FATIMA SEGHIRA | Engineer   NADIA BENABDALLAH | Doctor   NASREDDINE BENAHMED | Doctor
University of Tlemcen, P.O. Box 119 (13000), Tlemcen, Algeria

MRI Probe Offers High-Q Analysis

This high-Q MRI probe was designed with the aid of method-of-moments (MoM) computer simulations and constructed with coupled coaxial transmission lines for use at 433 MHz.

Magnetic resonance imaging (MRI) is a powerful tool for medical research—specifically, for studying the condition of internal organs in humans and animals. To construct an MRI probe for animal research, the characteristics of a transverse-electromagnetic (TEM) coil were analyzed and optimized using computer-simulation software and method-of-moments (MoM) computer-simulation approaches. An effective model for the MRI design was subsequently developed that optimizes the frequency response of the MRI probe at 433 MHz.
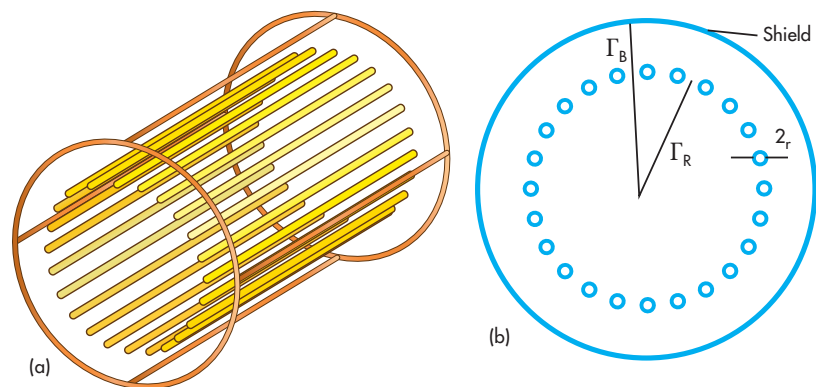
The MRI probe was designed using n-element coupled coaxial lines, with n = 24, 16, 12, and 8. As a reference, the MRI probe design was compared to the shielded birdcage TEM resonators commonly used for MRI probes. Numerical calculations for the probe were carried out using the MoM approach with LIN-PAR for Windows (Matrix Parameters for Multiconductor Transmission Lines, or MTL) two-dimensional (2D) analysis software. It was used to perform numerical evaluation of the quasistatic matrices ([L], [C], [R], and [G]) representing the multiconductor transmission lines forming the MRI probe.
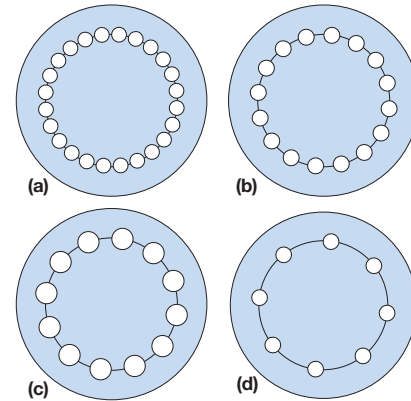
The S_{11} response of the MRI probe was optimized for 433 MHz using software tools based on MTL with MathWorks' (www.mathworks.com) MATLAB analysis software. The approach permitted evaluation of the probe's unloaded quality factor (Q). The impact of such parameters as the radius of the coaxial transmission lines (TLs) and the numbers of elements were studied in the analysis.

An RF coil is an essential component in an MRI system. Many different types of RF coils have been developed for MRI, with each generation offering some performance improvements. Prior to the introduction of the TEM resonator in 1994,[1] the birdcage resonator was the most widely used type of RF coil for MRI probes.[2] A TEM resonator has several advantages over a birdcage coil, including improved excitation field homogeneity, high quality factor (Q), and ease of tuning.[3-5] The first descriptions of TEM resonator structures appeared in several patents, which provided descriptions of TEM resonator structures.[6,7]

Other work on TEM resonators focused on modeling the resonators using TL concepts. In one approach, the resonator consisted of a section of coaxial TL terminated by capacitors.[1] A lumped-element approach with conductors operating as inductors with mutual coupling and capacitors was used to model a TEM resonator at 143 MHz.[8] In addition, a simplified coupled TL model of a TEM resonator was developed.[9,10] Using the boundary element method (BEM), researchers developed a 12-element lumped-element

