Improved signal detection with metamaterial magnetic yokes

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Introduction

Metamaterials are composite materials with effective permeability and permittivity determined by their structure rather than by the intrinsic properties of the material components [1]. One implementation of a metamaterial, the Swiss roll structure, has been shown to be capable of guiding the RF magnetic flux in MRI experiments [2,3]. Here, we numerically investigate whether Swiss rolls can improve signal detection in imaging and spectroscopic applications.

Concept

In an MR experiment, a small element of a sample produces a dipolar magnetic field that is to be detected by a receiver coil located outside the sample. By analogy with magnetostatics, we expect that the coupling between source and receiver can be increased by providing a low-reluctance return path for the magnetic flux originating from the dipole, in the form of a yoke made of Swiss rolls tuned so that $\mu_{\text{eff}} >> 1$. Such a yoke could have a DC permeability of 1 and so would not disturb the static field B_0.

Method

Two geometries were investigated. In the first, linear arrays of Swiss rolls were present on both sides of the sample, at the centre of which is the magnetic dipole. In the second geometry, a full return path for the magnetic flux was provided by a rectangular yoke. In previously reported experiments, the real part of the relative permeability was measured to reach a peak of 17 [3]. In the present calculation, the resistive and dielectric losses in the rolls (given by the imaginary part of the permeability) were ignored. The arrays of Swiss rolls were modelled as a uniform medium with an effective permeability tensor μ_{eff}: rolls oriented along the z axis would have $\mu_{xx} = \mu_{yy} = 1$ and $\mu_{zz} = 17$ (all non-diagonal elements are zero). The flux patterns were obtained by solving Poisson's equation for the vector magnetic potential: $\nabla\times\mu_{\text{eff}}^{-1}\nabla\times\vec{A}=0$. This was accomplished numerically with the method of finite differences, where the potential is defined on a discrete, uniformly spaced grid. For simplicity, a cylindrical symmetry was assumed, with the dipole placed on the symmetry axis. The dimensions of the linear arrays and of the yoke are given in fig. 1.

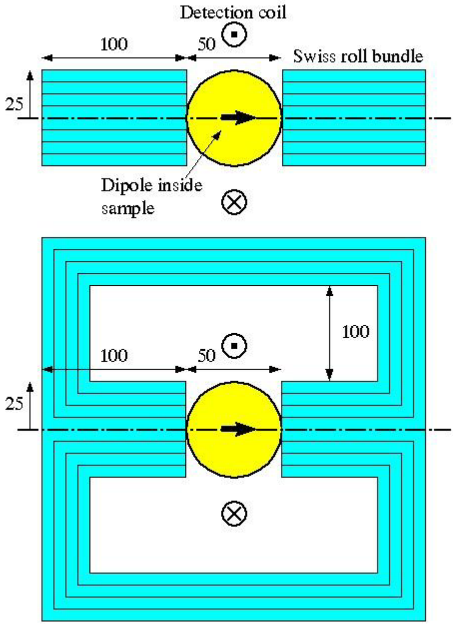

Fig. 1: Setup geometry for the linear arrays of Swiss rolls (top) and for the full yoke (bottom). All dimensions are expressed in units of the finite-difference grid spacing.

Results

Fig. 2 shows the gain in the detected signal as a function of the coil diameter, *d*, referenced to the case of the sample alone. With a coil diameter twice as large as the width of the gap in the rolls (*d*=100), the gain (with $\mu_{\text{eff}} = 17$) was 1.2 dB for the linear arrays and 1.9 dB for the full yoke. This gain arises because the yoke, and to a lesser extent the linear arrays, partially guide the flux lines around the receiver coil (fig. 3). Further gains are possible by increasing μ_{eff}: in the limit of $\mu_{\text{eff}} \rightarrow +\infty$, the gains were 1.4 and 2.5 dB for the linear arrays and the yoke respectively. The gain generally increases with the coil size, although this is accompanied by a decrease in the absolute detected signal. The dimensions of the yoke also influence the gain: as the total length of arms of the yoke decreases, the gain increases.

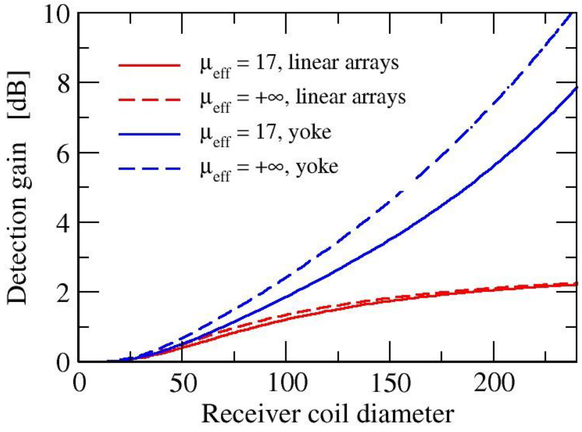

Fig. 2: Detection gain for both geometries; in the reference case (0 dB), only the sample is present.

Discussion

The calculations presented here show that metamaterials are capable of assisting with signal detection in an MR experiment, and that more gain in the received signal can be provided by using the full yoke geometry. Increasing the permeability and reducing losses would also improve performance. Moreover, it should be noted that experimental evidence [2,4] shows that in fact very little flux escapes from the length of a Swiss roll, whereas some leakage is seen in the present model. This indicates that a practical system could be more effective than is suggested here. Another advantage to increasing μ_{eff} is that carrying the magnetic flux further away, without losses, could facilitate the detection by allowing the receiver coil to be positioned away from the sample. While efforts to improve the quality of metamaterials continue, more detailed calculations are needed to better understand how metamaterials can improve signal detection and the SNR in realistic experimental geometries.

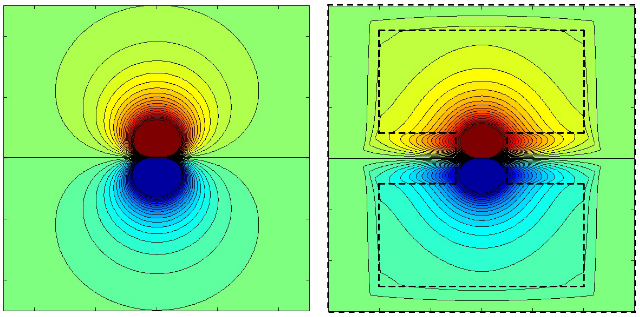

Fig. 3: Flux line pattern from the sample alone (left) and from the sample placed in the yoke (right).

References

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