils (Column 2 and 4) when $d$ is 5 and 25 mm. The results of the unshielded case are included in the last column for reference. The normalization of each row was done with respect to the maximum of the results of that row. The average of the normalized values and the IHs are labeled. Comparing Row 1 to Row 2 in Figure 8, it is observed that the measured data agree with the simulated ones. The discrepancy between the simulated and measured $B_1$-field map could be attributed to the imperfections in fabrication of the constructed coils. Moreover, limited accuracy in the measurement and higher copper loss in the experiments could also add to the discrepancies.

Moreover, comparing the first two columns to the third and fourth columns in Figure 8, it shows that a further away shield leads to a higher average $B_1$ where the effects of the distance of the shield to $B_1$ is experimentally validated. For the experimental data, at the same $d$ comparing the results of the FSS-shielded coils to their copper-shielded counterpart, the $B_1$-field of the FSS-shield is 91.3% higher than the copper one at $d = 5$ mm, and 7.8% higher at $d = 25$ mm.

Figure 9(A) shows the measured $S_{11}$ plot of the constructed coils. The measured 10 dB fractional bandwidths (FBW) and quality factors, ($Q = \frac{f_0}{\Delta f}$) are extracted and tabulated in Table I.

Table I: Measured bandwidth and Q-factor of the constructed coils

<table>
<thead>
<tr>
<th>$d = 5$ mm</th>
<th>$d = 25$ mm</th>
<th>No shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBW (%)</td>
<td>Copper FSS</td>
<td>Copper FSS</td>
</tr>
<tr>
<td>2.39</td>
<td>0.74</td>
<td>0.35</td>
</tr>
<tr>
<td>0.97</td>
<td>0.28</td>
<td>0.21</td>
</tr>
<tr>
<td>Q-factor</td>
<td>41.84</td>
<td>135.14</td>
</tr>
<tr>
<td>357.71</td>
<td>476.19</td>
<td>476.19</td>
</tr>
</tbody>
</table>

Figure 9(B) shows the analytically calculated, simulated, and measured inductance of the considered cases of coils. For the FSS-shielded coils, as shown by the blue symbols, the analytically calculated inductances agree with the simulated ones within $\sim5\%$ deviation, and they agree with the measured ones within $\sim15\%$ deviation. For both types of shielding, the agreements among the analytic, simulated, and measured results are better at $d = 10$ mm and 15 mm, while the difference is much bigger at $d = 5$ mm. The reason for the deviation can be attributed to the inevitable fabrication inconsistencies which can contribute more when $d$ is small.

Figure 9(C) and (D) shows the measured FID in both the time domain and frequency domain of the MRI scan using the built shielded ($d = 5$ mm)/unshielded solenoids in the in-house-built MRI system. Comparing the shielded cases in red and yellow to the unshielded case in blue, it can be easily seen that the noise is suppressed significantly. When the results of the two shielded cases are compared, the FSS-shielded one has much higher signal-to-noise ratio than the copper-shielded one.

VI. DISCUSSION

Overall, the proposed FSS-shielded solenoid at $d = 5$ mm shows a good balance among the shielding effectiveness, the coil sensitivity, the bandwidth, and the input inductance. Additionally, the FSS structure with inductive mesh grid is lightweight due to the periodic discontinuities. They are lighter compared to the copper-shields of same profile and dimension.

The lightweight FSS using high-pass inductive mesh grid is proposed to shield RF solenoid coils in a close proximity at 2.84 MHz for a portable MRI system with a transverse $B_0$-field averaged at 67 mT. The $B_1$-sensitivity and noise shielding effectiveness of the FSS-shielded solenoid coils with a conductor center-to-center proximity distance of 5-25 mm were investigated by numerical simulation and compared with the copper-shielded ones. The performance of the solenoid coil with the proposed FSS-shield was validated via experimental results.
The proposed FSS-shield has good shielding effectiveness at different conductor center-to-center distances. It compromises less on the reduction of $B_1$-sensitivity compared to its copper-shielded counterparts. The FSS-shielded solenoid at $d=5$ mm is compact, lightweight, and shows a $B_1$-sensitivity of more than 50% higher than the copper counterparts with comparable shielding effectiveness. Compared to an unshielded coil, it shows a wider bandwidth which benefits the excitation of an MRI system that has less homogeneous fields and a smaller inductance which indicates less trapping of energy and thus can enable different pulse sequence programming by taking this approach. This study shows that the proposed FSS-shield around an RF coil with close proximity is promising for RF shielding, thus a shielding box is not needed. The proposed approach will contribute to the compactness of a portable MRI system.

