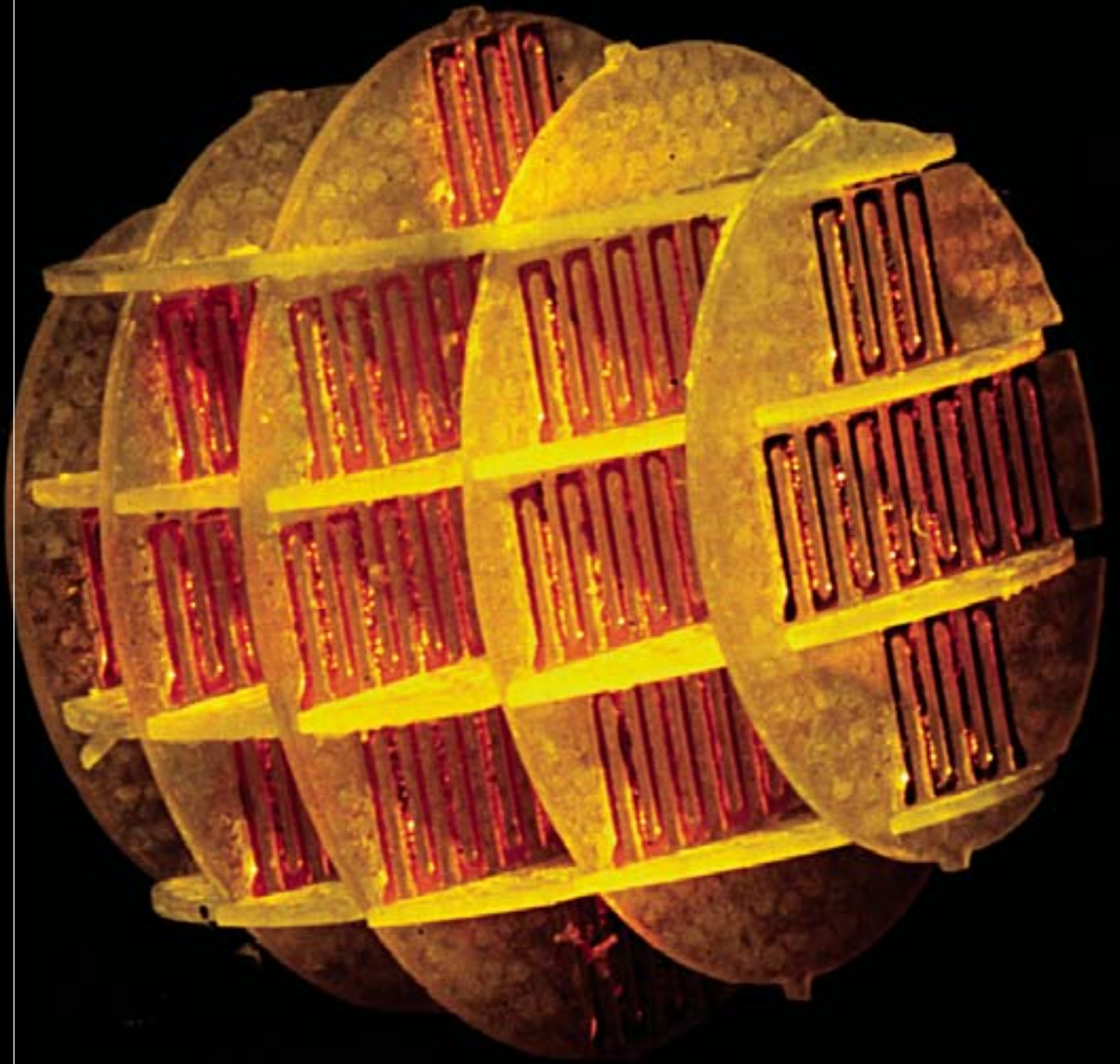
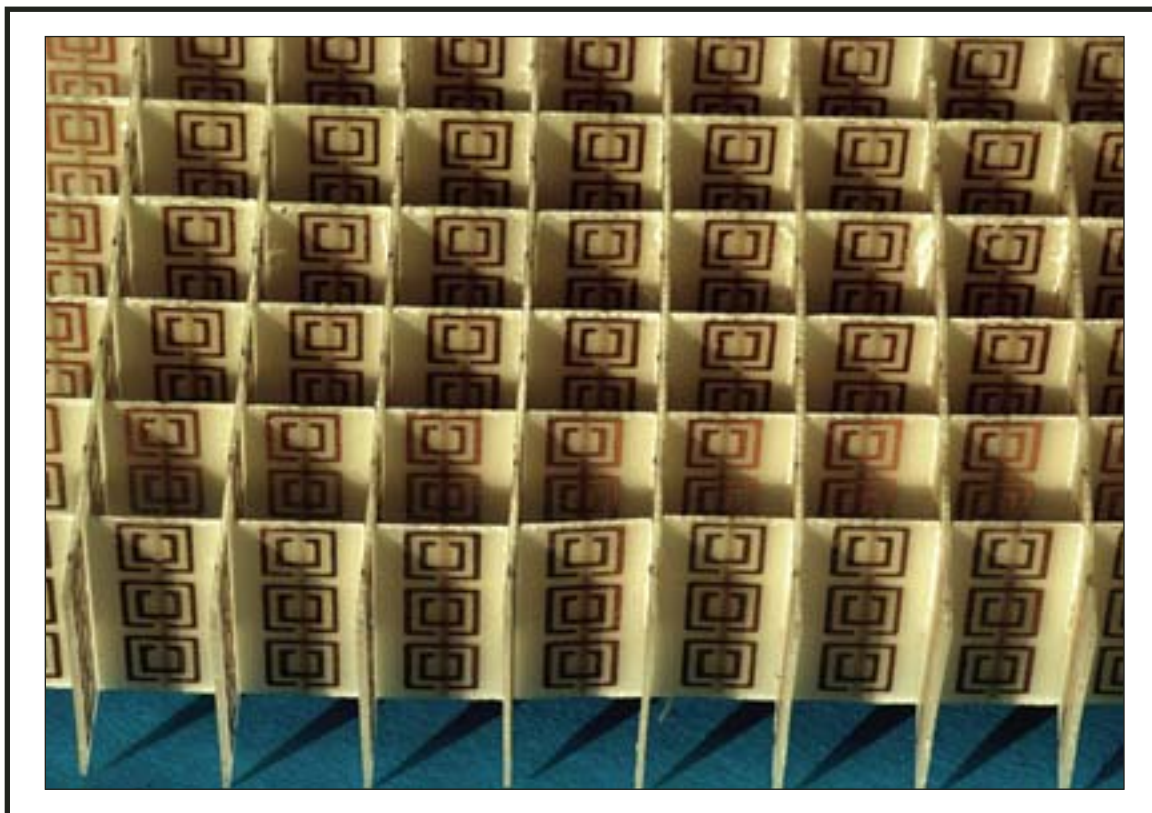


