Volume coil for MRI based on metasurface

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***Abstract*—Conventional birdcages are radiofrequency coils for magnetic resonance imaging (MRI) that consists of closed, right-hand or left-hand transmission lines with sub-wavelength periodicity. Analyzing these coils in terms of metasurface leads to engineering their properties as will and achieve original applications. To that end, we control the intrinsic impedance and the phase shift of each unit cell. As a demonstration, we use this concept to break the periodicity of the structure in order to provide a wide aperture allowing an easy access to the region of interest. We show that this coil, that we have called opencage, achieves good isolation between two driving ports and high homogeneity of the magnetic field. The results of measurements realized with phantom and in-vivo in MRI are presented. These results have confirmed the good performances predicted by our theoretical approach and the numerical calculations. This opencage coil could be used for many applications such as pre-clinical imaging of small animals or human head clinical imaging.**

***Index Terms*— Opencage, Birdcage, LHTL, MRI, RF coils.**

I. INTRODUCTION

Magnetic resonance imaging (MRI) is a unique apparatus that allows to gather biological information about human or animal tissue. This principle is based on probing the Larmor precession of some nuclei under the strong static magnetic field. Nuclei of hydrogen (^1H) allows to obtain information about any part of the body. This process requires specific antenna called radiofrequency (RF) coils. These devices are used to excite the nuclei spins and receive back their echoes. One of the main RF coil used in MRI is the birdcage coil [1],[2]. This coil provide homogeneous signal in the whole volume, the region-of-interest (ROI). A birdcage can be seen as a circular metallic ladder closed on itself, the magnetic field being generated by the current in the legs (or treads).

In certain applications the birdcage coil is not convenient to use due to a short distance between neighbor legs. This short distance can block the access to the sample that can be an issue for some medical applications that require an access. A conventional loop coil can be used for that task. The disadvantage of using a loop is a smaller field of view (FOV) compared to a volume coil such as a birdcage.

This problem can be resolved by breaking the periodicity of the birdcage coil in order to provide a wide aperture allowing the access to the ROI.

A previous work successfully broke the periodicity of a birdcage to build elliptical birdcage [3]. The drawback of this approach is that the characteristic impedance and the phase on each leg (unit cell) are not be assessed explicitly making it difficult to generalize.

This can be done by considering the birdcage coil as a closed metasurface based transmission line, in other words, as a metacage. Thereby, different configurations of the legs of the metacage, that could be required by certain applications such as small animals imaging or imaging of a human head, can be achieved. The approach is based on impedance matching and unit-cell phase adjusting that enables the engineering of the geometry and the characteristics of metacages. We use this approach to increase the distance between two neighbored legs of the birdcage in required area. We show that with such structure, that we have called opencage, it is possible to provide a wide access to the ROI. A demonstration of the opencage made for the ultra-high MRI at 7T for small animal imaging is presented.

II. OPENCAGE DESIGN

A birdcage coil can be described by the transmission line (TL) theory. For a high-pass birdcage with a number N of legs, the equivalent TL is a closed array of N unit cells. Each unit cell is composed of a parallel inductance L_i, a serial inductance L_{ring} and a serial capacitance C_i. The inductance L_i is the effective inductance of the leg while the L_{ring} is the effective inductance of the ring. The capacitance C_i the capacitance inserted on the both end rings. The effective inductance of the leg is mainly given by the sum of the self-inductance of one leg and the mutual inductance between legs that can be calculated using approximations of mutual coupling of several thin filaments explained in the references [4],[5],[6]. Similar approach can be applied for the effective inductance of the ring.

In this work we propose to design an opencage with of 6 legs as illustrated in Fig. 1a. We propose to use a structure of 4 legs on the bottom side that provide 45^{o} on each cell. Two legs are then used in the top side to provide 90^{o} on each cell. The electrical phase shift between the legs should correspond to the geometrical one. The total phase shift after one loop should be equal to 360^{o} leading to the fundamental mode that generate an homogeneous circularly polarized magnetic field.