1. These two views show (a) a detailed illustration of the coupled coaxial line TEM-resonator and (b) its key parameters.
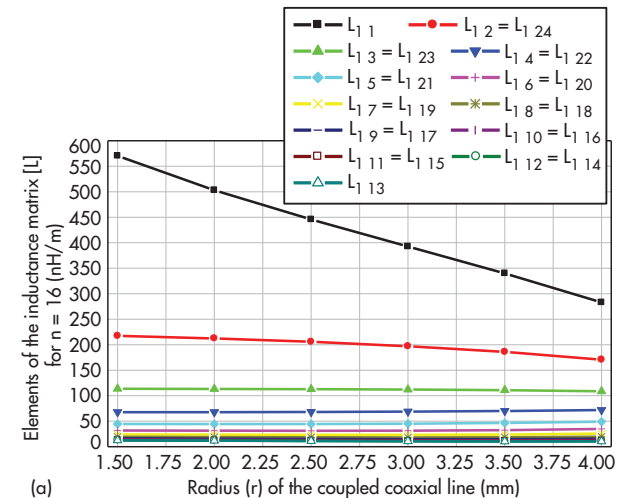

2. Augmentation of the charged surfaces of the coupled coaxial-line TEM resonator is shown for: (a) n = 24, (b) n = 16, (c) n = 12, and (d) n = 8.

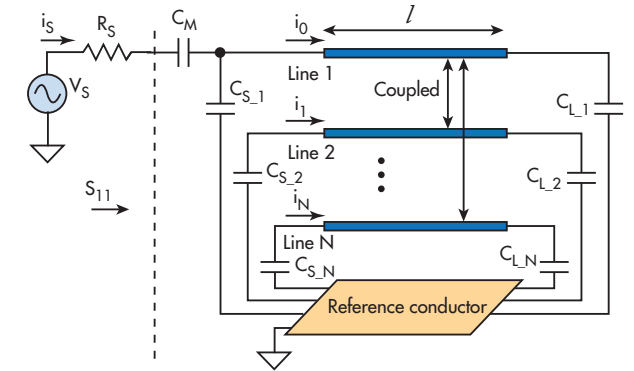TEM resonator model at 200 MHz. Note that this model is invalid at higher frequencies.[11]

In previous work by the current authors,[12] a numerical tool was demonstrated based on the finite element method (FEM). Its purpose was to analyze an eight-element unloaded coaxial line transverse electromagnetic (TEM) resonator and design an MRI-probe for studies at 4.7 T. That MRI probe has −62.81 dB minimum reflection and Q of 260 at approximately 200 MHz.

To build upon that work, the current studies describe a model for multiple-conductor TLs transmission lines. This includes the exact calculation of the primary parameter matrices ([L] and [C]) from ref. 12, adapted to full potential using MoM via a LINPAR for MS Windows analysis environment.[13] The current reported efforts were applied to characterize the behavior of a TEM resonator at a Larmor frequency of 433 MHz for a high-Q (20-dB) MRI probe. A probe was designed and developed by varying the number and the radius of the n-elements coupled coaxial lines (n = 24, 16, 12, 8), used to form the MRI probe.

Figure 1 shows a TEM resonator. It consists of a number (n) of inner circular conductors (coaxial lines) distributed in a cylindrical pattern (2rR) in a particular diameter and connected
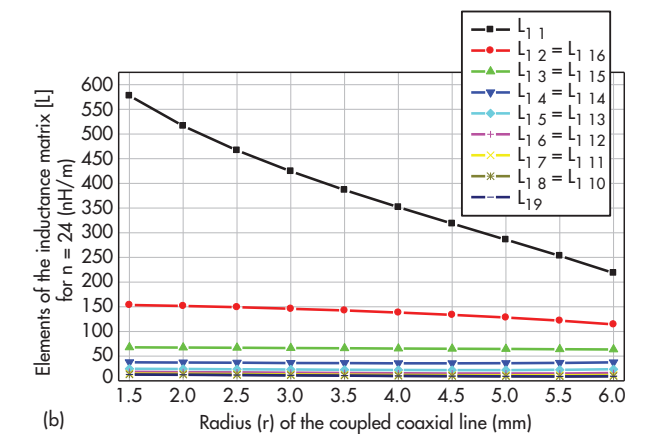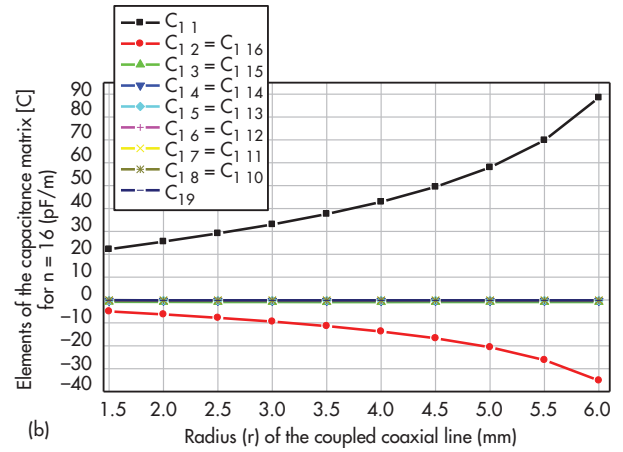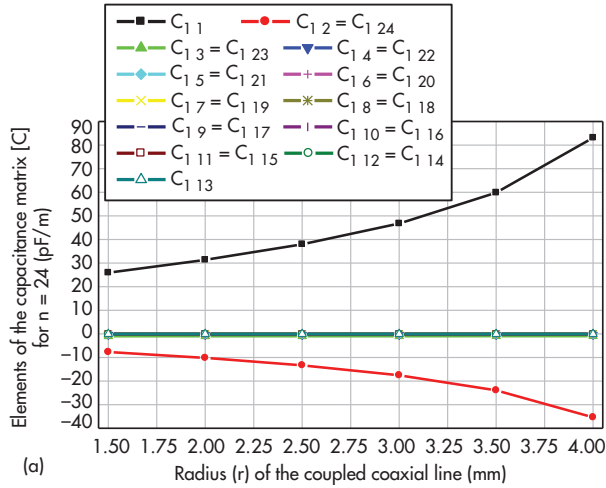

