Metamaterial design for magnetic field shielding

Mustafa Boyvat[1], Christian Hafner[2]
[1,2] Electromagnetic Fields and Microwave Electronics Laboratory
Gloriastrasse 35
CH-8092 Zurich
Switzerland

[1] mustafa.boyvat@ifh.ee.ethz.ch
[2] Christian.Hafner@ifh.ee.ethz.ch

Summary. Metamaterials, usually composed of large arrays of coupled resonators, have been studied mostly for high frequency applications. However, they provide an alternative to conventional shielding techniques at very low frequencies, i.e. 50-60 Hz. In this work, we show how to analyze and design such metamaterials and we evaluate the effect of the polarizabilities, the geometric arrangement and the number of resonators using quasi-static approximation to shield magnetic field.

1 Introduction

Metamaterials are artificial structures, which enable naturally unavailable electromagnetic properties and engineering of them. Metamaterials have been studied for years extensively, mostly aiming for optical frequency applications. However, metamaterials also have the potential to be used at very low frequencies, such as the shielding of magnetic field at power frequencies.

A metamaterial is usually composed of coupled resonators and shows complex behaviour. This complication brings the need for simulation and optimization tools. At very low frequencies, the resonators, which are the basic unit of metamaterials, are simple LC resonators formed by lumped circuit elements, i.e. inductors and capacitors. Shielding may be obtained mainly by the following mechanism: The incident magnetic field induces currents in the inductors which then loads the connected capacitors. In [1], it has been shown that it is possible to use metamaterials to shield magnetic field at very low frequencies.

In this paper, the effects of the polarizabilities and the geometric arrangement of resonators are analyzed for the shielding application whereas the number of LC resonators is considered as a parameter to be kept low, because of high costs.

2 Design

As shown in [1], metamaterials are naturally anisotropic materials and this gives the possibility to obtain high shielding factors. Electromagnetic properties of metamaterials such as effective permeability can be obtained by effective medium approximations. To be able to use effective medium approximations, there must be a high density of LC resonators in the metamaterial block. One of the discussed points in this work is that although decreasing the number of LC resonators prevents us from using these approximations, it is still possible to obtain high shielding factors. In this case, the metamaterial becomes a set of 'meta-sheets', as illustrated in Figure 1. The shielding of a meta-sheet of which the coil axes are oriented in the direction of the source magnetic field (i.e. x direction in Figure 1) is realized by opposing magnetic field produced by LC resonators. The shielding of such a sheet is shown in Figure 2. The LC resonators are ideal (no resistance) and the meta-sheet is inhomogeneous.

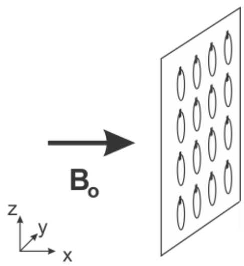

Figure 1: A meta-sheet, which is composed of LC resonators. B_0 shows the source magnetic flux density vector and is in x- direction where as the meta-sheet is in y-z plane.

3 Numerical Method

The LC resonators are modelled by current loops. The magnetic field of a current loop is given in [2]. The currents in LC resonators are obtained by equating the magnetic flux density to zero at some test points in the region to be shielded and this results in a linear matrix equation (see Equation (1)) [1]. $B'_{ji,k}$ is the k component of the magnetic flux density produced by the j^{th} current loop with unit current at the i^{th} test point. $B_{oi,k}$ is the source magnetic flux density and I_j is the current in the j^{th} loop.

$$\underbrace{\begin{pmatrix} B'_{11,x} & B'_{21,x} & \cdots & B'_{N1,x} \\ B'_{11,y} & B'_{21,y} & \cdots & B'_{N1,y} \\ B'_{11,z} & B'_{21,z} & \cdots & B'_{N1,z} \\ \vdots & \vdots & \vdots & \vdots \\ B'_{1M,y} & \cdots & \cdots & B'_{NM,y} \\ B'_{1M,z} & \cdots & \cdots & B'_{NM,z} \end{pmatrix}}_{B} \underbrace{\begin{pmatrix} I_1 \\ I_2 \\ \\ \vdots \\ \\ I_N \end{pmatrix}}_{C} = \underbrace{\begin{pmatrix} -B_{o1,x} \\ -B_{o1,y} \\ \\ \vdots \\ \\ -B_{oM,y} \end{pmatrix}}_{D} \quad (1)$$

By using more test points than necessary for the linear matrix equation, the problem turns into the optimization of vector C, which is formed by the currents in the loops (See Equation (1) and (2)) [1], [3].

$$\min_C \frac{1}{2} \left\| BC - D \right\|_2^2 \quad (2)$$

Putting additional coils with axes are oriented in y and z directions, the shielding can be improved by also trapping the magnetic field, similar to the shielding by high permeability materials.

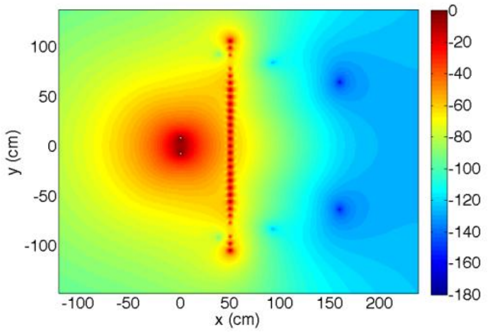

Figure 2: Shielding of an inhomogeneous meta-sheet. The color map shows the magnetic flux density in dB scale at z=0. The magnetic field source is a coil located at (0,0,0) and the meta-sheet is located at x=50 cm.

4 Conclusions

Metamaterials can be used to shield magnetic field at very low frequencies. The number of LC resonators can be decreased by using meta-sheets and the shielding characteristic can be improved by modifying polarizabilities and the geometric arrangement of resonators. A numerical method for the design of meta-sheets has been presented. Since this method is based on a linear matrix equation, it is efficient and fast.

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References

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