# Ring Structured RF Coils for Ultra-High Field MRI

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## Introduction

A conducting ring can resonate with mode such that one complete sine wave is around the ring. Out of the ring plane, this resonant structure can generate a transverse $B_1$ field that is useful for transmit and/or receive. While this field may not be uniform enough for low field MR systems, at ultra-high fields, when the object dominates the $B_1$ uniformity, it provides a new tool that can be used for new coil designs. RF coils made of one or more conducting rings can be used as surface or volume coils for proton T/R or T/SENSE, or double tuned for multi-nuclear applications. With proper ring and shield designs, coil transmit efficiency can be improved for practical use.

## Methods

Consider a conducting ring with the radius of r, one resonant mode is when a whole wavelength $\lambda$ travels along the ring. This mode generates a $B_1$-field parallel to the plane of the ring in regions above and beneath the ring. The resonant frequency is determined as $f \sim c/\lambda = c/(2\pi r)$, where c is the speed of light in free space. For a ring with radius r ~15cm, which is a typical radius of a head coil, the resonant frequency is f ~318MHz. It is possible to use this conducting ring for ultra-high field MRI, such as at 7T and above (≥300MHz).

As an example, we model a conducting ring with 15cm-radius and 1cm-width using a FDTD numerical method (XFDTD software package, Remcom, Inc., State College, PA) (see Figure 1a). We plot $B_1$-field vs. frequency at the position 12cm above the center of the ring. The resonant frequency corresponds to the frequency with the peak $B_1$-field. For the ring only, the first mode is at 330MHz (Figure 2, blue curve). The $B_1$-field spectrum is very broad with a very low Q-factor. Such a ring coil is not efficient for transmitting at ultra-high fields. However, when we place a flat shield with open access 2cm below the conducting ring (see Figure 2b), $B_1$-field spectrum becomes narrower (Figure 2, red curve). The flat shield reduces the radiation loss in one direction and increases the Q-factor. The resonant frequency is also shifted lower to 305MHz. Further more, when a 17cm-radius cylindrical shield is placed to surround the conducting ring and the flat shield (see Figure 1c), peak $B_1$-field is dramatically increased (Figure 2, black curve). The cylindrical shield shifts the resonant frequency further lower to 290MHz. Based on the combined resonant structure as Figure 1c, it is possible to build a transmit or transmit/receive head coil for MRI at 7T.

There are several factors that can affect the resonant frequency of the ring structured resonator: radius of the ring, the distance between the ring and the flat shield, and the diameter and length of the cylindrical shield. The ring can have an axial width or be flat. When a flat ring is placed above a flat shield with a dielectric substrate sandwiched between them, a microstrip transmission line (MTL) ring is formed. Furthermore, gaps can be opened along the conducting ring, where ring capacitors can be placed in these gaps to tune the resonance frequency to a desired value. Particularly, when the number of capacitors is an integer multiple of 4, and the capacitors are evenly distributed around the ring, the ring behaves like the end ring of a birdcage coil. Useful transverse $B_1$-field is generated in the enclosed space of the cylindrical shield when one complete sine wave is around the ring.

To understand the performance of a coil based on the ring resonator, we model a head-sized volume coil made of two MTL rings placed at each end of a RF shield (see Figure 3). The volume coil has the shield diameter of 35cm and shield length of 23cm. The MTL ring has a conducting width of 1cm, thickness of 1cm and diameter of 29cm. 16 ring capacitors are evenly distributed in each ring. For comparison, a conventional 16-element shielded high-pass birdcage volume coil, which has the coil diameter of 34cm and length of 24cm, is also modeled. A 20cm-diameter spherical phantom ($\sigma = 0.86$S/m, $\varepsilon_r = 80$) is use to load the two coils. Both coils are tuned to the resonant frequency of 298MHz ($^1$H at 7T). The ring-based volume coil is excited by using 1-port feed at each top and bottom MTL ring with opposite voltage source and 90-degree phase difference, which is equivalent to quadrature feed. The birdcage coil is 2-port quadrature feed. $|B_1^+|$-field is calculated in three central orthogonal slices of the phantom [1]. Transmit efficiency is also calculated as $|B_1^+|_{ave}/P_{abs}^{1/2}$, where $|B_1^+|_{ave}$ is the average $|B_1^+|$ over the central transverse slice of the phantom and $P_{abs}$ is the total absorbed power.

