Metamaterial endoscope for magnetic field transfer: near field imaging with magnetic wires

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Abstract: We report on the development and use of a highly anisotropic magnetic metamaterial for near-field imaging. The material consists of an array of Swiss Roll structures, resonant near 21.3 MHz, with a peak value of relative permeability ~35. At this peak, the material transfers an input magnetic field pattern to the output face without loss of intensity and with a spatial resolution equal to the roll diameter. It behaves as a near-field imaging device consisting of a bundle of magnetic wires.

OCIS codes: (110.0110) Imaging Systems; (160.1190) Anisotropic Optical Materials; (350.5500) Propagation; (260.0260) Physical Optics

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1. Introduction

The recent development of metamaterials with hitherto unattainable physical properties provides new ways of manipulating the electromagnetic near field. For example, Pendry [1] predicted that a "perfect lens" could be achieved using a material with a refractive index of $n = -1$: this could bring both the propagating and evanescent fields to a focus. Better performance is predicted from alternating parallel sided layers of $n = -1$ and $n = +1$ material,

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which also act as a lens [2, 3, 4]. The effective medium made up of such a multi-layer stack can be described as having massive form birefringence [5], with $n_z = \infty$ and $n_x = 0$ where n_x and n_z are the refractive index components in directions parallel and perpendicular to the layer boundaries respectively. However, when we are concerned only with the very near field, the electric and magnetic fields are largely decoupled, and we can manipulate the electric field with the permittivity and the magnetic field with the permeability, quasi-independently of one another. This is the case, for example, in magnetic resonance imaging (MRI) at the clinically relevant field strengths of 0.2 – 1.5 T (operating frequencies 8 – 63 MHz). Recognizing this, we have explored the use of a magnetic metamaterial as a near field imaging device.

Metamaterials can have values of relative permittivity (ε) and relative permeability (μ) that are unobtainable in nature. By incorporating suitable microstructure, materials can be fabricated from non-magnetic components, that nevertheless show a magnetic response when they interact with electromagnetic radiation of the correct frequency [6]. Of these magnetic metamaterials, the "Swiss Roll" structure is particularly suitable for operation in the 1 - 100 MHz radiofrequency (RF) regime. Wiltshire et al [7] reported using "Swiss Rolls" as an RF flux guide material in an MRI experiment at 21.3 MHz (0.5 T). However, this material, which had a peak relative permeability of ~3, did not preserve any spatial image information: this was all encoded in a conventional way by the field gradients in the MRI machine. Improved materials have now been made that offer much greater permeability. These are uniaxial, so they have a highly anisotropic effective permeability. We have recently shown [2,3] that, in such highly anisotropic systems, the transverse wavevector components (k_x, k_y) of an incident field pattern should be decoupled from the longitudinal component (k_z), so that the field pattern should be transferred from the input to the output face of a slab of material without degradation of the image information. In this paper, we investigate this prediction. In Section 2, we describe the construction of a "Swiss Roll" material with high permeability. In Section 3, we develop a theory to describe its near field imaging performance. In Section 4 we report on measurements that enable a comparison between prediction and experiment to be made, and draw our conclusions in Section 5.

2. Material development and characterization

The "Swiss Roll" medium exhibits a frequency dependent anisotropic permeability [6, 7]

$$\mu_z(\omega) = 1 - \frac{F}{\left(1 - \omega_0^2/\omega^2\right) + i\,\Gamma/\omega}, \quad \mu_x = \mu_y = 1 \tag{1}$$

in which F is a filling factor, ω_0 is the resonant angular frequency, Γ is the damping, and we have taken the z-direction along the axis of the roll. The resonant frequency ω_0 is determined by the construction, whereas the damping Γ includes the resistance of the conductive layer and the dissipative part of the permittivity of the dielectric layer. In our earlier work [7], the former dominated, because the conductive layer was only a few nm thick. Here, however, we use copper / polyimide laminates as the basic material, with copper thickness of >10μm, so the dielectric losses dominate. For optimum performance, both the conductor and the dielectric layer are required to be as thin as possible, with no lossy glue layer between them. Espanex SC18-12-00FR was selected as the most suitable available laminate: this has 12μm of polyimide deposited directly onto 18μm of copper, and the dielectric has $\tan(\delta) \approx 0.015$ at 10MHz.

50mm wide strips of this material were wound onto 10 mm diameter acetal mandrels (Fig. 1(a)). 11 turns of laminate gave a resonant frequency close to 21.3MHz. A typical

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permeability plot for a single roll is shown in Fig. 1b, where the filling factor in Eq. (1) is taken as unity. We note that the peak values of the real and imaginary parts of the permeability are approximately 17 and 35 respectively and the quality factor Q is about 60.