REFERENCES


APPENDIX

For a normally incident $\text{TE}_\rho$ and $\text{TM}_\rho$ waves propagating on the $xy$-plane (shown in Figure 1(D)), at the boundary of the shield, i.e. at $\rho = R_{\text{shield}}$, their surface impedance $Z_{\text{FSS}}^{\text{TE}}$ and $Z_{\text{FSS}}^{\text{TM}}$, can be defined by (6) and (7), respectively,

$$Z_{\text{FSS}}^{\text{TE}} = \frac{E_\phi^{\text{TE}}}{H_\phi^{\text{TE}}}$$

(6)

$$Z_{\text{FSS}}^{\text{TM}} = -\frac{E_\phi^{\text{TM}}}{H_\phi^{\text{TM}}}$$

(7)

where, $H_z^{\text{TE}}$ and $E_z^{\text{TM}}$ are the total H- and E-field of the respective $\text{TE}_\rho$ and $\text{TM}_\rho$ waves in the presence of the cylinder which are given by the sum of the forward travelling incident field and the backward travelling scattered field as shown in (8), and (9), below

$$H_z^{\text{TE}} = H_0 \sum_{n=-\infty}^{\infty} [j^{-n} J_n(k_0\rho) + a_n H_n^{(2)}(k_0\rho)] e^{jn\phi}$$

(8)

$$E_z^{\text{TM}} = E_0 \sum_{n=-\infty}^{\infty} [j^{-n} J_n(k_0\rho) + a_n H_n^{(2)}(k_0\rho)] e^{jn\phi}$$

(9)

and $E_\phi^{\text{TE}}$, and $H_\phi^{\text{TM}}$ are the $\phi$-components of the total E- and H-field of the respective $\text{TE}_\rho$ and $\text{TM}_\rho$ waves which are obtained by applying Maxwell’s equation in cylindrical co-ordinates as shown below in (10) and (11),

$$E_\phi^{\text{TE}} = \frac{1}{j\omega\mu} k_0 H_0 \sum_{n=-\infty}^{\infty} [j^{-n} J'_n(k_0\rho) + a_n H'_n^{(2)}(k_0\rho)] e^{jn\phi}$$

(10)

$$H_\phi^{\text{TM}} = \frac{1}{j\omega\epsilon} k_0 E_0 \sum_{n=-\infty}^{\infty} [j^{-n} J'_n(k_0\rho) + a_n H'_n^{(2)}(k_0\rho)] e^{jn\phi}.$$  

(11)

The cutoff frequencies, $f_{n\rho}^{\text{TE}}$ and $f_{n\rho}^{\text{TM}}$ of the $\text{TE}_\rho$ and $\text{TM}_\rho$ waves can be obtained from the roots of Eq. (12) and (13) below when boundary conditions are applied

$$Z_{\text{FSS}}^{\text{TE}} J_n(k_0^\epsilon R_{\text{shield}}) - j Z_0 J'_n(k_0^\epsilon R_{\text{shield}}) = 0$$  

(12)

$$Z_0 J_n(k_0^\epsilon R_{\text{shield}}) - j Z_{\text{FSS}}^{\text{TM}} J'_n(k_0^\epsilon R_{\text{shield}}) = 0$$  

(13)

where $Z_0 = 377\Omega$ is the impedance in air, $R_{\text{shield}}$ is the shield radius, $n$ is the azimuthal mode number, $J_n(p)$ is the Bessel’s function of first kind, $J'_n(p)$ is the first derivative of $J_n(p)$, $p = k_0^\epsilon R_{\text{shield}}$, $k_0^\epsilon$ is the wave number of the cut-off mode for the waves propagating in $xy$-plane. $Z_{\text{FSS}}^{\text{TE}}$ and $Z_{\text{FSS}}^{\text{TM}}$ can be calculated from the surface impedance of the periodic circumferential gratings [41] and the surface impedance of the periodic vertical gratings [42] from Eq. (14) and (15), respectively.

$$Z_{\text{FSS}}^{\text{TE}} = j k_0 Z_0 \alpha \log \left( \frac{\csc \left( \frac{\pi w}{2a} \right)}{\csc \left( \frac{\pi w}{2a} \right)} \right) \left( 1 - \frac{n^2}{k_0^2 R_{\text{shield}}^2 (\epsilon_r + 1) / 2} \right)$$

(14)

$$Z_{\text{FSS}}^{\text{TM}} = j k_0 Z_0 \alpha \log \left( \frac{\csc \left( \frac{\pi w}{2a} \right)}{\csc \left( \frac{\pi w}{2a} \right)} \right) \left( 1 - \frac{\cos^2 \theta}{\epsilon_r + 1} \right)$$

(15)

where $k_0 = 2 \pi f \sqrt{\mu_0 \epsilon_0}$ is the wave number of the incident wave with frequency $f$, $\mu_0$ and $\epsilon_0$ are respectively the permeability and permittivity of air, $\theta$ is the incident angle, and $\epsilon_r$ is the relative permittivity of the medium inside the cylinder. The $a$ and $w$ are the parameters for a 2D mesh grid FSS (as shown in Figure 1(F)), where $a$ is the edge length, $w$ is the width of the wire.

Eq. (12) and (13) are derived by assuming that, at the frequency of cylindrical resonant modes, the scattering by the cylindrical FSS-shield is minimum and therefore the scattering coefficients are assumed to be negligible, the finite losses in the mesh grid FSS are negligible, the medium inside FSS is air ($\epsilon_r = 1$) and the plane wave is incident normally ($\theta = 90^o$ as shown in Figure 1(D)).

The cutoff frequencies, $f_{n\rho}^{\text{TE}}$ and $f_{n\rho}^{\text{TM}}$ for $\text{TE}_z$ and $\text{TM}_z$ waves propagating in the z-direction (shown in Figure 1(E)) of an infinitely thin shield can be obtained from the boundary conditions in Ref. [43] which are the same as the ones obtained from Eq. (12) and (13), respectively.