Performance Enhancement of an MTL Coil Loaded With High-Permittivity Dielectric Liner for 7 T Brain MRI

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ABSTRACT In a multi-element microstrip transmission line (MTL) transmit array coil, the transmit field \( B_{\text{1}}^+ \) distribution is inhomogeneous due to its standing-wave nature, and the interference effects can severely degrade the \( B_{\text{1}}^+ \) and imaging. Therefore, to improve the homogeneity and strength of \( B_{\text{1}}^+ \), this study focuses on the development of a multi-element MTL transmit array coil integrated with a dielectric liner (DL) material. Furthermore, the transmission efficiency \( (T_{\text{x,eff}}) \) is improved in the head region. An eight-element MTL transmits array head coil is investigated using thinner DLs, and the optimized dimensions of the DL are found from its resonant mode at 7 Tesla (T). Simulations and measurements are performed with an MTL transmit array coil at 7 T, and the performance is analyzed for the DL positions and dimensions. Remarkably, the proposed DLs-integrated transmit array coil system offered significant improvements in the \( T_{\text{x,eff}} \) at different DLs positions. Compared to the case without the DL, the \( T_{\text{x,eff}} \) is improved by 9% (DL close to the head model), 15% (DL at center), and 39% (DL close to the RF coil). Interestingly, the DL acts as an efficiency tuner element exhibiting a 9% to 39% \( T_{\text{x,eff}} \) tuning range of improvement. In addition, the RF-shimming technique improves the \( B_{\text{1}}^+ \) homogeneity and \( T_{\text{x,eff}} \) of the coil with DLs by 21% and 42%, respectively, compared to the case without the DL. Moreover, the specific absorption rate (SAR) analysis of the MTL transmit array coil with the DLs is performed. The peak 10g-averaged SAR is reduced from 3.1 W/kg to 2.13 W/kg in the head using DLs and RF-shimming technique. Finally, we used the bench measurement setup to obtain the measured magnetic field. The proposed work exhibits salient features with a smaller DL size and multi-element MTL transmit array coil than other proposed works.

INDEX TERMS 7 T, dielectric pad, eight-element, MTL transmit array, radio frequency (RF) coil, RF shimming, region of interest.

I. INTRODUCTION

Due to advancements in the magnetic resonance imaging (MRI) modalities, 7 Tesla (T) magnets are used to obtain high signal-to-noise ratio (SNR) and spatial resolution as compared to the 1.5 T and 3 T systems. However, at ultra-high-field (UHF) MRI, the wavelength becomes smaller than the human head and causes significant interference effects in the \( B_{\text{1}}^+ \), which can severely degrade the image quality [1], [2]. The interaction between the RF field and the human body can impose additional challenges such as the higher RF transmitter power and the RF power deposition or specific absorption rate (SAR) [3], [4]. Various types of coils such as birdcage (BC), microstrip transmission line (MTL), and surface coil are used in the UHF MRI. Among them, the MTL transmit array coils hold the potential to provide improved homogeneity and SNR [3]. An MTL transmits array coil contains MTL resonators, which are mutually decoupled and operated as independent transmit coils [5]. The amplitude and phase of each resonator can be varied (\( B_{\text{1}}^+ \) shimming) to approach the desired transmit field (\( B_{\text{1}}^+ \)) distributions [6], [7].

