Tunable all-dielectric RF-coils for magnetic resonance microscopy

S. Kurdjumov(1), M. A.C. Moussu(2,3), L. Ciobanu(4), E. Nenasheva(5), B. Djemai(4), M. Dubois(2), A. Webb(6), S. Enoch(2), P. Belov(1), R. Abdeddaim(2), and S. Glybovski*(1)

(1) ITMO University, 197101 St. Petersburg, Russia, s.glybovski@metalab.ifmo.ru
(2) Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, 13013 Marseille, France
(3) Multiwave Innovation SAS, Hotel Technoptic, 2 rue Marc Donadille, 13453 Marseille, France
(4) DRF/I2BM/Neurospin/UNIRS, 91191 Gif-sur-Yvette Cedex, France
(5) Ceramics Co.Ltd, 10, Kurchatova St., Saint-Petersburg, 194223, Russia
(6) Department of Radiology, C.J. Gorter Center for High Field MRI,
Leiden University Medical Center, Leiden, The Netherlands

Magnetic Resonance Microscopy (MRM) is a specialized imaging technique for visualization of samples with tiny structural details with dimensions of less than 100 µm with an extremely high resolution (voxel dimensions are typically less than 100 µm). However, in practice it is limited by the signal-to-noise ratio (SNR) of the MRM setup and can be insufficient for the required visualization resolution. In order to increase SNR as high as possible, the constant magnetic field B_0 of the MR system should be ultra high (7-21 T). Averaging of obtained images can also improve the SNR, increasing, however the overall scan time. In biomedical applications the scan time is limited by the lifetime of a biological sample. Therefore, any methods to increase SNR for the given B_0 and the scan time are of a great interest in MRM applications.

Typically, tiny wire loops (surface microcoils) and metal solenoidal coils (volumetric probes) are used in MRM both for transmission and reception [1]. Though they have formed the main work set of radiofrequency (RF) coils for MRM, their SNR is limited by the intrinsic losses. In the case of the solenoid coil, losses come from the finite conductivity of wire windings as well as from the lumped capacitors used for tuning the solenoid to the operational frequency of the scanner and matching the input impedance of the solenoid to 50 Ohm. Furthermore, the solenoidal coils create conservative electric field inside the sample, which also reduces the loaded quality factor Q and, therefore, SNR.

An alternative recently proposed approach is using high-permittivity dielectric resonators as transceive RF coils in MRM [2]. Due to high permittivity of the material of these coils (commercially available materials $CaTiO_3$ and $Ba(Sr)TiO_3$) the electric field is mostly concentrated in the resonator while the magnetic field is located inside the sample being scanned [3,4]. These RF coils demonstrate better transmit efficiency and SNR in the conditions of MRM than the conventional solenoidal ones due to much higher loaded Q-factor and the absence of conservative electric fields in the sample [5].

In this work, we demonstrate the possibility to considerably overcome the limitations of the SNR of conventional solenoidal probes, using a tunable coil which consists of two identical dielectric resonators with an adjustable separation. Each resonator has the shape of a hollow circular cylinder and is made of a ceramic material with high relative permittivity to resonate around the Larmor frequency of protons at 17 T (723 MHz). The fine tuning to the operational frequency of the scanner was achieved by adjusting the distance between the resonators, while matching of the input impedance of the all-dielectric coil to 50 Ohm was done by varying the position of an inductively coupled circular wire loop connected to the feeding coaxial cable and placed close to the upper resonator without using any lumped elements and additional metal parts for tuning and matching.

For comparison of loaded Q-factors, the all-dielectric coil (Fig. 1a) and the conventional solenoidal coil (Fig. 1b) were studied numerically and experimentally on the bench. The dielectric coil was made of the mixture of $BaTiO_3/SrTiO_3$ powders with Mg-containing additives specially prepared [6] to have the permittivity of 530 and dielectric loss tangent of 0.0008 at 723 MHz. Each dielectric resonator had the length L=10 mm, internal diameter of D_i=5.6 mm and the external diameter of 18 mm. To contain the sample of the same dimensions, for our comparison, a solenoid with the length L=20 mm, internal diameter of D_i= 6 mm made of 5 turns of a thin copper 0.4-mm-thick wire was taken. In the commercial software CST Microwave Studio both RF-coils were tuned to 723 MHz and matched to the input impedance 50 Ohm. In order to estimate the transmit efficiency and the SNR of both coils, the ratio between the magnetic field in the center of the sample to the square root of the accepted power and the loaded quality factor of the coils were studied. These characteristics were numerically calculated depending on the diameter of the sample, being a plastic tube filled with water with ε_r=81 and σ=0.59. The simulation results are shown in Fig.1c, d, e.