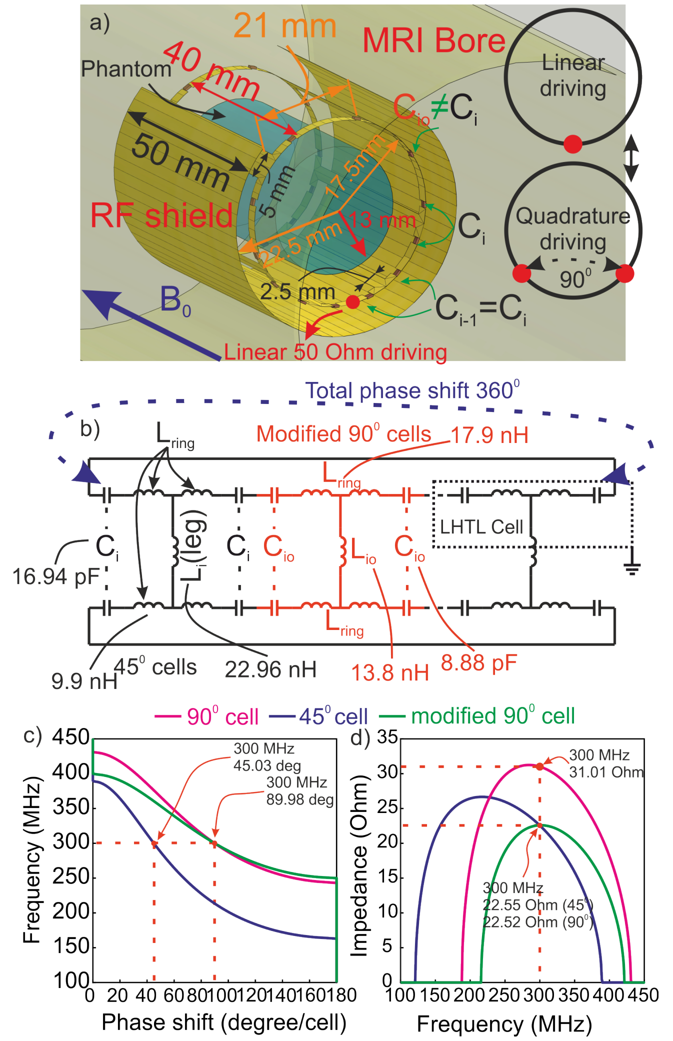

Fig. 1. The proposed opencage composed of 6 legs: (a) the design of the opencage. (b) The equivalent circuit of the considering structure. (c) Calculated dispersion diagram of the several LHTL cells. (d) Calculated characteristic impedance.

It is obvious that characteristic impedance of the considering cells has to be the same to avoid miss-matching reflections.

The design of the opencage can be achieved by using the transmission matrix approach [7]. By computing eigenvalues and eigenvectors of the transmission matrix for the considered unit cells (Fig. 1b) the characteristic impedance and the phase shift can be found. The calculated phase shift and the characteristic impedance of several LHTL with different values of capacitance and inductance are presented in Fig. 1c and d. Indeed, the values of the inductance and the capacitance of the cell have to be modified in order to obtain simultaneously the required phase shift and the impedance matching. In our configuration, to maintain these two conditions, the effective inductance (L_{io}) of the modified leg has to be changed from 19 nH to 13.8 nH, while the effective inductance of the ring can be kept to 17.9 nH. The capacitance (C_{io}) has to be increased from 7.63 pF up to 8.88 pF compared to the initial value for the conventional 90° cells. The inductance of the leg is mainly imposed by the width of the leg. To achieve the proper inductance of the modified legs, the initial width (2.5 mm) has to be doubled. The values for the 45° cells to get the characteristic impedance and the phase are the following: $L_i = 22.96$ nH, $L_{ring} = 9.9$ nH, $C_i = 16.94$ pF.

III. Simulations

The opencage has been tested numerically using the Frequency Domain Solver of the commercial software CST Microwave Studio 2018. The opencage is driven by two 50 Ohm ports to create a circular polarized field. The ports are placed in parallel for the two capacitors to form 90° angle between each other (quadrature driving in Fig. 1a). A shield without any windows is used to avoid parasitic effect. The opencage is loaded by the homogenous 105mm-long cylindrical phantom ($\epsilon = 45.3$ and $\sigma = 0.87$ S/m.). Its radius equals 13 mm. The phantom is placed inside the coil (Fig. 1a). Moreover, the whole setup is placed inside a long (1000 mm) metallic cylinder of diameter 90 mm which correspond to the MRI bore.