Previously, a different number of resonators have been used in MTL transmit array coil to improve the RF efficiency and \( B_{\text{1}}^+ \) shimming at UHF MRI in [8]–[10]. Moreover, other
techniques such as modifying the shape and geometry of the resonator [1], [11], the use of adjustable coils [12], and dielectric pads or dielectric liners (DL) were introduced. By modifying the shape of the resonators [1], [11] the overall field distribution was enhanced up to certain limits; however, the field intensity drastically decreased in the near field region due to the large distance between the coil and the human head. Thus, adjustable coils were used in [12]; nevertheless, the coil adjustment was manually controlled, which makes it time-consuming and impractical. On the other hand, the dielectric liner (DL) materials have been used as a convenient and feasible solution in many applications to improve the local sensitivity and/or homogeneity of the RF \( B_1^+ \) in human MRI systems [13]–[26]. Gel-based pads [13], aqueous [14], and simple dielectric materials [15], [16] were used to improve the field distribution in head imaging at 3 and 7 T. It is worth mentioning here that the BC coils were used in combination with these dielectric materials; however, in modern multichannel UHF MRI systems, the BC coil may be impractical for some applications requiring high \( B_1^+ \) homogeneity over the brain. Modern UHF MRI systems require multichannel coils in combination with the independent control of the phases and amplitudes of each channel independently to achieve a homogeneous magnetic field and high SNR, which is impossible in BC coils MRI due to its 2-channel configuration and fixed phase. Furthermore, the much thicker gels or aqueous water pads were placed inside the plastic bags, and their properties could change during an MRI scan [18]. A new deformable pad made of Calcium Titinate (CaTiO\(_3\)) powder mixed with water has shown good improvements in the area of the temporal lobe for brain imaging [23], but the pad had immense linear dimensions of 100 mm × 140 mm placed alongside the head. In [24], the dielectric materials have been used in combination with BC coil to resolve a signal drop-off issue in the right hemisphere of the brain. However, only a single large pad is placed at the right-hand side of the human head, which can only be used for specific head area imaging. A transceiver array coil was used with DL to increase the signal locally [25]; however, the investigated large cylindrical DL placed around the cylindrical phantom which can be useful for homogenous phantoms. The thick cylindrical shape of the DL makes it complicated for the heterogeneous human study. Recently, a dipole coil configuration was studied using the dielectric pad to improve the magnitude \( B_1 \) in [26]. Although the pad improved the \( B_1 \) homogeneity and magnitude, only a single dipole coil with a large size dielectric pad was used. Recently, in [27]–[30], DL and pads were investigated either for the reduction of mutual coupling between the channels or for the field improvement; however, the major drawbacks are that the RF coil is BC and the DL size is much larger.

Most of the above studies used larger pad sizes and different numbers of the pads near the target phantoms. Moreover, most of the dielectric pads used in the above studies are hard to maintain the specific dimensions and shapes; however, the radio frequency response and its fields are dependent on the shape and especially on the dimensions of the pads, which has been not studied yet. Similarly, several studies have focused on the effects of pads with the BC coil; yet, the pad effects with MTL transmit array coils had never been discussed in earlier literature. Furthermore, the pads used previously had large thickness, which limits the head-MRI bore area and sometimes hard to fit for big heads. Therefore, the thinner and compact DL with stable dielectric properties can be advantageous in multi-channel head-MRI systems.

This paper introduces solid ceramic-based thin DLs in combination with an eight-element MTL transmit array RF coil for the enhancement of transmission efficiency (\( T_{x,\text{eff}} \)) and field improvement. Moreover, in contrast with previous literature, the effect of DL size based on the operating frequency has been discussed. The DL size and position are the critical factors for the \( B_1^+ \) field enhancement. Further, the DL size should be optimized relative to the MTL coil size and operating frequency. The DLs with a small thickness of 0.5 cm, relative permittivity (\( \varepsilon_r \)) of 78, and conductivity (\( \sigma \)) of 0.0001 S/m were placed near the RF transmit coil. The \( T_{x,\text{eff}} \) and the relative \( B_1^+ \) inhomogeneity of the coil without and with DL were calculated through the mean of the \( B_1^+ \) and coefficient of variation (CV), respectively. Additionally, the numerically generated MRI images were compared without and with the DLs for the SNR improvement. Finally, the proposed work was compared with previously related published papers of DLs in Table I. The proposed DLs improved the field homogeneity and \( T_{x,\text{eff}} \) by 21% and 39%, respectively, with a compact size and ultra-stable dielectric properties, which is suitable to use with MTL head coils.

