České vysoké učení technické v Praze
Fakulta elektrotechnická

Czech Technical University in Prague
Faculty of Electrical Engineering

Ing. Lukáš Jelínek, Ph.D.

Magnetické metamateriály a jejich využití v magnetickém rezonančním zobrazování

Magnetic Metamaterials and their Application in Magnetic Resonance Imaging

Summary

This text briefly presents a selected part of the scientific career of Lukas Jelinek and serves as an underlying document for the habilitation lecture presented at the Czech Technical University in Prague. In particular, the text presents a brief introduction to magnetic metamaterials made of resonant rings and to magnetic planar lenses, with a particular focus on possible improvements to image acquisition in magnetic resonance imaging.

Souhrn

Předložený text stručně shrnuje vybranou část vědecké kariéry Lukáš Jelínka a slouží jako podklad pro habilitační přednášku prezentovanou na Českém vysokém učení technickém v Praze. Text obsahuje především stručný úvod do magnetických metamateriálů vytvořených z rezonančních prstenců a dále stručný úvod do magnetických planárních čoček a jejich využití v magnetickém rezonančním zobrazování.

Klíčová slova

Metamateriály; Magnetické rezonanční zobrazování; Elektromagnetické čocky; Magnetismus; Homogenizace

Keywords

Metamaterials; Magnetic Resonance Imaging; Electromagnetic Lenses; Magnetism; Homogenization

Contents

1 Introduction

A metamaterial is most commonly understood as an artificial medium with macroscopic electromagnetic characteristics (permittivity, permeability, conductivity), i.e. constitutive parameters that are not attainable in natural materials. During their development over the last 15 years, the metamaterials have became a mature topic and an inseparable part of the classical electromagnetic field theory. The fundamental theory of metamaterials and a detailed history of them can nowadays be found in public Internet sources and in several eminent textbooks, see for example [1–3].

2 The Perfect Lens

Particular examples of metamaterials of great importance are materials with negative values of their constitutive parameters. These materials have attracted a lot of attention among physicists and electrotechnical engineers, and have also led to proposals for interesting new devices. Probably the most important is the perfect lens [4], which consists of an isotropic slab of thickness d_{lens} with material constants ε_{in} and μ_{in}, surrounded by another isotropic material with parameters ε_{out} and μ_{out}. If the materials are chosen [4] in such a way that $\varepsilon_{\text{out}} = -\varepsilon_{\text{in}}$ and $\mu_{\text{out}} = -\mu_{\text{in}}$, the slab behaves as a perfect lens that transfers all plane waves, including all evanescent harmonics, from the source plane at a distance d_{source} in front of the lens, to the image plane, which is situated at a distance d_{image} behind the lens, provided that the distances are chosen such that $k_z^{\text{out}} d_{\text{source}} + k_z^{\text{out}} d_{\text{image}} = k_z^{\text{in}} d_{\text{lens}}$, where k_z is a wavenumber component perpendicular to the slab. Figure 1 depicts the superior properties of the perfect lens in comparison to the conventional lens when subwavelength details are to be imaged. Due to the inability of the conventional lens to transfer the evanescent part of the planewave spectrum, the image suffers from loss of details and also from loss of intensity.