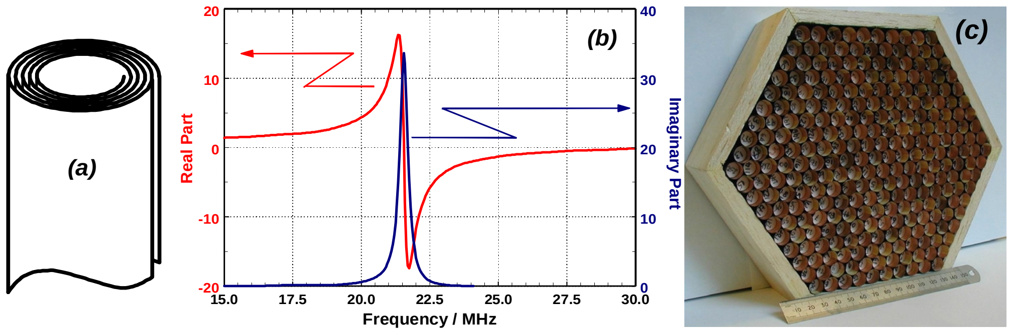

Fig. 1. (a) Schematic diagram of a single Swiss roll: the Espanex is wound in a spiral on a cylindrical mandrel. (b) Permeability vs. frequency for Swiss Roll material. (c) The assembled slab of material, consisting of 271 Swiss Rolls, tuned to 21.5 MHz

Over 300 nominally identical rolls were constructed, but it was found that there was a distribution of their resonant frequencies whose width was approximately 2 MHz, much greater than the width of the individual resonance. Each roll was therefore individually tuned [8] using a 40 mm wide, capacitively coupled sleeve. This protruded by 10 mm, and its length was adjusted so that the combination of roll and sleeve had a resonant frequency of 21.5±0.1MHz, and the peak of the real part of the permeability lay at 21.3 MHz. 271 tuned rolls were assembled as a hexagonal array in a balsawood box to create a slab of material, which had 200 mm long diagonals and was 60 mm thick (Fig. 1(c)).

3. Theory

The performance of this material can be predicted by considering the propagation of electromagnetic waves through highly anisotropic effective media. We start from Maxwell's equations for a monochromatic field with angular frequency ω and wave vector $\mathbf{k}$,

$$i\mathbf{k}\times\mathbf{E}=i\omega\boldsymbol{\mu}\mu_0\mathbf{H}, \qquad i\mathbf{k}\times\mathbf{H}=-i\omega\boldsymbol{\varepsilon}\varepsilon_0\mathbf{E} \tag{2}$$

The medium is magnetically active but dielectrically inactive, so on eliminating $\mathbf{E}$ we find

$$-\mathbf{k}\times\mathbf{k}\times\mathbf{H}=\omega^2c_0^{-2}\boldsymbol{\mu}\mathbf{H} \quad \text{or} \quad -\mathbf{k}\left(\mathbf{k}\cdot\mathbf{H}\right)+k^2\mathbf{H}=k_0^2\boldsymbol{\mu}\mathbf{H} \tag{3}$$

where k_0 is the free space wavevector, ω/c_0.

In the effective medium approximation, the material is isotropic in the *x-y* plane, so we can confine our calculations to the *x-z* plane without loss of generality. It is convenient to rewrite Eq. (3) in terms of $\mathbf{B}$, whereupon expanding gives

$$\begin{bmatrix} \mu_x^{-1}k_z^2 & -\mu_z^{-1}k_xk_z \\ -\mu_x^{-1}k_xk_z & \mu_z^{-1}k_x^2 \end{bmatrix}\begin{bmatrix} B_x \\ B_z \end{bmatrix}=k_0^2\begin{bmatrix} B_x \\ B_z \end{bmatrix} \tag{4}$$

The condition for solution is

$$k_z^2=\mu_xk_0^2-\frac{\mu_x}{\mu_z}k_x^2 \tag{5}$$

and the associated eigenvectors are

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$$\begin{bmatrix} B_x \\ B_z \end{bmatrix} = \begin{bmatrix} \mu_z^{-1} k_x^2 - k_0^2 \\ \mu_x^{-1} k_x k_z \end{bmatrix} \tag{6}$$

In the limiting case, when $\mu_x = 1$ and $\mu_z \to \infty$, the eigenvalues reduce to $k_z = \pm k_0$ and the eigenvectors become

$$\begin{bmatrix} B_x \\ B_z \end{bmatrix} = \begin{bmatrix} -k_0 \\ \pm k_x \end{bmatrix} \tag{7}$$

The important point is that k_z is now independent of k_x, so all the transverse Fourier components of an object propagate along the z-axis with the same relative phase: if we measure the intensity we see a perfect image. In the electric field equivalent of this situation [3], we saw that an incident electric field distribution is transported through the material as if the faces of the slab were connected by perfectly conducting wires. By analogy in the present case, we can imagine magnetic "wires", composed of a perfect magnetic conductor, transporting the magnetic image information across the material slab.

