Design of High Frequency Volume Coil Using MTL Resonators: A Simple Solution to the RF Volume Coil Design at Ultra-High Magnetic Fields

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INTRODUCTION Microstrip transmission line (MTL) coil designs have been successfully used for high and ultra-high field MR applications (1-5). In this work, we propose a simple and efficient approach to designing high and ultra-high frequency RF coils. As an example, a 400-MHz MTL volume coil was designed and constructed. The prototype coils were also tuned and tested at an extremely high frequency up to 1.4 GHz for the coil size designed in this work.

METHOD The resonant frequency of a single MTL resonator can be derived as

$$f_r = \frac{2\pi Z_0^2 C_t C_{t1} - 1}{2\pi Z_0 (C_t + C_{t1})} \tan\left(\frac{2\pi l\sqrt{\varepsilon_{eff}}}{c} f_r\right)$$

where C_t and C_{t1} are the capacitance of the terminating capacitors connected at the two ends of the microstrip resonator as shown in Fig 1 and l is the length of the MTL resonator. In open-ended case, $C_t = C_{t1} = 0$. When N single MTL resonators (or MTL resonant elements) are vertically placed around a circle and electromagnetically coupled each other, it yields an MTL volume coil. This MTL volume coil satisfies Kirchhoff's Voltage Law and its current distribution in circumference follows the cosine function:

$$\begin{pmatrix} L - \frac{1}{\omega^2 C} & k_{12} & k_{13} & \cdots & k_{1N} \\ k_{12} & L - \frac{1}{\omega^2 C} & k_{23} & \cdots & k_{2N} \\ k_{13} & k_{23} & L - \frac{1}{\omega^2 C} & \cdots & k_{3N} \\ \vdots & \cdots & & \ddots & \vdots \\ k_{1N} & k_{2N} & k_{3N} & \cdots & L - \frac{1}{\omega^2 C} \end{pmatrix} \begin{pmatrix} \cos\frac{2\pi}{N}\cdot 0 \\ \cos\frac{2\pi}{N}\cdot 1 \\ \cos\frac{2\pi}{N}\cdot 2 \\ \vdots \\ \cos\frac{2\pi}{N}\cdot (N-1) \end{pmatrix} = 0$$

where k_{ij}'s are coupling coefficients between resonant elements i and j (i, j = 1, 2, 3, …,N and i ≠j). The resonant frequency of the MTL volume coil with N single MTL resonant elements can be derived from the above equation:

$$f_{volume} = \frac{\omega}{2\pi} = \frac{1}{\sqrt{1 + \frac{1}{L}\sum_{i=1}^{N-1} k_{1(i+1)} \cos\frac{2\pi}{N} i}} \cdot f_r$$

Based on the above, two MTL volume coils with different substrates were built and tested. The first MTL volume coil was built on an acrylic tube with dimensions of 6.3-cm O.D. by 5.7-cm I.D. by 8-cm length. The strip conductors of the 16 or 24 MTL resonant elements were 36 μm adhesive-backed copper tape with a width of 3-mm and they were simply taped on the inner surface of the acrylic tube equidistantly as shown photographically in Fig 2. The ground planes of the MTL resonant elements were formed by wrapping a single piece of 18-μm thick copper foil on the outer surface of the acrylic tube. Each MTL resonant element was an open-circuited transmission line resonator (no terminative capacitors or $C_t = C_{t1} = 0$). All the MTL resonant elements were coupled electro-magnetically which made the whole volume coil resonant in the multimode manner. With a similar building procedure, the second MTL volume coil was built on a Teflon tube (dimensions measured 7.0-cm O.D. by 6.4-cm I.D. by 8.0-cm length) with 16 MTL resonant elements. The length and width of its MTL resonant elements were the same as that of the acrylic coil. To lower its resonant frequency down to 400 MHz for MR imaging at 9.4T, 6-pF terminative capacitors were connected to each end of the MTL resonant elements. Because this coil was an unbalanced circuit, it can be connected directly to system through a matching capacitor. No need to have a balun. The B_1 field distribution of the coil was evaluated by using a 5-mm shielded sniffer with a HP 4396A network analyzer.