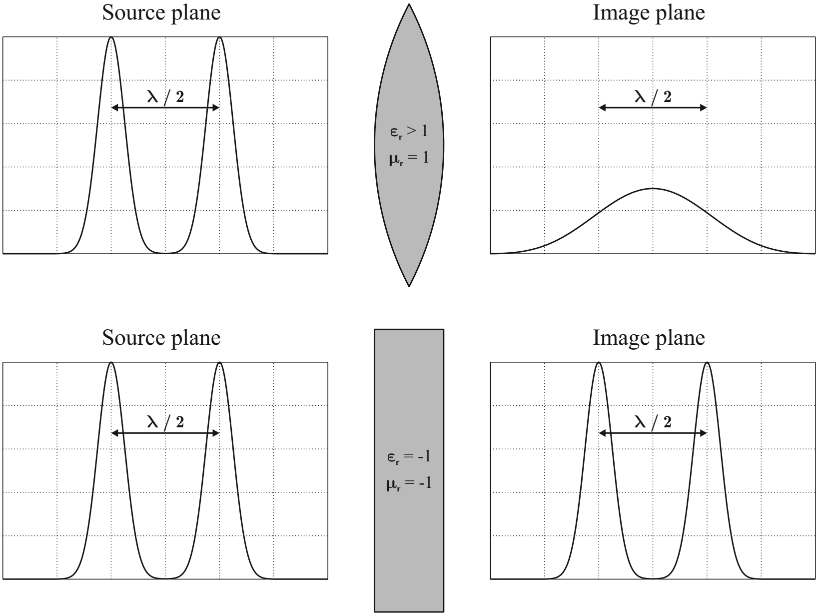

Figure 1: A sketch of the imaging properties of the conventional lens and the perfect lens. A vacuum surrounding is assumed. The amplitude curves represent a transversal variation of an unspecified electromagnetic field component in the source plane and the image plane.

3 Use of the Perfect Lens in Magnetic Resonance Imaging

Magnetic resonance imaging is a technique of eminent importance in medical diagnostics. In this method, the magnetic field generated in spin transitions of hydrogen is usually picked up by simple resonant coils, which are tuned to a specific frequency of the spin transition in a particular part of the imaged tissue. The major issue in magnetic resonance imaging is the signal-to-noise ratio, the low value of which is mostly due to the very low signal coming from the imaged tissue. There are two reasons for this.

First, the source itself (a cube of properly magnetized tissue) is very weak. Second, the radiating piece of tissue does not lie on the surface of the body, since it is also necessary to image the internal part of the body. This means that the source of the radiation is located at some distance from the pick-up coil, and the coil generally loses its sensitivity with growing distance. There is practically no cure for the first of these problems. The second problem can however be solved by using an imaging device that virtually shifts the pick-up coil to within the tissue - i.e. by using the perfect lens [5], [6], see Fig. 2a. Knowledge of the electrical sizes of the pick-up coils indicates that the perfect lens is an appropriate device for this task. In widely used imaging systems with a static magnetic field of 1.5 T the diameter of the pick-up coils is close to $\lambda/50$, where λ is the wavelength at the operation frequency (approximately 64 MHz). The field patterns of such electrically small coils cannot of course be imaged by a conventional lens, the resolution of which is limited to approximately $\lambda/2$, see Fig. 1.

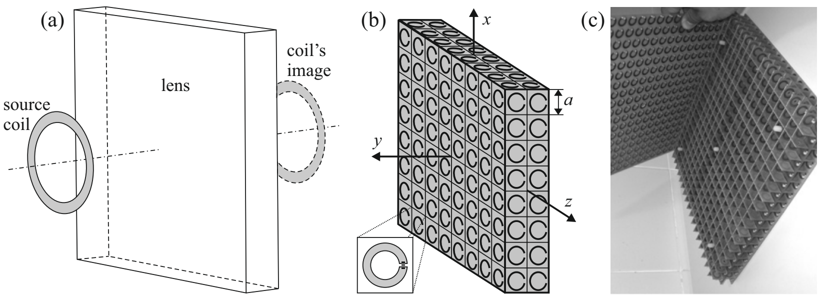

Figure 2: (a) A sketch of the use of the perfect lens in magnetic resonance imaging. The pick-up coil sensing the magnetic field coming from the imaged tissue is virtually imaged into the depth of the body. (b) A sketch of a magnetic lens made of a lattice of resonant conducting loops (c) Practical realization of the magnetic lens

Realistic construction and use of the perfect lens unfortunately faces three difficulties. The first is the need for simultaneously negative permittivity and negative permeability, which is rather difficult to achieve with present-day metamaterials. However, this does not pose a serious problem when using the perfect lens in magnetic resonance imaging, which performs the imaging solely within the near-field of the source, where the electric and magnetic fields are reasonably decoupled. In such a case it can be shown [4] that a dominantly magnetic source (TE waves along the optical axis, as in magnetic resonance imaging) can be imaged using only negative permeability, while a dominantly electric source (TM waves along the optical axis) can be imaged using only negative permittivity. The second difficulty is the inherent frequency dispersion of all known metamaterial designs, which greatly narrows the useful bandwidth of realistic metamaterial lenses. This however also does not pose a serious obstacle for their use in magnetic resonance imaging, which is a narrow band system operating at a fractional bandwidth smaller than 1 %. The third difficulty is due to the inherent losses in all metamaterial designs, which is naturally connected with the dispersive behavior. This is the only serious challenge for the use of the perfect lens in magnetic resonance imaging, since the losses enhance the thermal noise.