The capacitance in the opencage is slightly scaled to tune the coil at 300.1 MHz (Fig. 2a), in addition, in the intermediate area (connecting of 45° and 90° cells) the capacitance has to be doubled. At this frequency the coil can be matched, meantime the isolation level S_{12} can be very high due to the proper values of the adjusted inductance and capacitance that provides as expected a phase shift of 90°. Here the isolation level is almost equal to -20 dB. The circularly polarized magnetic field in the transverse plane B_1 is clearly observed at this frequency. Indeed, the observed magnetic field B_1^+ is maximum (Fig. 2b) and the counter-rotating field B_1^- is minimum (Fig. 2c) in the ROI. This effect indicates the effectiveness of the approach of the metasurface engineering.

IV. Prototype

The prototype of the opencage is presented in Fig. 3a. The frame of the opencage is printed using 3d printer. The legs and the rings are made of a copper tape on the frame. Its thickness is 0.035 mm. The opencage is connected through a cable trap to the preclinical MRI scanner Bruker PharmaScan 7T. Two nonmagnetic tunable capacitors are used for the tuning and matching of the coil [8]. Of course all the components are compatible with the strong magnetic field (7 Tesla). Here, one of the tunable capacitor replaces a fixed one for slightly correcting the resonant frequency of the coil (tuning). The other one is placed in serial to the feeding line to achieve the proper matching level ($S_{11} < 20$ dB). There is only one excitation port. Indeed, this linear excitation is preferable for the small animal imaging due to the technical difficulties of connecting the two channels to the used MRI system.

V. Phantom Imaging

In the experiment, the opencage is loaded with a container filled with a liquid phantom. The dimension and the material

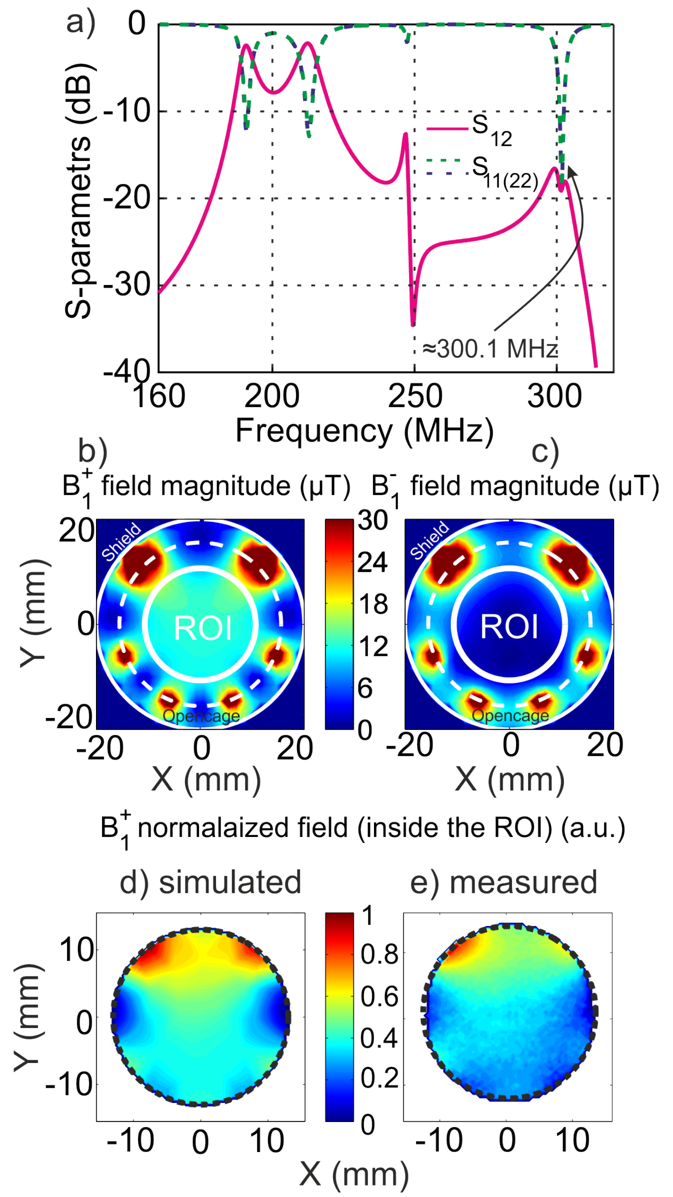

Fig. 2. The results of the numerical simulations. (a) The S parameters of the 2 ports. The opencage is tuned and matched at 300.1 MHz. (b) B_1^+ (right circularly polarized magnetic field component) field inside the RF shield of the opencage. (c) B_1^- (left circularly polarized magnetic field component). (d) Simulated and (e) measured, respectively, field B_1^+ of the single port driven opencage inside the ROI.