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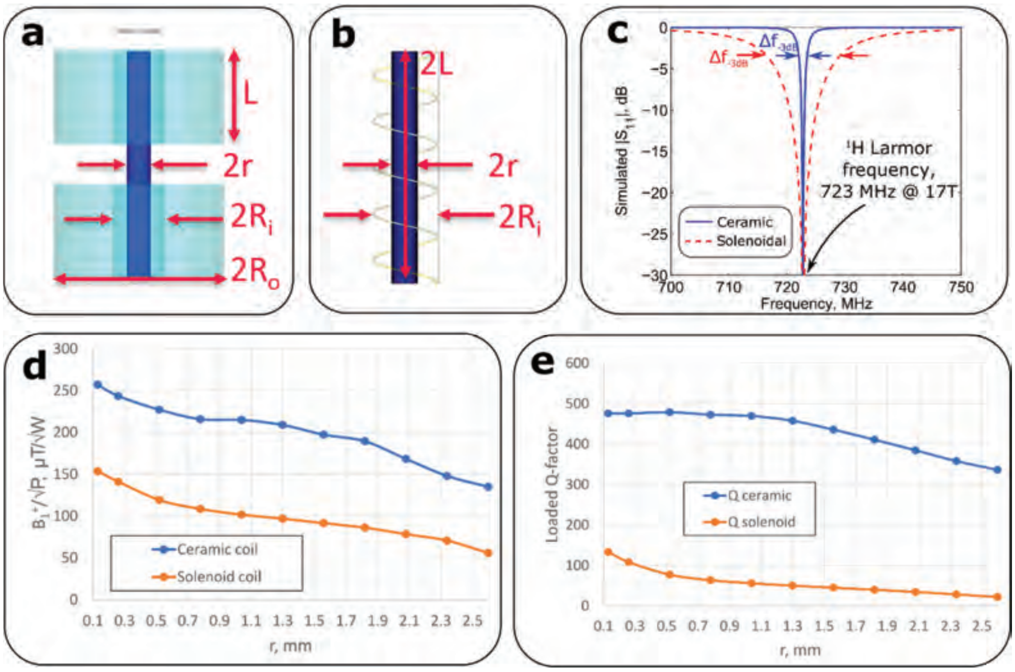

Figure 1. Geometry of ceramic (a) and conventional solenoidal (b) coils; numerically calculated S11 of both coils (c), loaded Q-factor (d) and power efficiency (e) vs. sample radius.

As follows from Fig. 1, the ceramic coil has almost twice higher power efficiency in the transmit regime, which means, it can provide twice higher SNR in the whole range of sample sizes. As it can be seen from the numerical simulation, this SNR increase is accompanied by 10-15 times Q-factor increase depending on the sample radius in the range 1.5-2.5 mm.

At the next step, the increased gain in the loaded Q-factor was experimentally confirmed by building prototypes of the proposed ceramic coil and the solenoid one. A water-filled tube of the radius 2 mm was used in the experiment as the sample. The photo of both prototypes is shown in Fig. 2a,b, while the S-parameters, measured by a vector network analyzer (VNA), are given in fig 2c. As can be seen, the ceramic coil has much narrower band and the loaded Q-factor determined from the S-parameter curve, which is 34 times larger than for the solenoid.

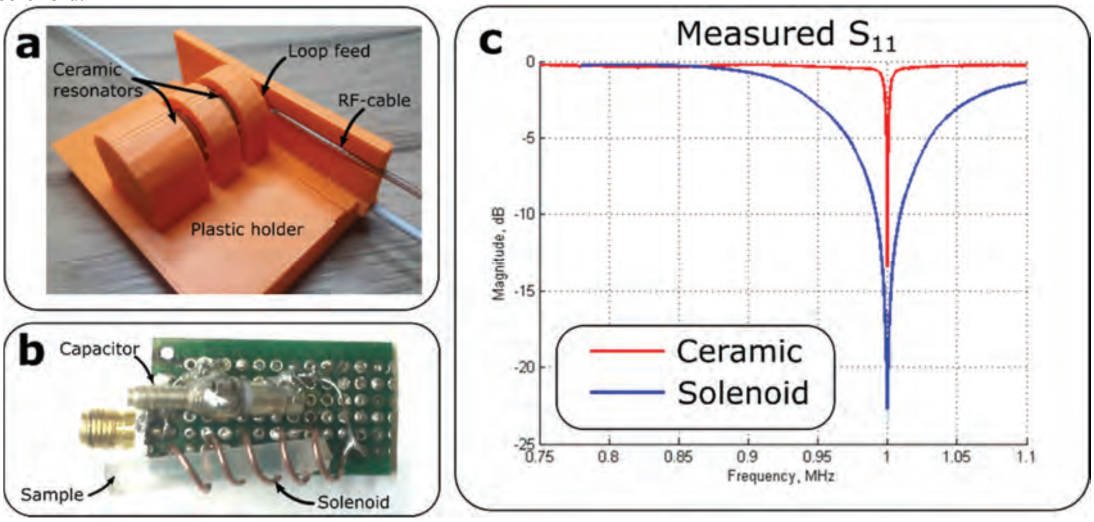

Figure 2. Manufactured ceramic (a) and solenoid (b) coils and their S11 around the operational frequency f0=723 MHz measured on VNA (c).

Therefore, in the simulation was shown that for the same size of a contained water sample, the new ceramic coil composed of two identical ceramic resonators provides an almost twofold SNR gain along with up to 15 times higher loaded Q-factor. Our on-bench experimental test has shown even higher Q-factor gain of 34, which can be explained by additional losses in the capacitors connected to the solenoid coil for tuning and matching. Indeed, their intrinsic losses were not considered in the simulations. The gain in the quality factor means higher reactive power of the magnetic RF-field in the sample for the same absorbed power. This effect is due to lower electric field created by the ceramic coil in the sample and low intrinsic losses of the employed ceramic material. The results have shown that the coil composed of two ceramic resonators of permittivity 530 is a very interesting alternative to a conventional solenoid coil of the same overall length. This ceramic coil is, therefore capable of providing images with much better quality for the same scan time and settings.

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