In our practical implementation operating at 21.3 MHz, the wavelength *in vacuo* is about 14 m, so our length scales are very much less than a wavelength and the losses will dominate in Eq. (5). At resonance, we can write the permeability as

$$\mu_z(\omega_{res}) = i\beta^2 \tag{8}$$

Assuming that $k_x^2 / \beta^2 >> k_0^2$, Eq.(5) gives

$$k_z^2 \approx i k_x^2 / \beta^2 \tag{9}$$

Thus for finite loss, k_z has an imaginary component, and the material does not transport the image perfectly: the higher Fourier components degrade faster with distance. For a material thickness d the attenuation will become significant when $\mathrm{Im}(k_z) \approx 1$ or, using Eq. (9), when $k_x(\max) \approx \beta / d$. The resolution is therefore limited to

$$\Delta \approx 1/k_x(\max) \approx d/\beta \tag{10}$$

In the present case, we have $\beta \approx 6$ and $d \approx 60$ mm, so that $\Delta \approx 10$ mm, approximately equal to the diameter of the individual rolls. Thus, we do not expect loss effects to degrade the resolution of any transmitted structure beyond the intrinsic granularity of the Swiss Rolls.

4. Experiment

Preliminary characterization was carried out using 3 mm diameter loops as both source and receiver. The source was placed centrally on the outside of the base of the box, about 5 mm from the base of the Swiss Roll array. The receiver loop was scanned across the surface of the array, 68 mm above the source, and the signal was measured using a network analyzer that recorded 401 frequency points between 15 and 35 MHz at each location.

The intensities at 15 and 21.3 MHz are shown as the red lines in Fig. 2, as a function of distance from the centre of the slab measured along a diagonal. The material was then removed, and the scan repeated (at a height of 68 mm); the results are the black lines in Fig. 2. Finally, the receiver was set at a height of 8 mm, the equivalent height had the 60 mm long Swiss Rolls not been present, and the scan repeated. This is shown as the blue line in Fig. 2.

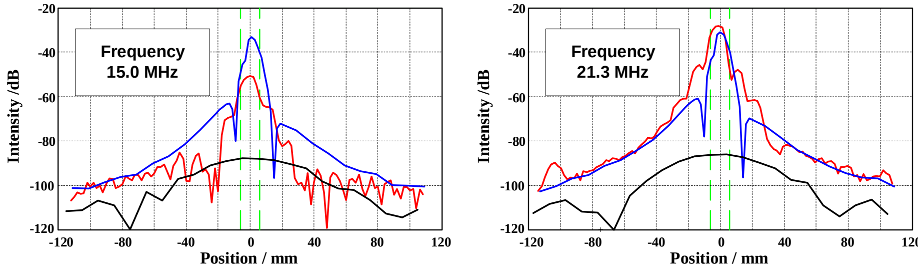

Fig. 2. Surface scans at two frequencies, below resonance and on resonance. The source is a 3 mm diameter loop, 5 mm from the rear surface, on the centre line. Red lines: scanning across the surface of the material along a diagonal at a height of 68 mm. Black lines: scanning at a height of 68 mm with no material. Blue lines: scanning at a height of 8 mm with no material. The extent of the central roll is indicated by the dashed green lines.

At low frequency (15 MHz), the permeability is slightly elevated ($\mu = 1.4$), and the signal through the material slab lies between the two background scans, and the peak intensity is 20 dB below the 8 mm reference level. At 21.3 MHz, however, the signal matches the reference level closely, across the whole extent of the scan, except at the nearest neighbor positions, where the reference signal passes through a minimum. This discrepancy is due to the transverse coupling of intensity between neighboring rolls [9], which overcomes the lack of signal from the applied field. Of particular note is that the peak intensity through the material slab equals (or, indeed, slightly exceeds) the reference level. It should also be mentioned that, at slightly lower frequency (20.8 MHz), the minima in the reference field are better represented in the signal through the material: the effect of the inter-roll coupling is weaker off-resonance. At higher frequency, the inter-roll coupling allows a spectrum of excitations [9] to be seen, leading to a complex range of behavior extending to about 30 MHz. In this paper, however, we concentrate on the behavior at 21.3 MHz, just below resonance.

