Modelling Metamaterials for MRI

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Introduction: Metamaterials are artificial materials that can be used to manipulate electromagnetic fields by virtue of their designed permeability and permittivity[1], and can have properties that are well matched to MRI and NMR applications. We have made preliminary demonstrations of the use of a metamaterial structure to duct B_1 fields in MRI [2,3], and the concept of a yoke to provide a low reluctance pathway has been discussed [4]. Metamaterials are generally described by an effective medium formalism [5], and analytical predictions [6] of their behavior have been developed. However, for practical applications, more detailed simulations using numerical models are required, and the question remains whether the effective medium description is adequate. Here we compare measured transmission data through a metamaterial slab with the results of an analytical theory and a detailed numerical simulation

Materials and Methods: The metamaterial sample was a hexagonal prism, consisting of ~300 "Swiss Rolls" [5] that we have reported previously [2,3,6]. This showed a resonant effective permeability with a Lorentzian form in which the resonant frequency was 21.6 MHz, set to be slightly higher than the operating frequency of a 0.5T MRI system. For this work, small loops, approximately 4 mm diameter were used as both the source and detectors of RF excitation. The source loop was placed centrally immediately below the prism, and the detector was scanned across the output face. The detected signal at 21.6 MHz was recorded, and found to be strongly peaked (see Figure 1) at the centre of the scan. According to the analytical theory [6], the width of the transmitted signal on resonance should be approximately $\Delta \sim d/\beta$ where d is the thickness of the prism and the permeability on resonance is given by $\mu = i\beta^2$. In the present system, d = 60 mm, and β = 6, suggesting a resolution limit of ~10 mm, the same size as the individual Swiss Roll elements. Transmission calculations were made using the conventional Fresnel formulae for a semi-infinite slab, and the wavevector dependent eigenvectors of Maxwell's equation in an anisotropic medium. The MicroWave Studio [7] simulation package was then used to calculate the field distribution from a small loop source through a metamaterial prism, described with the measured form of the permeability. Plots were made both of the internal field distribution, and of that on the exit face for comparison with the experimental data and the analytical model.

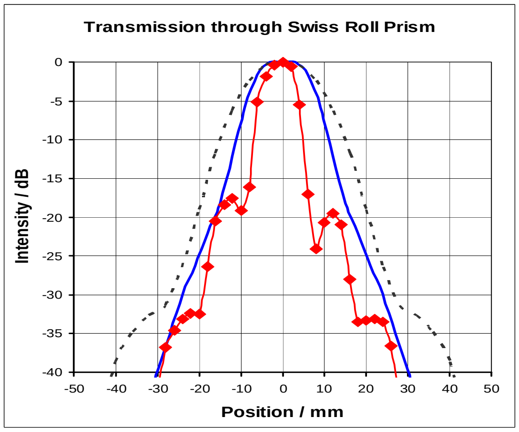

Figure 1. Transmitted field intensity from a small dipole loop through a Swiss Roll prism. The points and red line are the measured data, the blue line shows the prediction of the analytical theory, and the dotted black line the results of the numerical simulation.

Results and Discussion: The results are summarised in Figure 1. At the resonance frequency, the measured signal (points and red line) is very sharply peaked at the scan centre (note the dB scale), and the influence of the individual rolls, each 10 mm in diameter can be seen. The analytical model can not model the detailed structure, but does describe the envelope of transmission extremely well (full blue line). On resonance, this model predicts that the flux is transmitted through the prism in a tightly confined "jet", emerging, in the ideal case, as the exact replica of the input field pattern, as if it had been transported by an ensemble of "magnetic wires". In reality, this is degraded by the losses in the material as seen here. The numerical simulation allows us to visualise the transmission process, as shown in Figure 2. This clearly confirms the prediction of the analytical model. The intensity profile just above the output face is shown as the black dotted line in Figure 1. This is slightly wider than that predicted by the analytical model, possibly because the meshing in the simulation was insufficiently fine. Further work is underway to determine the source of this slight discrepancy and to explore the validity of the numerical models under a wider range of operating conditions.

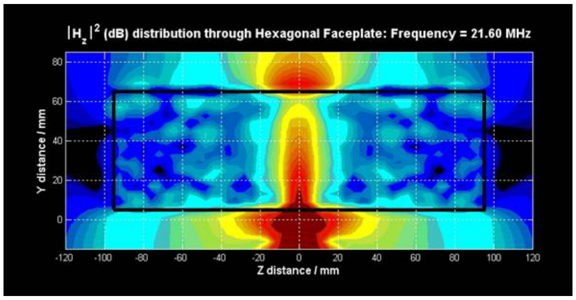

Figure 2. Numerical simulation of the field distribution on resonance through a cross-section of the metamaterial prism, excited by a small dipole source at the origin. The plot has a dynamic range of 60 dB, and shows the "jet" of field through the material.

Conclusion: This work confirms that the effective medium description does provide a valid basis for exploring the performance potential of metamaterials in an MRI context using both analytical and numerical approaches.

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