4 The Design of the Magnetic Lens

The previous section introduced the possibility of using a lens made of a negative permeability material with otherwise positive permittivity for magnetic resonance imaging applications. This is a considerable simplification, as a material of this type can be relatively simply designed using resonant rings [7, 8]. The simplest (but for magnetic resonance applications sufficient) design of the resonant ring is a capacitively loaded ring (CLR), originally proposed in [7], see Fig. 3a, which consists of a metallic ring loaded in its gap by a capacitor. Assuming that the CLR is significantly smaller than the operation wavelength ($kr \ll 1$), which is a necessary condition for being a component of a ho-

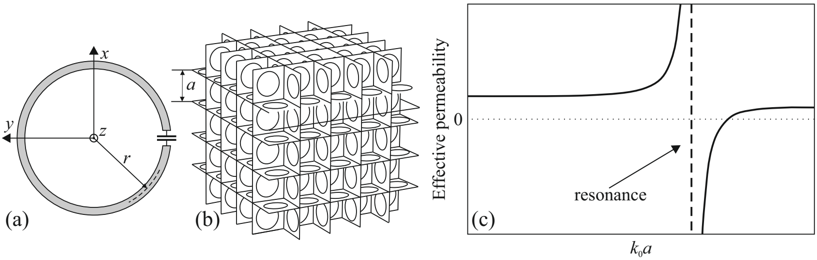

Figure 3: (a) A metallic ring loaded by a capacitor, (b) A cut of an infinite 3D cubic lattice of resonant rings forming a magnetic metamaterial, (c) A sketch of the frequency dependence of the permeability of the ring lattice from panel (b).

mogenizable material, its polarization can be well described by the induced electric dipole moment $\mathbf{p}$ and the magnetic dipole moment $\mathbf{m}$. Following the standard notation [9], these dipole moments are connected to exciting fields via the polarizability tensors as

$$\begin{aligned} \mathbf{p} &= \left[\alpha_{ij}^{\mathrm{ee}}\right] \cdot \mathbf{E} + \left[\alpha_{ij}^{\mathrm{em}}\right] \cdot \mathbf{B} \\ \mathbf{m} &= \left[\alpha_{ij}^{\mathrm{me}}\right] \cdot \mathbf{E} + \left[\alpha_{ij}^{\mathrm{mm}}\right] \cdot \mathbf{B}, \end{aligned} \tag{1}$$

where within the defined coordinate system

$$\begin{aligned} \left[\alpha_{ij}^{\mathrm{ee}}\right] \approx \begin{bmatrix} \alpha_{xx}^{\mathrm{ee}} & 0 & 0 \\ 0 & \alpha_{yy}^{\mathrm{ee}} & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \left[\alpha_{ij}^{\mathrm{mm}}\right] \approx \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \alpha_{zz}^{\mathrm{mm}} \end{bmatrix} \\ \left[\alpha_{ij}^{\mathrm{em}}\right] \approx \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \alpha_{yz}^{\mathrm{em}} \\ 0 & 0 & 0 \end{bmatrix} \quad \left[\alpha_{ij}^{\mathrm{me}}\right] \approx \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -\alpha_{yz}^{\mathrm{em}} & 0 \end{bmatrix} \end{aligned} \tag{2}$$

and where the reciprocity theorem [10] has been used to equate $\alpha_{zy}^{\mathrm{me}}$ and $-\alpha_{yz}^{\mathrm{em}}$. The form of the electric polarisability $\alpha_{ij}^{\mathrm{ee}}$ and magnetic polarisability $\alpha_{ij}^{\mathrm{mm}}$ is quite intuitive, and the magnetic polarizability can in fact be easily estimated from Faraday's law as

$$\alpha_{zz}^{\mathrm{mm}} = \frac{-\mathrm{j}\omega\pi^2 r^4}{\mathrm{j}\omega L + \frac{1}{\mathrm{j}\omega C}}, \tag{3}$$

where L is the self-inductance of the closed loop and C is the loading capacitance.

The form of the magnetic polarizability (3) shows that the ring resonance can be seen as the resonance of a serial resonance circuit in which the inductance is given by the ring, while most of the capacitance is concentrated inside the gap. The form of (2),(3) also suggests that the cubic system of such CLRs depicted in Fig. 3b resembles a homogeneous medium with permeability [11] according to Fig. 3c. The permeability of such a medium can be negative in a narrow frequency band above the resonance frequency, and proper frequency tuning can cast the permeability to the desired $\mu_\mathrm{r} = -1$. The corresponding magnetic lens can be designed as a slice of such a medium.