II. MATERIALS AND METHODS

A. FULL-WAVE EM SIMULATIONS

Full-wave electromagnetic simulations were performed using a finite difference time domain (FDTD) simulator Sim4Life (v. 3.0.1.1201). The MRI RF coil configuration of interest is illustrated in Fig. 1(b) and consists of an eight-element head MTL transmit array coil array and a Duke body model. The Duke model consists of all the various tissues of the male body obtained from the virtual family dataset [31]. The RF transmit coil consists of the finite ground plane, a dielectric substrate, and MTL to transmit the RF field in the head model. Each element of the MTL transmit array coil was modeled by an MTL element on a low loss Teflon (PTFE) bar with \( \varepsilon_r = 2.1 \) and \( \delta = 0.004 \), height, width, and length of 1.8, 5, and 15 cm, respectively, as shown in Fig. 1(a). The resonant length of the microstrip element is foreshortened from \( \lambda/2 \) using capacitors (\( C_p = 8.2 \) pF and \( C_t = 2.73 \) pF) at the ends, and a matching capacitor (\( C_m = 3.4 \) pF) in series with the load. We used different values for the port and terminal capacitors to match the MTL array coil with the head, and after loading the Duke model, the \( C_t/C_m \) has been re-adjusted to achieve 50-ohm impedance matching.

Thereafter, a DL made of Barium samarium titanate (BaSmTi) oxide composition was designed for \( T_{x,\text{eff}} \)
TABLE 1. Comparison of the proposed high dielectric liner (DL) with prior work.

| Ref.   | Pad or DL                     | DL thickness (cm) | Permittivity value | RF Coil Type   | MRI Tesla | Purpose of study                      |
|--------|-------------------------------|-------------------|---------------------|----------------|-----------|---------------------------------------|
| [13]   | Gel pad                       | 2                 | Skin (65)           | Head birdeage  | 3T        | Reduction of dielectric artifact      |
| [14]   | Water pad                     | 4                 | 78                  | Head TEM       | 7T        | Manipulation of image intensity       |
| [16]   | Ultrasound gel or water       | ------            | 78                  | Body-array     | 3T        | Improvements in image homogeneity     |
| [17]   | BaTiO3 in deuterated water    | 1                 | 286                 | High-pass birdeage | 7T       | Improving spatial resolution of ear.  |
| [21]   | CaTiO3 with water             | 2                 | 156                 | Head birdeage  | 7T        | Tailoring the B1+                     |
| [23]   | polyvinylchloride (PVC) with CaTiO3 | 1                 | 110                 | Quadrature birdeage | 7T       | Medial lobe MRS improvements         |
| [25]   | BaTiO3 powder suspension      | 2                 | 78, 150             | Transceiver Array | 4.7T  | Increase the signal and homogeneity  |
| [26]   | CaTiO3 and D2O oxide          | 1                 | 110                 | Dipole coil    | 7T        | Improve the B1 homogeneity            |
| [27]   | BaTiO3 powder suspension      | ------            | 150                 | Transceiver Array | 4.7T  | Maximize the homogeneity              |
| [28]   | MTM liner                     | 1                 | ------              | Birdcage coil  | 4.7T      | SAR prevention                        |
| [29]   | BaTiO3 and CaTiO3 powder with water | 2                 | 298, 110            | Head birdeage  | 7T        | Improving SNR and Transmission efficiency |
| [30]   | BaTiO3 suspension             | 1.5               | 300                 | Birdcage coil  | 3T        | Improving Homogeneity                 |
| This work | Barium samarium titanate (BaSmTi) oxide | 0.5               | 78                  | MTL transmit array | 7T        | Improving Transmission Efficiency (39%) |

Improvement, as shown in Fig. 1(a). In the simulations, we used a dielectric liner having \( \varepsilon_r \) of 78 and conductivity \( (\sigma) \) 0.0001 S/m, while for the fabrication, we used the solid ceramic block made of BaSmTi to get our desired dielectric constant value in the lossless condition. The material is unique to MRI research and is highly soluble, which allows it to be modified in different ways. Two distinct DL sizes of 5 cm \( \times \) 15 cm \( \times \) 1 cm and 5 cm \( \times \) 15 cm \( \times \) 0.5 cm were evaluated to find the optimum size for the \( T_{x,eff} \) improvement.