To test the two-dimensional imaging performance of the material, we constructed an antenna from a pair of anti-parallel wires, bent into the shape of the letter M (Fig. 3(a)). This generated a line of magnetic flux, so providing a characteristic field pattern for imaging. It was placed horizontally, and the material was positioned on top of it (Fig. 3(b)).

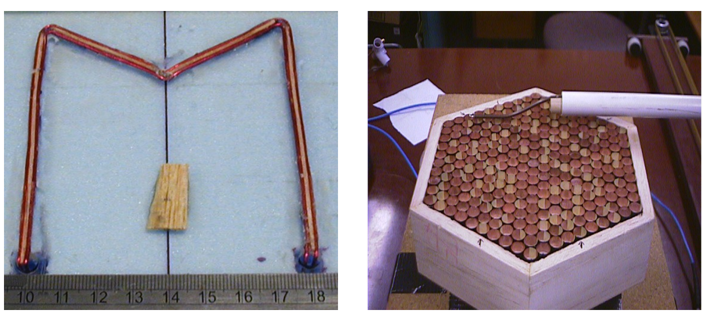

Fig. 3. (a) The M-shaped antenna, constructed from two antiparallel wires held 1 mm apart. (b) The slab of Swiss Rolls placed on the antenna, and the scanning loop help above it.

The transmitted field was measured by scanning a 3 mm diameter loop probe in a horizontal plane, about 2 mm above the surface of the material (see Fig. 3(b)). Measurements were made on a grid, 2 mm square, again recording the signal at 401 frequency points between 15 and 35 MHz using a network analyzer. The pattern thus

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observed at 21.3 MHz is shown in Fig. 4, in which the Swiss Roll structure is overlaid on the field pattern.

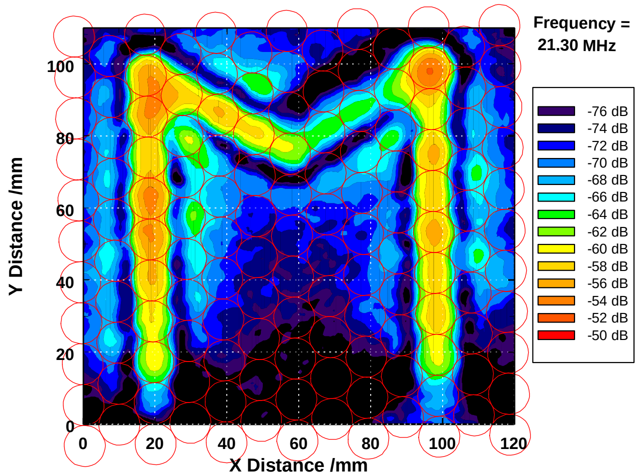

Fig. 4 The field pattern observed at 21.3 MHz in a plane approximately 2 mm above the surface of the material slab. The Swiss Roll structure is overlaid.

Figure 4 clearly shows that the material does indeed act as an image transfer device for the magnetic field. The shape of the antenna is faithfully reproduced in the output plane, both in the distribution of the peak intensity, and in the "valleys" that bound the M. These mimic the minima in the input field pattern either side of the central line of flux. The upper right arm of the M itself was twisted, so that the flux pattern was launched with a much reduced vertical component. This is reproduced in the weaker intensity observed in this region.

5. Discussion

In our previous work [7], the material had a peak permeability of ~3.3 and a quality factor Q of the resonance of ~ 9. According to the present theory, such a material would act as a transfer device only for thicknesses < 18 mm. Since the rolls were 200mm long, it is clear that no spatial information could be preserved: all the image information lay in the phase and frequency encoding imposed by the MRI machine. The present material has much less loss, resulting in much higher Q and peak μ. Moreover, the rolls are only 60 mm long. These conditions have allowed us to demonstrate the preservation of spatial image information through the material. An ideal, lossless material would transfer magnetic potential from one side to the other without any spreading, leading to the concept of the magnetic "wire". The real material does have loss, so the "wires" are not perfect; they allow the image to spread, reducing the resolution. Moreover, the diameter of the rolls themselves limits the potential resolution: we do not expect to see structure within the area of a single roll. Both criteria, therefore, suggest a limiting resolution of ~10 mm for the present material, and that is what we observe. Thus we have confirmed the prediction that structure in the magnetic near field can be transferred using an anisotropic metamaterial.

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