3. This schematic circuit shows how the MRI probe uses an n-element coupled coaxial line TEM-resonator.

with capacitors to a cylindrical outer shield of 2rB diameter.[11,12] The length of the resonator is sized with respect to the wavelength (of 433 MHz) in free space, λ_0 = 17.32 cm. To evaluate the [L] and [C] matrices in a LINPAR environment, it was necessary to estimate the cross-section of the MRI resonator and all relevant dielectric characteristics using general programs in PASCAL. *Figure 2* shows the segmentation of the charged surfaces of the n-element coupled coaxial MRI resonator using LINPAR for WINDOWS software.

Numerical analysis was performed *(Fig. 2)* to determine the electromagnetic (EM) parameters for the [L] and [C] matrices of the TEM resonator. Once these parameters were calculated, it was possible to estimate the resonance spectrum (S_{11} response) of the MRI probe based on a TLM approach *(Fig. 3)*.[14] The MRI probe consists of shielded coupled coaxial lines with length l, matching capacitor (C_M), and terminating capacitors C_{Si} and C_{Li} (where i = 1…n) *(Fig. 3)*. The unloaded quality factor (Q = −20 dB) of the MRI system can be deduced from a reflection parameter (S_{11}) sweep with frequency:[11,12]

$$Q_{-20\,dB} = f_r / (f_u - f_l) \quad (1)$$

4. These plots show the impact of radius, r, of the coupled coaxial conductor on the elements of the inductance matrix [L] for (a) n = 24 and (b) n = 16.

5. These plots present the impact of radius, r, of the coupled coaxial conductor on the elements of the capacitance matrix [C] for (a) n = 24 and (b) n = 16.

where:

f_r = the resonance frequency of the probe,

f_u = the −20-dB upper frequency limit of the probe

f_l = the −20-dB lower frequency limit of the probe

Based on previous work that employed the MoM approach, f,[15-17] a software program was created to calculate the electromagnetic parameters of the MRI probe using n-element coupled coaxial lines. Every parameter is strongly dependent upon the resonator features and properties of the sample. Simulations conducted with this software indicate whether or not fabrication of a particular MRI probe design will ultimately be practical.
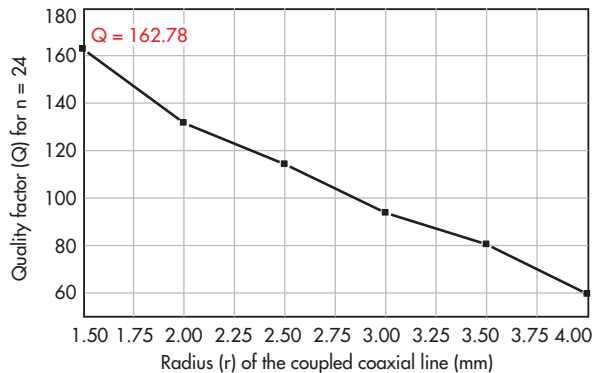
To design high-Q probes operating at 433 MHz, the structure of *Fig. 2* was studied with n inner circular conductors (n = 24, 16, 12, 8) and coaxial radius r, and having the following geometric parameters:

Outer cylinder radius, r_B, of 52.5 mm;

Inner cylinder radius, r_R, of 36.25 mm;

Conductivity, σ, of $5.8 \times 10^7 \, \Sigma/m$; and

Relative dielectric constant, $σ_r$, of unity (1).