It was found from the analysis of the resonant mode of the DL that the 0.5 cm provided one of the resonant modes at 298 MHz (7 T). Therefore, the thickness of the DL was set to 0.5 cm. Finally, the DLs were placed at three different positions: close to the head, close to the coil, and between the head and the RF coil to investigate the areas where the \( B_1^+ \) can be affected. The DL positions relative to the coil are shown in Fig. 1(a). Furthermore, in our simulation setups, the effect of DLs was investigated at two different angles or configurations (“A” and “B”). For DLs’ lossy and lossless condition, various \( \sigma \) values (0.0001 S/m and 0.5 S/m, and 1 S/m) were used. Moreover, the head SAR was calculated for \( \varepsilon_r \approx 78 \) value of the DL and plotted in axial, coronal, and sagittal slices. To assess the SNR of RF coil arrays, MUSAiK V2.0 was used for simulations. The MUSAiK provides SNR and parallel imaging capabilities by importing the simulation results. For the Duke head model, the total number of mesh cells (voxel size) over the entire simulation volume amounted to 11.249 million cells, and 0.5 spatial resolution was used for simulations.

The axial, sagittal, and coronal slices were used as the target slices to depict the field distributions inside the head for the \( B_1^+ \) improvement and performance comparison at 7 T, as shown in Fig. 1(a). The anatomically Duke head model was used as a load in Sim4Life for the RF coil simulations. In this paper, three optimization parameters were evaluated in the head slice. The first parameter is the \( B_1^+ T_{x,eff} \), which can be measured in \( \mu T / \sqrt{W} \) and defined by:

\[
T_{x,eff} = \mu / \sqrt{P_{in}} \tag{1}
\]

where \( \mu \) is the mean value of the \( B_1^+ \) and \( P_{in} \) is the total input power. All the \( B_1^+ \) fields were calculated based on the simulated input power of 8 W. We kept a 45° phase shift between the adjacent channel of the MTL transmit array. The second parameter is the CV = (standard deviation (\( B_1^+ \)) / \( \mu \)), while the third parameter is the peak 10g-averaged SAR value in W/kg. The spatially averaged SAR values were evaluated in Sim4Life using the psSAR[IEEE/IEC62704-1] averaging method.

B. RF-SHIMMING OR MATLAB OPTIMIZATION ROUTINE

A routine was implemented in Matlab to achieve the higher \( B_1^+ \) homogeneity and minimize the 10-g peak SAR values.
FIGURE 1. (a) Design of the single-element MTL transmit RF coil and DL. (b) Simulation setups for the configurations “A” and “B” showing the RF coil and high dielectric liner (DLs) positions around the head. The DL position could be one of the three positions. The diameter of the cylinder on which the MTL elements are mounted is 26 cm. Summary of the dimensions are as follows: \( a = 15, b = 5, c = 0.5, h = 15, l = 5, p = 2, w = 1.8 \) (Units: centimeters).

C. BENCH MEASUREMENT SETUPS AND MRI

Finally, the MTL transmit array coil was fabricated to measure the S-parameters and magnetic field. Fig. 2(a) illustrates the developed eight-element RF coil prototype without and with the DL. In the setup, the MTL transmit array was mounted on a Teflon substrate, and two V9000 variable capacitors (\( C_m \) and \( C_t \)) were used. These V9000 capacitors are specifically used in the implementation of MRI RF coils. The Voltronics manufacturer provides the non-trimmer capacitors in the range of 1 pF to 10 pF. On the posterior side of the Teflon, the ground was attached to provide the current loop in the coil. For the validation of the simulated results, a commercial DL made of BaSmTi oxide composition (E5080, EXXELIA\textsuperscript{TEMEX}) was fabricated, as shown in Fig. 2(a). The matching and tuning of the RF coil at 7 T without and with the DL was found by changing the knob of the V9000 variable capacitors. For the magnetic field measurement, a single channel of the array coil and an H-probe connected to a signal generator (MS2830A, Anritsu) was used, as shown in Fig. 2(b). The H-probe was located inside the head phantom filled with a saline solution, and the magnetic field was measured at various points. Deionized water, sugar, and salt (NaCl) were used in the preparation of saline solution to imitate the human brain properties. The magnitude of the magnetic field was calculated by collecting the \( H_x \) and \( H_y \) components of the field at every point using the H-probe. The field was measured in 10 cm \( \times \) 10 cm and normalized to the maximum value.