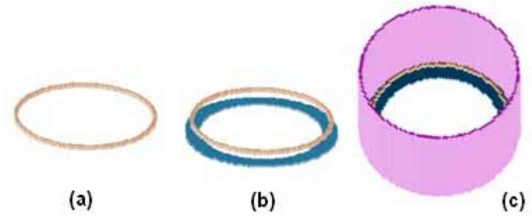

**Figure 1. (a) a conducting ring; (b) a ring with a flat shield beneath; (c) a ring with a flat shield and a cylinder shield.**

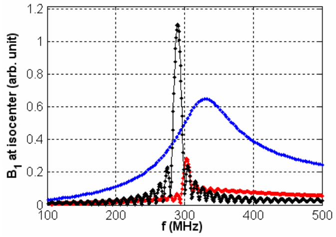

**Figure 2. $|B_1^+|$ vs. f spectrum.**

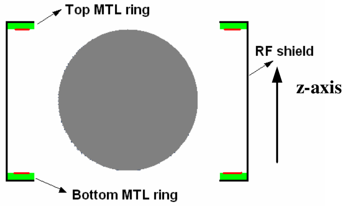

**Figure 3. A head-sized volume coil made of two MTL rings and a cylindrical shield, loaded with a spherical phantom.**

## Results

In Figure 4, we show the normalized $|B_1^+|/|B_1^+|_{ave}$ in three central slices of the spherical phantom for the two modeled volume coils. As seen, $|B_1^+|$-field distribution inside the phantom is almost identical due to the dominant effect of the load. In Table 1, we list the calculated $|B_1^+|$-field standard deviation (no unit) in three slices and the transmit efficiency. It shows that, the ring-based volume coil has almost equal $|B_1^+|$ uniformity as the birdcage coil. The transmit efficiency is 10% lower than that of the birdcage coil. This is understandable since the ring-based volume coil resonates like a birdcage coil except there is no $|B_1^+|$-field contribution from the rungs. However, the lack of rungs can provide a large useful space inside the coil, which makes the ring-based volume coil ideal for transmit and to work together with other receive coils. A SENSE receive coil could be easily fit inside this volume transmit coil for high sensitivity SENSE imaging.

## Conclusions

We proposed a new class of RF coils for ultra-high field MRI based on one or more ring resonators. The modeling of a two-ring based head-sized volume coil at 7T reveals similar $|B_1^+|$ uniformity as a birdcage volume coil, though a little less coil efficiency. The disadvantage of the ring-based volume coils is the likelihood of having higher SAR than that of a birdcage coil due to the concentration of large E-field near the rings. However, the advantage of such coils is the large useful space inside the coils which are suitable for work with SENSE receive coils. Another new application is that, a TEM coil, which has only rungs, can be integrated inside a ring-based volume coil to form a multi-nuclear coil. The ring resonators can be tuned to the proton frequency for $^1$H decoupling, while the inside TEM coil can be tuned to other nuclear frequencies such as $^{31}$P or $^{13}$C. Since there is no ring current in the TEM coil, the coupling between the ring resonators and the TEM rungs are minimum, which makes it a perfect double-tuned T/R coil. Further more, since the TEM coil can by itself be double-tuned using the interleaving rungs [2], a triple-tuned T/R coil is also possible.

## References

[1]. D. I. Hoult, Concepts Magn. Reson. 12 (4): 173-187 (2000).
[2]. J. T. Vaughan, et. al., MRM.32: 206–218 (1994).

| Volume coils | $\lvert B_1^+\rvert$ deviation | | | Transmit efficiency |
|---|---|---|---|---|
| | T | C | S | |
| 2-MTL based | 0.20 | 0.34 | 0.34 | 0.45μT/W$^{1/2}$ |
| Birdcage | 0.22 | 0.32 | 0.33 | 0.50μT/W$^{1/2}$ |

**Table 1. Comparison between a two-ring based volume coil and a birdcage volume coil at 7T.**

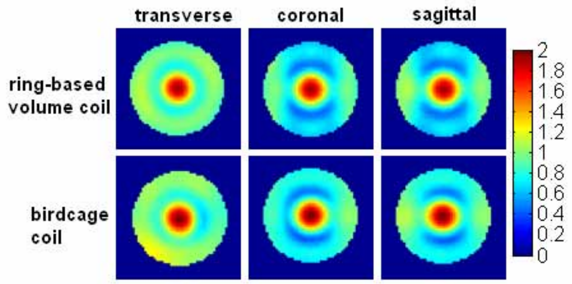

**Figure 4. Calculated $|B_1^+|/|B_1^+|_{ave}$ in a sphere phantom.**