*Figures 4 and 5* show the impact of r values for the probe's circular conductors on the values of the elements of the inductance matrix and on the values of the elements of the capacitance matrix of the TEM-resonator for 24- and 16-element coupled coaxial lines, respectively. *Figures 6 and 7* shows variations of Q (−20 dB) for n = 24 and n = 16, as calculated by Eq. 1.

Each of the two 24- and 16-element coupled coaxial MRI probes presents a higher Q (−20 dB) value for r = 1.5 mm and 2.0 mm, respectively. Similarly, a study was made of the influence of r on the Q of TEM MRI probes with 12- and 8-element coupled coaxial lines. The highest Q (−20 dB) value was found for n = 12 for a radius (r) of 2.5 mm. The highest Q (−20 dB) value for an n = 12 probe was found for a radius (r) of 1.5 mm.

Tables 1 and 2 (all tables are in the online version of this story at mwrf.com) provide results for MRI probes designed for the Industrial-Scientific-Medical (ISM) band at 433 MHz. *Table 1* contains the values required to construct for a probe's [L] and [C] matrices.[11,12,18] *Table 3* contains features for optimum MRI probe configurations operating at 433 MHz with n-element coupled coaxial lines based on the design configuration of *Fig. 3*.

6. These plots illustrate the influence of r on the Q of a 24-coupled-element coaxial MRI-probe.
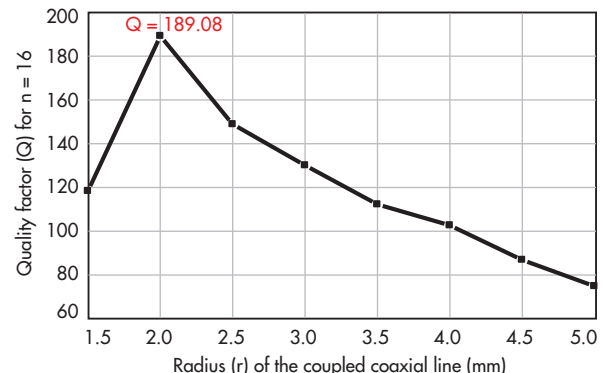
7. These plots show the influence of r on the Q of a 16-coupled-element coaxial MRI probe.
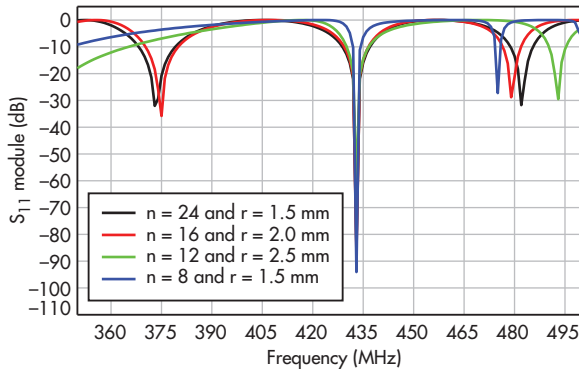
8. These curves show scattering parameters for optimized MRI probes using n-coupled TEM coaxial lines designed for operation at 433 MHz.

Figure 8 shows simulated frequency responses with variations of the reflection coefficient (S_{11}) at the input of these optimum MRI probes designs. These frequency responses for MRI probes with n-coupled TEM coaxial lines exhibit minimum values around a chosen working frequency—i.e., 433 MHz. The minimum reflection for this MRI probe design is extremely low, reaching −94.06 dB for n = 8.
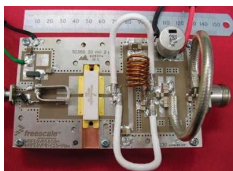
In summary, these studies have revealed the impact of the number of coupled lines and the radius of the probe structure on achieving high-Q performance with a TEM MRI probe structure. Optimization was performed by varying the number of elements and the radius.