A specific slice selective gradient recalled echo (GRE) sequence was used with a 2.5 ms (T1-weighted) and 100 ms (T2-weighted) echo time (TE), a 500 ms (T1-weighted), and 3000 ms (T2-weighted) relaxation/repetition time (TR), a 30° flip angle, a 128 \( \times \) 128 image acquisition matrix, a 2 mm slice thickness, and a 23 cm \( \times \) 23 cm field-of-view (FOV) to obtain the MR images. These parameters were fed into a Bloch simulator described in [33] to generate all the MR images with the MTL numerically. An axial slice was used to...
FIGURE 3. Simulated S-parameters of the eight-channel transmit array coil. (a) Reflection coefficients. (b) Transmission coefficients. The reflection coefficients of all elements are lower than $-20$ dB, while the transmission coefficients between the MTL array coil’s adjacent elements were achieved lower than $-15$ dB.

target the center of the head model for the MR images of the eight-element MTL coil.

III. RESULTS AND DISCUSSION

A. EM SIMULATIONS FOR EIGHT-ELEMENT RF COIL WITH DL

To investigate the effects of DLs in the heterogeneous head phantom and achieve realistic results, the eight-element RF coil and DLs were simulated using the FDTD-based Sim4Life. All the MTL transmits array coil elements are tuned and matched at the 7 T resonance frequency (298 MHz), as shown in Fig. 3(a). The return loss value of all elements is lower than $-20$ dB. The coupling between the MTL transmit array coil’s adjacent elements was achieved lower than $-15$ dB, as shown in Fig. 3(b). After loading the DL in the RF coil environment, the high $\varepsilon_r$ value of the DL detuned the coil’s resonant frequency. Hence, the variable capacitor $C_t$ value was changed to retune the RF coil at 298 MHz.

We computed the field distributions without the DLs ($B_{+1}^+$) and with the DLs ($B_{+1}^+$) at the target slices. The primary purpose of using DL with the MTL coil was to maximize the transmit field intensity in a particular region (center of the head). Fig. 4 illustrates the simulated axial, sagittal, and coronal slices of the $B_{+1}^+$ field within the Duke head model for the MTL transmit array coil without and with the DL. The DLs improved the $T_{x,eff}$ in the head slices and minimized the field inhomogeneity. After using the DLs with MTL transmit array coil, the higher central $B_{+1}^+$ values were pronounced at the center of the head with maximum $B_{+1}^+$ intensity. The results showed that the DL with MTL coil improved the $T_{x,eff}$ by 39% in the head compared to the case without DL. It can be observed from the figure that the $\mu$ value in the head slices for configurations “A” was increased from 0.56 $\mu$T to 0.78 $\mu$T. For configuration “B”, the $\mu$ value in the head was improved from 0.58 $\mu$T to 0.77 $\mu$T. Additionally, the CV value was decreased from 0.37 to 0.32 using DLs, which showed that the DLs case provided homogeneous field distribution. Using the DLs not merely increases the $B_{+1}^+$ field in the center of the head but increases the field strength in the whole head slice as well, resulting in the improvement of field homogeneity throughout the slice. All the numerical values of the $\mu$, $T_{x,eff}$, and CV are summarized in Table 2. The DLs provide additional $B_{+1}^+$ strength due to the displacement current ($J_d$), leads to power balancing, reduced tissue dissipated power, and destructive cancellation of field components inside the head. The DLs act as absorbing layers,
TABLE 2. Summary of the simulated \( B_1^+ \) field in \( \mu T \), \( T_x^{\text{eff}} \) in \( \mu T/\sqrt{W} \), and CV in the head slice with DL. The MTL array coil was fed with the simulated power of 8 W.

| Configuration “A”  | 5 mm | 10 mm | 5 mm and \( \sigma = 0.5 \) | 
|-------------------|------|-------|-----------------------------|
| Close to head DL  | 0.61 | 0.216 | 0.36                        |
| Middle of head and coil DL | 0.64 | 0.227 | 0.35                        |
| Close to RF coil DL | 0.78 | 0.276 | 0.32                        |
| DL thickness DL  | 0.69 | 0.244 | 0.34                        |
| Lossy (\( \sigma = 0.5 \)) DL | 0.66 | 0.233 | 0.35                        |
| RF Shimming w/o DL | 0.53 | 0.187 | 0.31                        |
| RF Shimming with DL | 0.75 | 0.265 | 0.29                        |

which eliminate the reflected waves from the object’s surface and boundaries between tissues. Therefore, they reduce the effect of destructive interference, which shapes a conservative E-field and thereby improves the \( B_1^+ \) field in the head.