5 Performance of the Realistic Magnetic Lens

A lens of the type introduced in the previous section has been designed [6] from a two unit cell thick slab of cubic ring material, see Fig. 2b,c. Although a two unit cell thick slab clearly cannot be considered to be made of a homogeneous medium, the real life performance of this lens has been very good [6], see Fig. 4. In order to understand the lens in greater detail, a proper homogenization scheme taking into account its small thickness has been developed [13]. The results surprisingly showed that within the realm of quasi-static TE waves the lens can in fact be approximated by a slab of a homogeneous medium, which explained its performance. Subsequently, the lens has been tested in various scenarios [12], both experimentally and theoretically, by means of the detailed discrete model [14].

So far the lens has been used for compensating of the amplitude loss between the source plane and the image plane, but its subwavelength resolution has not been employed. However, a magnetic resonance imaging technique exists where the resolution in the transverse plane is of great importance. The method is called parallel imaging, and it relies on an array of small pick-

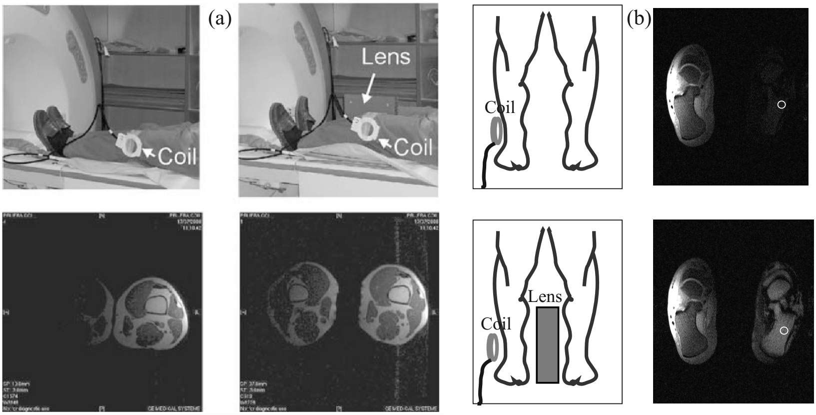

Figure 4: (a) Imaging of knees - a comparison of the same scenario with the lens (right) and without the lens (left), as depicted in [6] (b) Imaging of ankles - a comparison of the same scenario with the lens (bottom) and without the lens (top), as depicted in [12].

up coils that makes the image acquisition in parallel. However, a necessary prerequisite is very small overlap of the regions from which each coil picks up its signal. Ideally, each coil should see only the tissue in column below it. This is of course increasingly difficult with growing depth of the image. It is exactly this issue with that the magnetic lens can offer great help, due to its ability to effectively project the pick-up coil array to within the tissue, thus retaining the original small overlap between the coils. The potential of the lens in parallel imaging technology has been shown to be considerable [12].

The study on parallel imaging also raised the question of the actual transversal resolution of the real magnetic lens. A detailed study [15] has been performed, and it showed that the lens resolution can be deeply subwavelength, reaching a size around six unit cells (see Fig. 5), i.e. around $\lambda/50$, with lambda being the operation wavelength. It has also been shown that the resolution of a realistic magnetic lens is actually limited by the finite size of the unit cell of the ring metamaterial that is used.

