Improved material for passive RF shimming with high dielectric pads

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Introduction: In a growing number of applications, high dielectric materials (HDM) have been successfully used to improve the sensitivity and homogeneity of the transverse electromagnetic field (B_1^+ and B_1^- field) in human MRI. For example, simple aqueous and gel-based bags of dielectric material with electrical properties close to human tissue were used to improve the local sensitivity in head imaging [1] or homogeneity of the B_1^+ field in abdominal imaging [2,3]. Brain imaging with bags filled with distilled water or a suspension made by calcium titanate ($CaTiO_3$) powder in distilled or deuterated water surrounding the patients' head have shown a significant increase in SNR, especially in the temporal lobe area [3]. Recently we developed and characterized a composite material using distilled water and sintered beads of barium titanate ($BaTiO_3$). The bead/water composite shows higher dielectric constant (ε_r') and (at least at 123MHz) lower conductivity (σ) compared to a powder/water slurry, which should result in performance a stronger effect on field distribution for a given amount of material while introducing less noise.

Methodology: The $BaTiO_3$ powder/water slurry was made by mixing the $BaTiO_3$ powder (Inframat Advanced Materials) with distilled water in powder volume/water volume ratio up to 0.35, at which point the slurry becomes saturated. The dielectric constant and conductivity of the $BaTiO_3$ suspension were measured using an Agilent 85070D dielectric probe kit. The dielectric composite consists of distilled water and $BaTiO_3$ beads of 1 mm diameter. The $BaTiO_3$ beads were made by spraying a binding agent, 2% polyvinyl alcohol (Air Products), onto the $BaTiO_3$ powder and the resulting mixture was formed into 1 mm size beads using a standard laboratory sieve. The $BaTiO_3$ beads were then sintered in a custom-built furnace: 8 hours from room temperature to 400 ˚C, 4 hours from 400 to 600 ˚C, 2 hours from 600 to 1300 ˚C, 2 hours at 1300 ˚C, and a 2 hour drop from 1300 ˚C to room temperature. The sintered $BaTiO_3$ beads were mixed with distilled water in a 0.8 bead volume/water volume ratio to form the bead/water composite. The bead/water composite has a heterogeneous composition over a few millimeters, precluding use of the Agilent 85070D dielectric probe kit in measuring dielectric properties. Instead, a resonant cavity method was used to measure ε_r' and σ of the dielectric composite at approximately 123.2 MHz and 300 MHz. Using standard equations for mode resonances in a closed cylindrical cavity [5] and expected dielectric properties of the bead/water composite, we designed two cavities to have good isolation of the TE_{111} mode from other resonant modes at 125MHz (larger cavity) and at 300 MHz (smaller cavity). A resonant cavity consists of a cylindrical conducting wall shorted on both ends with conducting plates. The smaller cavity was constructed of a 15mm radius copper tube soldered to a copper base. A plunger constructed by fixing copper mesh to a delrin tube with a diameter slightly smaller than the copper tube formed the other conducting end of this cavity. Two coaxial ports were placed on opposite sides of the copper tube to excite and monitor the spectrum response with an HP 4195A spectrum analyzer. The larger cavity was constructed of an acrylic tube fixed at one end to a delrin base. The tube was fitted tightly into a circular well that was milled in the base and filled with silicone sealant to ensure a water-tight connection and structural stability was added with four long bolts connecting the base plate to a top plate milled with a ridge to accompany the top end of the tube and a hole to admit the plunger. Copper tape was carefully placed on the inner surface of the tube and on the area of the base inside the cavity after the cavity body was built. An adjustable plunger constructed by fixing copper mesh to a delrin tube formed the other conducting end of the cavity. Two coaxial ports were installed on opposite sides of the conducting wall, 5 cm above the base. The cavity size (radius *a* and height *d*), resonant frequency f_r of the TE_{111} mode, and its bandwidth Δf were required to calculate the ε_r' and σ of the dielectric composite [5]. The height of the cavity was adjuste by adding or removing composite material then inserting the plunger to rest on the composite. By changing *d*, f_r could be tuned and *d* was varied by controlling the amount of the dielectric composite present in the cavity. The conductive plunger that defined the top of the cavity was placed against the top surface of the dielectric composite in every case. Connecting the two measurement ports with a spectrum analyzer, a spectrum in S_{21} or S_{12} mode revealed all the resonant frequencies for the different modes and their bandwidths. Then, f_r at the TE_{111} mode was identified with reference to a mode chart. Once f_r was identified, Δf was obtained using the same spectrum. By providing the dimension of the cavity and the f_r of TE_{111} mode, the ε_r' and σ at f_r was calculated as $f_r = c/(2\pi\sqrt{\mu_r\varepsilon_r'})\sqrt{(p/a)^2 + (\pi/d)^2}$ and $\sigma = 2\pi\epsilon_0\epsilon_r'\Delta f$, where c is the speed of light in vacuum, Δf is the bandwidth of f_r, $p' = 1.8412$, the vacuum permittivity $\varepsilon_0 = 8.854 \times 10^{-12}\, F/m$, and relative permeability μ_r is assumed to be one in this study.

Result: The calculated ε_r' and σ of the dielectric composite with volume ratio of 0.8 at 126.5 MHz, 132.5 MHz, 297.5 MHz, 300 MHz, and 309.25 MHz are shown in Table 1. A comparison of electrical properties between $BaTiO_3$ suspension (v/v 0.35) and dielectric composite (v/v 0.8) at approximate 123 MHz and 300 MHz are shown Table 2.

Discussion: Both resonant cavities were tested with distilled water and the ε_r' measured on distilled water using these cavities were in 5% error, assuming $\varepsilon_r'[H_2O]=78$. A general expectation for electrical properties are that ε_r' drops and σ increases with a frequency increase. The results from this study agree with this expectation. There are several factors that could introduce errors in this study: 1) the accuracy of the cavity dimension measurement, 2) the assumption that the cavity was perfectly cylindrical, 3) the neglect of the spaces occupied by the measurement probes, 4) the assumption that barium titanate beads were uniform in size, and 5) the accuracy on the readouts of the f_r and their Δf. To avoid above errors, the cavity dimensions were taken from an average of several measurements. The cavities were built as perfectly cylindrical as possible and the shape of cavity walls are guaranteed by the material vendors. The 1-mm diameter of the barium titanate bead is not uniformly accurate by its manufacture process. Combining with the neglect of the spaces occupied by measurement probe, the distortion of the electromagnetic field distribution would be introduced in the cavity. But based on the results of identified resonant frequencies on different modes in the spectrum, this distortion was not significant and the effects on the final results should be small. Lastly, the readouts of the f_r and Δf have an error of less than 1 MHz, which could introduce an error as high as 8% in conductivity in the worst case.

Table 1: Electrical properties of $BaTiO_3$ dielectric composite

f_r [MHz]	*a* [mm]	*d* [mm]	ε_r'	Δf [MHz]	σ [S/m]
126.5	30.15	22.10±5	514.825	--	--
132.5	30.15	13.60±5	512.2479	12.21	0.3208
297.5	15.06	49.83±1	486.6209	38.25	1.0355
300	15.06	47.27±1	489.7301	39.5	1.0762
309.25	15.06	42.74±1	484.3426	42.5	1.1452

Table 2: Comparison of electrical properties

BaTiO3	f_r [MHz]	ε_r'	σ [S/m]
Powder/water slurry	~123	333.80	0.73
Bead/water composite	~123	514.83	0.32
Powder/water slurry	~300	318.66	0.97
Bead/water composite	~300	486.90	1.08

Figure 1: Cylindrical resonant cavities used in this study.

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