Furthermore, the comparison of the \( B_1^+ \) distributions for the DLs with thicknesses of 0.5 cm and 1 cm was carried out for configuration “A”. Fig. 5(a) illustrates the axial \( B_1^+ \) distributions within the Duke head model. The DLs with a thickness of 0.5 cm provided better field improvement than those with a thickness of 1 cm. For the DL with a thickness of 1 cm, the \( T_x^{\text{eff}} \) value in the head slice was improved approximately 23%, while the improvement value for 0.5 cm thickness was 39%. Moreover, the \( B_1^+ \) distributions were compared for the DLs with thicknesses of 0.5 cm positioned close to the head model, in the middle of the RF coil elements and the head model, and close to the RF coil, as shown in Fig. 5(c). At the corresponding DLs positions, the \( T_x^{\text{eff}} \) values in the head slice were improved by about 9%, 15%, and 39%, respectively. From these values, it is worth noting that the thinner DLs near the RF coil performed better in the field improvement. Table 2 summarizes the numerical field-values comparison at DL thicknesses for the different positions relative to the RF coil and head.

Fig. 5(b) displays the axial \( B_1^+ \) distributions within the Duke head model for \( \sigma = 0.5 \) S/m. From the \( B_1^+ \) distributions, the \( T_x^{\text{eff}} \) value in the head slice was improved by approximately 18%. This value showed that the lossless condition (\( \sigma = 0.0001 \) S/m) provided improved \( T_x^{\text{eff}} \) (39%) within the head model, whereas, at the lossy condition (\( \sigma = 0.5 \) S/m, 1 S/m) the field improvement was less effective. At \( \sigma = 1 \) S/m, the field improvement becomes negligible. A parametric study was carried out to further justify the DL of 0.5 cm thickness by simulating DLs with different thicknesses from 10 mm to 1 mm. From all simulations and \( B_1^+ \) distributions, DLs with the optimal thickness of 0.5 cm showed better RF coil performance and yield the maximum field distribution in the head.

B. RF SHIMMING WITHOUT AND WITH THE DLs

For the homogeneous field distributions in the head, the optimum values of the applied source and phase were selected for each element in the multi-element RF configuration “A”. Fig. 6 (upper row) displays the RF shimmed \( B_1^+ \) distributions within the head of the Duke model at axial, sagittal, and coronal slice. The CV value decreased from 0.37 to 0.32 in the target head slices. The value shows that the technique improved the \( B_1^+ \) homogeneity.

After achieving the RF shimmed \( B_1^+ \), the DLs were introduced to improve the \( T_x^{\text{eff}} \) in the head of the Duke model and to minimize the RF field interference. Fig. 6 (lower row) displays the simulated \( T_x^{\text{eff}} \) of the RF shimmed \( B_1^+ \) produced...
by the eight-element RF coil with DLs within the Duke head model. The higher signal intensity in the head slices was achieved using the DLs than the case without DLs. It can be observed from the simulation results that the insertion of DLs in the RF coil setup achieved an improvement of 42% in the $T_{x,eff}$ in the target slices of the head model. The field distributions at the target slices were more intense in the head, and the $\mu$ value was improved from 0.53 $\mu$T to 0.75 $\mu$T. The RF-shimming technique and the DLs improved the $B_{i+1}$ homogeneity by approximately 21%, and the CV value was decreased from 0.37 to 0.29 in the target head slices. All the numerical values of the $\mu$, $T_{x,eff}$, and CV for the RF-shimming technique without and with the DLs are summarized in Table 2. The values show that the DL is effective in the head model, and the field distribution is improved in the target slices.