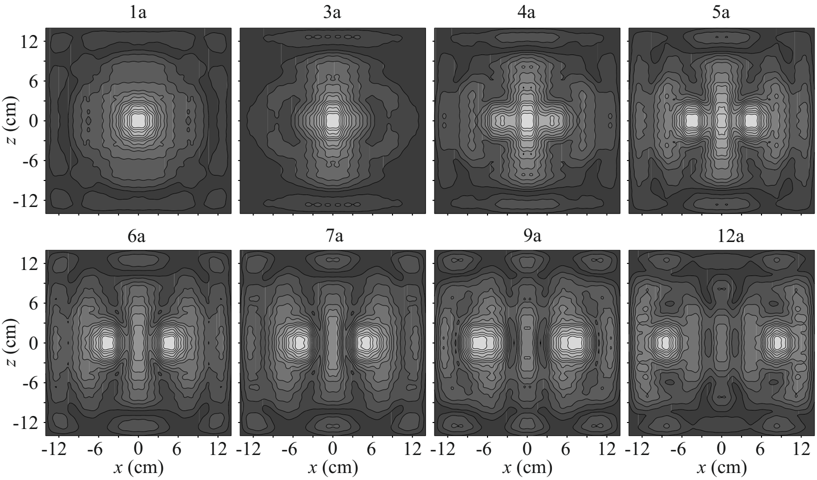

Figure 5: Axial component of the magnetic field observed at imaging frequency in the image plane of the lens for two small source coils of negligible radius placed in the source plane of the lens. The source coils are separated by distance $1a$–$12a$, where a is the lattice constant of the resonant ring metamaterial.

6 Conclusions

The emergence of metamaterials stimulated a wave of interest in classical electromagnetism, though at that time this area of physics had been considered to be almost exhausted. The major reason was that, in the past, the importance of material properties was often underestimated, or materials were even taken as parasitic components needed only to support metallic structures. Metamaterials have however shown that constitutive parameters are extremely valuable and offer an extremely flexible degree of freedom which can bring whole new functionalities in even the simplest geometries, e.g. a simple slab behaving as a perfect lens [4].

The text presented here has dealt with one of the major branches of metamaterials, i.e. materials made of resonant rings, which aim to manipulate the magnetic properties. The text has laid particular emphasis on the usage of negative permeability metamaterials for constructing a magnetic lens that can considerably enhance the performance of present-day systems for magnetic resonance imaging. The improved image acquisition has been presented on a realistic lens fabricated from a 3D lattice of capacitively loaded rings.

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7 Ing. Lukas Jelinek, Ph.D.
born the 28th of July, 1980

	Education
2006	Ph.D. degree, title of the thesis: "New Bulky Metamaterial Structures and Their Applications in Microwave Technology"
2004 - 2006	Doctoral studies at the Department of Electromagnetic Field, Czech Technical University in Prague (Czech Republic)
2004	Ing. degree in radioelectronics (equivalent to MSc.)
1998 - 2004	Undergraduate studies at Czech Technical University in Prague (Czech Republic)
	Work Experience
2013 - now	Researcher at the Department of Electromagnetic Field, Czech Technical University in Prague (Czech Republic), supported by the project of Czech Science Foundation, no. 13-09086S
2009 - 2012	Researcher at the Department of Electromagnetic Field, Czech Technical University in Prague (Czech Republic), supported by the project of Czech Science Foundation, no. 102/09/0314
2007 - 2009	Post-Doc researcher at the Department of Electronics and Electromagnetism at the University of Seville (Spain), supported by the project no. P06-TIC-01368 of Spanish Ministry for Science and Innovations

2006 - now	Head of the National Reference Laboratory for Non-Ionizing Radiation, National Institute of Public Health (Czech Republic)
2002 - 2006	Technician in the National Reference Laboratory for Non-Ionizing Radiation, National Institute of Public Health (Czech Republic)
	Pedagogical Experience
2012 - now	Two semesters of lectures in doctoral subject on advanced electromagnetic field theory
2006 - now	Two Ph.D. students (one in progress, one successfully defended in 2013)
2006 - now	Two lectures per year (on average) on health effects of non-ionizing radiation for members of the public health system of Czech Republic and physicians undergoing attestation
2004 - 2006	Four semesters of computational seminars in electromagnetic field theory I (basic course) and II (waves) at Czech Technical University in Prague
	Spoken Languages
	English – fluent German – basic
	Scientific Interests
	Metamaterials (especially resonant ring systems), Homogenization of Artificial Media, Wave Propagation in Complex Media, General Field Theory, Numerical Techniques
	Other Experiences
	Referee work for Physical Review, Journal of

	Applied Physics, Applied Physics Letters, Infrared Physics & Technology, Metamaterials, New Journal of Physics, Optics Express, IEEE Transactions on Antennas and Propagation, IEEE Transactions on Microwave Theory and Techniques
	Projects (active participation)
	- Czech Science Foundation: 102/09/0314, 13-09086S - Czech Technical University in Prague: SGS10/271/OHK3/3T/13, SGS13/198/OHK3/3T/13 - EU FEDER funds: TEC2010-16948 - Spanish Ministry for Science and Innovations: CSD2008-00066, TEC2007-68013-C02-01/TCM - Junta de Andalucia: P06-TIC-01368
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