It was discovered that for a TEM MRI probe with 8-element coupled coaxial lines and radius, r, of 1.5 mm, a matching capacitor (C_M) of 18.59 pF and terminating capacitors C_{Si} and C_{Li}—both with a value of 1.61 pF, minimum reflection of −94.06 dB, and Q of 244.63—were measured. Consequently, the design and analysis approach made it possible to optimize high-Q TEM MRI probes for utilization in the ISM band at 433 MHz. **mw**

REFERENCES
1. J.T. Vaughan, H.P. Hetherington, J.O. Out, J.W. Pan, and G.M. Pohost, "High frequency volume coils for clinical NMR imaging and spectroscopy," Magnetic Resonance in Medicine, Vol. 32, 1994, pp. 206-218.
2. C.E. Hayes, W. A. Edelstein, J.F. Schenck, O.M. Mueller, and M. Eash, "An efficient highly homogeneous radio-frequency coil for whole-body NMR imaging at 1.5 T," Journal of Magnetic Resonance Vol. 63, 1985, pp. 622-8.
3. T.S. Ibrahim, "Design of radio-frequency coils for magnetic resonance imaging applications: A computational electromagnetic approach," doctoral dissertation, The Ohio State University, Columbus, OH, 2002.
4. G. Adriany, J.T. Vaughan, P. Andersen, H. Merkle, M. Garwood, and K. Ugurbil, "Comparison between head volume coils at high field," in Proceedings of the 3rd SMR and 12th ESMRMB annual meeting, Nice, France, 1995, p. 971.
5. J.W. Pan, J.T. Vaughan, R.I. Kuzniecky, G.M. Pohost, and H.P. Hetherington, "High resolution neuroimaging at 4.1 T," Magnetic Resonance Imaging, Vol. 13, 1995, pp. 915-921.
6. P. Röschmann, "High-frequency coil system for a magnetic resonance imaging apparatus," U.S. Patent No. 4,746,866, 1988.
7. J.F. Bridges, "Cavity resonator with improved magnetic field uniformity for high frequency operation and reduced dielectric heating in NMR imaging devices," U.S. Patent No. 4,751,464, 1988.
8. J. Tropp, "Mutual inductance in the birdcage resonator," Journal of Magnetic Resonance, Vol. 126, 1997, pp. 9-17.
9. P. Röschmann, "Analysis of mode spectra in cylindrical N-conductor transmission line resonators with expansion to low-, high- and band-pass birdcage structures," in Proceedings of the 3rd Annual Meeting of the International Society of Magnetic Resonance in Medicine, Nice, France, 1995. p.1,000.
10. G.C. Chingas and N. Zhang, "Design strategy for TEM high field resonators," in Proceedings of the 4th Annual Meeting of the International Society of Magnetic Resonance in Medicine, New York, NY, 1996. p. 1,426.
11. G. Bogdanov and R. Ludwig, "A Coupled microstrip line transverse electromagnetic resonator model for high-field magnetic resonance imaging," Magnetic Resonance in Medicine, Vol. 47, 2002, pp. 579-593.
12. N. Benahmed, M. Feham, and M. Khelif, "Analysis and design of a coupled coaxial line TEM resonator for magnetic resonance imaging," Journal of Physics in Medicine and Biology, Vol. 51, 2006, pp. 2,093-2,099.
13. A.R. Djordjevic, M.B. Bazdar, and T.K. Sarkan, LINPAR for Windows: Matrix parameters of multiconductor transmission lines, Software and user's manual, Artech House, Norwood, MA, 1999.
14. R. Bouhmidi, N. Benahmed, N. Benabdallah, K. Aliane, S.M. Meriah, and F.T. Bendimerad, "Optimization of a Transverse Electromagnetic Resonator for Magnetic Resonance Imaging at High Field of 9.4 T," 2012 Spring World Congress on Engineering and Technology (SCET), 2012.
15. N. Benabdallah, N. Benahmed, and B. Benyoucef, "Analyzing a resonator for MRI applications," Microwaves & RF, Vol. 46, No 11, 2007, pp.92-98.
16. N. Benabdallah, N. Benahmed, B. Benyoucef, R. Bouhmidi, and M. Khelif, "EM analysis of the slotted-tube resonator with circular cross section for MRI applications," Journal of Physics in Medicine and Biology, Vol. 52, 2007, pp. 4,943-4,952.
17. K. Aliane, N. Benahmed, N. Benabdallah, F.T. Bendimerad, and A. Benkaddour, "Resonators Support UHF MRI Systems," Microwaves & RF, Vol. 51, No. 4, pp. 84-92, 2012.
18. R. Bouhmidi, N. Benabdallah, N. Benahmed, and M. Khelif, "Design coupled microstrip resonators for MRI," Microwaves & RF, Vol. 46, No. 3, 2007, pp. 59-66.