C. SAR OF MTL COIL WITH DLs

To ensure the safety of MRI patients, the IEC/FDA has restricted the peak 10g-averaged SAR for the head tissues to 3.2 W/kg. The presented SAR values in the head tissues are the peak 10-g SAR, calculated for the MTL coil with the input power of 1 W for each channel (total 8 W). The compared SAR distributions for MTL coil without and with the DLs are plotted in Fig. 7. The MTL transmit array coil without a DL produced 3.1 W/kg SAR in the head, which complies with the standard limiting value of the head SAR in MRI. The higher SAR distributions were observed at the temporal lobe of the brain due to its closer distance to the transmits array coil. Therefore, the DLs were inserted to reduce the higher SAR distribution. From the sensor’s SAR distribution, it was observed that the MTL coil with DLs produced a peak SAR value of 2.5 W/kg. The above value shows that the peak SAR is reduced in the head slice when a DL is used. In our proposed configuration, the RF-shimming technique was also used to minimize the SAR in the head. After using the RF-shimming, the peak SAR value was reduced to 2.13 W/kg in the head, and lower SAR distributions were achieved at the temporal lobe areas of the slices. The figure shows the case where the DLs and the RF shimming was used to yield the minimum SAR values in the head. It is observed that the RF-shimming and DLs provided the best $B_{i+1}$ homogeneity and improved $T_{x,eff}$ field values with minimal peak SAR values in the head.

D. OPTIMUM SNR

The optimum SNR strength at every pixel without and with the DLs is illustrated in Fig. 8. It can be seen that the optimum SNR at the temporal or side area of the brain is a bit lower and darker without DL, whereas much higher and brighter SNR is achieved after the insertion of DL in the coil setup. The field slice shows that the optimum SNR is improved and increased in every region of the head slice. The numerical values at different regions over the transverse slice are also plotted.
slice SNR intensity obtained from both colors and numerical values shows that the DLs provide better optimum SNR over the entire area of the transverse slice. In this figure, the optimum SNR is improved by inserting DLs. Correspondingly, the comparison depicts the effectiveness of the DLs.

E. SIMULATED MRI ACQUISITIONS

A single simulated GRE sequence was used to obtain the MR images of the MTL transmit array coil without and with the DL. Fig. 9 shows the MR image comparison without and with the DLs at the center axial slice. The method described in [33] was used to numerically generate all the MR images with the MTL coil at 7 T. The results show that the images provide higher signal intensity, and the DLs pronounced bright field distributions at the head model compared to the images without DLs. The tissues were visualized in the MR image using the H-probe and the field maps were measured using the H-probe. The measured field maps show that the case with the DL provides higher field intensity than without the DL case. When the DL was inserted, the field propagates deeper in the head with higher intensity. The measured results are in good agreement with the simulation results; thus, the proposed DL is a promising solution for field improvement.

IV. CONCLUSION

In this study, an eight-element MTL transmits array head coil was used with small DLs at 7 T. The proposed RF coil and DLs were placed around the head in two configurations (“A” and “B”). Multiple dimensions of the DL thickness were simulated for selecting the optimum thickness. From all simulation results, it was observed that the DLs provided 39% \( T_{x,eff} \) improvement in the selected head slices compared to the case without DLs. The RF-shimming technique and DLs improved the \( B_1^+ \) homogeneity for the MTL transmit array coil with DLs by 21% in the central axial slice. The peak SAR in the head slices was minimized by DLs and RF-shimming. The proposed DLs improved the MRI images and modified the distribution of the RF electromagnetic fields. Hence, the DL materials with multi-element MTL transmit coils can enhance the transmitted field in the head model and improve the field distribution in the deep target region. Therefore, these materials can be the best candidate to use in the MRI system to obtain higher resolution images of the patients.