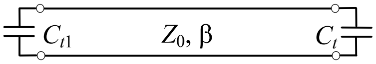

Fig.1 A single MTL resonator with terminative capacitors at two ends.

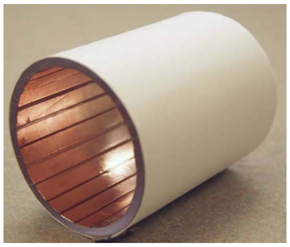

Fig.2 The prototype microstrip transmission line volume coil operating at ~1.2 GHz. It would be the simplest volume coil design with quadrature drive feature for such high resonant frequency.

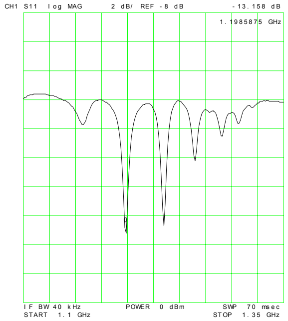

Fig. 3 The S_{11} plot of the 1.2 GHz MTL volume coil with 16 resonant elements. The multimodal resonance of this coil can be clearly identified. The second mode operating at ~1.2 GHz has a homogeneous B_1 distribution in the region of interest which usually is desirable for MR studies.

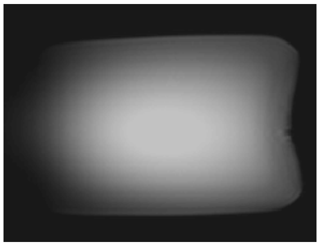

Fig. 4 water phantom image acquired using the MTL volume coil with Teflon substrate at 9.4 T. Dielectric resonance effect is observed due to the pure water phantom.

RESULTS The single MTL resonant element (open-circuited) with the acrylic substrate operated at 1.26 GHz. The resonant frequency of the prototype acrylic MTL volume coil with 16 MTL resonant elements was 1.2 GHz (1.16GHz with 24 MTL elements) as shown in Fig 3. From the S_{11} plot shown in Fig 3, the multimodal resonance behavior of this coil can be realized. The sniffer measurement showed that the second resonant mode have a homogeneous B_1 pattern in the region of interest. In the transverse plane of the coil center, the B_1 variation was measured to be within 1dB. Along the coil axis, the B_1 field pattern behaved similar to the primary resonance of a single λ/2 open-circuited MTL, i.e. stronger in the center and weaker on the two ends. The S_{21} measurement between the two quadrature ports indicated that the isolation between the two quadrature ports was greater than –25 dB. The resonant frequency of 16-element Teflon MTL volume coil was ~1.4GHz. With connection of 6pF-capacitors to the two ends of each MTL resonant element, the frequency of the Teflon MTL volume coil was dramatically dropped to the desired 400 MHz. A 1GHz-frequency-tuning range was achieved by the terminative capacitors of just 6-pF. The coils were well-matched to 50 Ω with only one serial-connected capacitor. Due to the confined B_1 field and unbalanced circuit of the microstrip transmission line, a reduced coil-cable interference and stable coil resonance was observed. The termination capacitors could also make B_1 distribution less inhomogeneous along coil's axis and save the unwanted electric fields on the two ends of the coil. Fig 4 shows a phantom image (a tap water bottle) acquired using the Teflon MTL volume coil at 9.4T. High signal intensity at the central area is related to the dielectric effect at high fields.

CONCLUSION This MTL volume coil design approach provides a simple and efficient solution for RF volume coil designs for ultra-high field MR applications. When tuned to GHz level, this coil can be potentially used for electron combined with EPR in rat Overhauser MRI (OMRI) applications *in vivo* (6).

REFERENCES 1) Zhang X, *et al*. *Magn Reson Med*, **46**: 443-450 (2001); 2) Zhang X, *et al*. *J Magn Reson*, **161**: 242-251 (2003); 3) Adriany G, *et al*, 11th annual meeting of ISMRM, 2002, p474; 4) Zhang X, *et al*, 9th annual meeting of ISMRM, 2001, 699; 5)Zhang X, *et al*, 10th annual meeting of ISMRM, 2002, 159; 6) Krishna MC, *et al*, *PNAS* USA 2002; **99**:2216-2221.

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