properties of the phantom are the same as in the numerical study. An original sequence is used to directly estimate B_1^+ field. The result is shown on Fig. 2e. To compare with, a simulation with a linear (single port) simulation has been performed (see Fig. 2d). The same trend can be observed at both patterns that indicates on the right choice of the mode in the experiment. Here, the B_1 field pattern of a birdcage mode are slightly perturbed due to the linear excitation and the gap made in the shield. This gap coincides with the window between the two modified 90^o cells. As it is mentioned previously, this opening can be used to get an easy access to the sample.

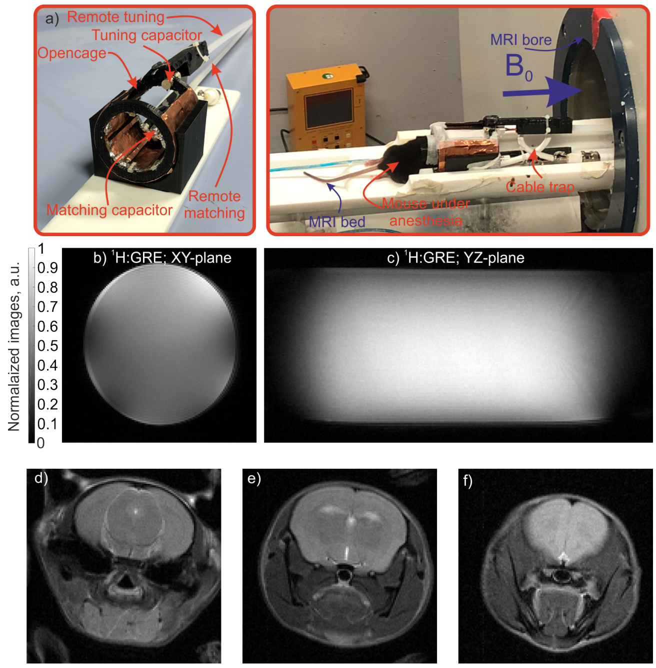

Fig. 3. The experimental validation of the proposed concept: (a) the prototype of opencage placed in the MRI bed. Transverse (b) and coronal (c) images of the phantom. Three $in-vivo$ transverse cross-sections (d, e, f) images of the brain of the mouse.

Several images of the phantom have been acquired (Fig. 3b and c) using conventional gradient-echo sequence (GRE). The opencage demonstrates high homogeneity of signal in the whole ROI. Here, the field of view is equal to 32 mm·32 mm·54 mm with size of voxel 25 mm^3. The acquired images of the phantom strongly correspond to the pattern of B_1^+ field (Fig. 2e). Indeed the four small regions at the coil bottom where field is enhanced near the legs are clearly visible on Figs. 3b and 2e.

VI. In-vivo imaging

The opencage is capable to scan half of the body of a mouse. The field of view provided by the opencage is broad enough to cover the full head of a small animal. Here the spin echo sequence is used with anisotropic voxel 0.125 mm^2 $\cdot$ 1mm, the FOV is 16 mm·16 mm·20 mm. Three cross-section of the mouse head are shown on Figs. 3d, e and f. The MRI image is homogeneous and the level of noise is low. The opencage demonstrates suitable homogeneity in a broad FOV that can be useful in real preclinical MRI applications with small animals.

VII. Conclusion

We have presented the concept of metacage radiofrequency coil for MRI that consists of metasurface based birdcage. We have developed an approach for the design of such metacages. This approach has been used to design an original coil, the so-called opencage, that provides a wide access to the region of interest. A demonstration of this opencage has been proposed for a preclinical MRI of small animals at 7 Tesla. We have shown analytically and numerically that the proposed coil achieves suitable homogeneity of B_1^+ field in a broad field of view. The experimental demonstration of the opencage in the preclinical MRI scanner has validated our approach. The concept of metacage could be adapted to different MRI applications.

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