REFERENCES

[1] C. E. Akgun, L. Delabarre, H. Yoo, S. M. Sohn, C. J. Snyder, G. Adriony, K. Ugurbil, A. Gopinath, and J. T. Vaughan, “Stepped impedance resonators for high-field magnetic resonance imaging,” IEEE Trans. Biomed. Eng., vol. 61, no. 2, pp. 327–333, Feb. 2014.
[2] H. David and D. Phil., “Sensitivity and power deposition in a high-field imaging experiment,” J. Magn. Reson. Imag., vol. 12, no. 1, pp. 46–67, 2000.
[3] J. T. Vaughan, M. Garwood, C. M. Collins, W. Liu, L. Delabarre, G. Adriony, P. Andersen, H. Merkle, R. Goebel, M. B. Smith, and K. Ugurbil, “7T vs. 4T: RF power, homogeneity, and signal-to-noise comparison in head images,” Magn. Reson. Med., Off. J. Int. Soc. Magn. Reson. Med., vol. 46, no. 1, pp. 24–30, 2001.
[4] A. M. Abduljalil, A. Kangarlu, X. Zhang, R. E. Burgess, and P.-M.-L. Robitaillle, “Acquisition of human multislice MR images at 8 Tesla,” J. Comput. Assist. Tomogr., vol. 23, no. 3, pp. 335–340, May 1999.
[5] X. Zhang, K. Ugurbil, and W. Chen, “Microstrip RF surface coil design for extremely high-field MRI and spectroscopy,” Magn. Reson. Med., vol. 46, no. 3, pp. 443–450, 2001.
[6] H. Yoo, A. Gopinath, and J. T. Vaughan, “A method to localize RF B1 field in high-field magnetic resonance imaging systems,” IEEE Trans. Biomed. Eng., vol. 59, no. 12, pp. 3365–3371, Dec. 2012.
[7] I. A. Elabayed, T. Herrmann, C. Bruns, J. Bernarding, and D. Enzi, “RF shimming and improved SAR safety for MRI at 7 T with combined eight-element stepped impedance resonators and traveling-wave antenna,” IEEE Trans. Microw. Theory Tech., vol. 66, no. 1, pp. 540–555, Jan. 2018.
[8] G. Adriony, P.-F. Van de Moortele, J. Ritter, S. Moeller, E. J. Auerbach, C. Akgun, C. J. Snyder, T. Vaughan, and K. Ugurbil, “A geometrically adjustable 16-channel transmit/receive transmission line array for improved RF efficiency and parallel imaging performance at 7 Tesla,” Magn. Reson. Med., vol. 59, no. 3, pp. 590–597, Mar. 2008.
S.-M. Sohn, L. DelaBarre, A. Gopinath, and J. T. Vaughan, “RF head coil
X. Yan, J. O. Pedersen, L. Wei, X. Zhang, and R. Xue, “Multichan-
VOLUME 9, 2021
S. Ullah, H. Yoo: Performance Enhancement of MTL Coil
Y. Takayama, H. Nonaka, M. Nakajima, T. Obata, and H. Ikehira, “Reduc-
W. M. Brink, A. M. van der Jagt, M. J. Versluis, B. M. Verbist, and
M. Kataoka, H. Isoda, Y. Maetani, Y. Nakamoto, T. Koyama, S. Umeoka,
Y. Cho, A. Basir, and H. Yoo, “Adjustable RF transmitter head coil:
Improving transmission efficiency with SAR management for 7-T magnetic
M. Kordzadeh and N. D. Zanche, “Control of mutual coupling in high-
A. M. Smith, “Reducing SAR and enhancing cerebral signal-to-noise ratio
K. Tamai, A. Kido, N. Morisawa, T. Saga, and K. Togashi, “MR imaging of
A. G. Webb, “High permittivity dielectric pads improve high spatial reso-
K. Haines, N. B. Smith, and A. G. Webb, “New high dielec-
K. Haines, N. B. Smith, and A. G. Webb, “High performance dielectric
to. “Invest. Radiol.,” vol. 49, no. 5, pp. 271–277, 2014.
V. Vorobyev, A. Shchelokova, I. Zivkovic, A. Slobozhanyuk, J. D. Baena,
V. Vorobyev, A. Shchelokova, I. Zivkovic, A. Slobozhanyuk, J. D. Baena,
W. Rascher, R. Janka, W. Bautz, J. Chen, B. Kiefer, P. Schmitt, H.-P. Hollenbach, J. Shen, M. Oberle, D. Szczterza, A. Kam, J. W. Guag, and N. Kuster, “The virtual family—Development of surface-based anatomical models of two adults and two children for dosimetric simulations,” Phys. Med. Biol., vol. 55, no. 2, pp. N23–N38, Jan. 2010.
C. Olson, H. Yoo, L. Delabarre, J. T. Vaughan, and A. Gopinath, “RF B1
field localization through convex optimization,” Microw. Opt. Technol. Lett., vol. 54, no. 1, pp. 31–37, Jan. 2012.
Z. Cao, S. Oh, C. T. Sica, J. M. McGarrity, T. Horan, W. Luo, and C. M. Collins, “Blob-based MRI system simulator considering realistic electromagnetic fields for calculation of signal, noise, and specific absorption rate,” Magn. Reson. Med., vol. 72, no. 1, pp. 237–247, Jul. 2014.
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