Manipulating the Near Field With Metamaterials



John Pendry



The near field is the awkward customer in electromagnetism: it refuses to radiate away from objects and therefore cannot be captured by a conventional optical system. Locked away in the near field are the fine resolution details of the object; their absence from a conventional image limits resolution to the order of a wavelength. New technology is enabling us to manufacture a class of electromagnetic materials engineered on a scale of much less than a wavelength, so that their structure is invisible to radiation. The new materials have properties not seen in nature—such as a negative refractive index—which are the key to controlling the near field. They imply short wavelength resonances on the surface which couple to and capture the near fields on neighboring surfaces. Most of the demonstrators have operated in the GHz region of the spectrum where engineering is easier, but structures exhibiting magnetism at THz frequencies have been built. At optical frequencies, metamaterial designs that exploit the plasma resonances of a free metal surface are waiting to be exploited.

(Facing page) A sphere constructed of metamaterial by David R. Smith of the University of California, San Diego, designed to mimic a plasma but with a resonance in the GHz region of the spectrum. The sphere has a diameter of about 10 mm. *(Above)* A split ring structure etched into copper circuit board plus copper wires to give negative ϵ and negative μ . The cell side is approximately 10 mm and the operating frequency around 10 GHz. (Courtesy David R. Smith, UCSD.)

Light creates images with a pencil no sharper than the wavelength, hence the limitations in performance of DVDs, optical lithography and a host of other imaging technologies. Or so we are led to believe. Yet, there are circumstances where electromagnetic fields define detailed structure on a much finer scale. Consider two very small and closely spaced dielectric spheres illuminated by visible light. Probing the electric dipole field around the spheres would clearly reveal the position of the spheres even if they were each only a nanometer in diameter and separated by as little as 10 nanometers. Only when we try to capture and focus the scattered light do we lose the fine details. This example shows that there are two sorts of light: the far field, which radiates freely and can be captured by a lens, and the near field, which does not radiate freely but contains the finest details of an object.

The near field is not some rare and exotic quantity; rather it is to be found whenever light is radiated or scattered. It is, in fact, the dominant component of the fields close to an aerial, and as such can be something of an obstacle to efficient radiation from mobile telephones.

Despite its ubiquitous nature and the valuable information it contains, the near field has proven difficult to control and exploit using the current generation of materials. This is the cue for the second theme of this article: scientists are creating new materials with entirely novel electric and magnetic properties not found in nature. These properties are created artificially by structuring the material on a length scale intermediate between the wavelength and the atomic scale. Hence the term "metamaterial." The material still appears to be homogeneous, but its electromagnetic properties are engineered through structure rather than relying on the response of constituent atoms.

Metamaterials are distinct from photonic bandgap materials: the latter derive their properties from diffraction of radiation and therefore by definition are structured on the same scale as the wavelength. Metamaterials, in contrast, are structured on a much finer scale, typically between $1/10^{\text{th}}$ and $1/1,000^{\text{th}}$ of the wavelength.

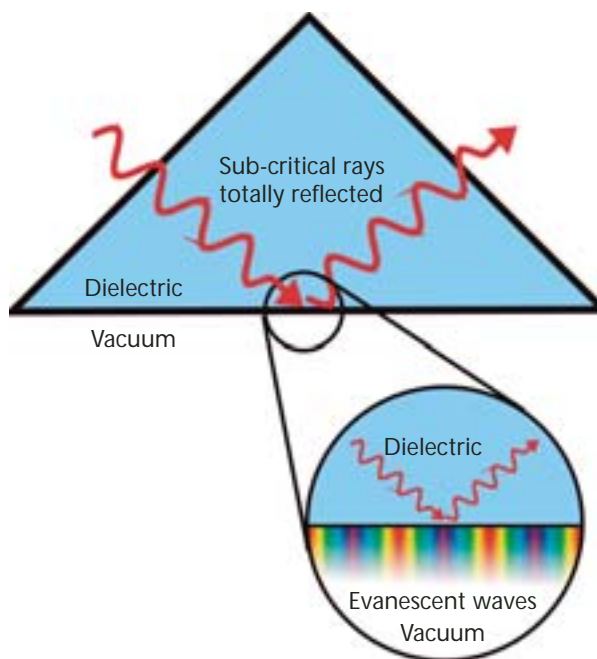


Figure 1. When light is totally internally reflected from a dielectric/vacuum interface, the field in the vacuum is not zero, but dies off rapidly away from the interface. This is an example of the near field.

The new materials, which can be designed to interact strongly with the near field, give a new dimension of control in electromagnetism. Practical realizations of these designs are, at the moment, largely confined to RF applications where the longer length scale makes the engineering easier, but this area of research is moving rapidly and technology appropriate to the visible region is being developed.

Let us get to grips with the near field. Perhaps its simplest manifestation occurs when a prism totally reflects light internally. Even though the light is totally reflected, some energy penetrates into the vacuum; the intensity decays rapidly away from the interface. We can describe this quantitatively by recognizing that if the light is propagating in the xy plane, the electric field has the form,

$$\mathbf{E} = \mathbf{E}_0 \exp(ik_x x + ik_y y - i\omega t)$$

and from Maxwell's equations,

$$k_y = \pm \sqrt{\epsilon \mu \omega^2 / c_0^2 - k_x^2}$$

where ϵ is the electrical permittivity and μ the magnetic permeability of

the medium. If $\epsilon \mu$ is large and k_x small, then k_y is real. This means that the wave can freely propagate toward the surface (positive sign to the square root) or away from the surface (negative sign to the square root). On the other hand, in the example we have chosen, in the vacuum $\epsilon \mu$ is now much smaller and the argument of the square root is negative, making k_y imaginary,

$$k_y = \pm i \sqrt{k_x^2 - \omega^2 / c_0^2}$$

causing the wave to decay exponentially away from the interface.

Another characteristic of the near field is that for $k_x \gg \omega c_0$, when the decay becomes extreme, the fields increasingly factorize into almost pure electrical and almost pure magnetic fields with little coupling between them. At length scales much smaller than the wavelength, electromagnetism reduces to electrostatics plus magnetostatics.

Dielectrics are not, in fact, very potent sources of the near field. For this we must look to the surfaces of hot resistive materials where very strong, short wavelength fluctuations can be found localized near the surface. These are largely of electrical

character and can be thought of as the Johnson noise fringing into the vacuum. They contain a far greater energy density than do the radiation fields that carry heat away from the surface. Evanescent fields carry no heat flux, unless there is a second surface nearby into which they can tunnel. Radiative heat transport between nanostructures is dominated by the near field.¹

Another example of the importance of the near field is the Van der Waals force. Quantum fluctuations of electromagnetic fields outside surfaces are largely near field in character, and it is the tunneling of these localized fields from one surface to another which produces the force. Their evanescent character explains the attractive nature of Van der Waals forces—in contrast to the *repulsive* forces which result from the exchange of radiative fields between surfaces.

Lenses and other instruments of optical control function because they are able to accept the propagating electromagnetic modes of which ordinary light is composed. To control the near field we must identify materials that accept the near field equivalent: strongly decaying modes that are rapidly spatially varying. Typically these modes are associated with surface plasmons; surface plasmons are a type of excitation of electronic charge density at a surface first identified and explained by Ritchie.²

Ritchie showed that in some materials, such as metals, there are electromagnetic states which are bound to the surface but have an oscillatory character in the surface plane. These electromagnetic states are associated with the interface between two materials: one with a positive dielectric function, the other with a negative one. For example, at the interface between a metal, such as silver, and vacuum, a surface plasmon of frequency ω_{sp} exists when $\epsilon(\omega_{sp}) = -1$. The negative values of the dielectric function are the key to the existence of surface plasmons and the key to controlling near fields of electrical character. Near fields of magnetic character require the complementary property of negative permeability.

A simple example of a metamaterial suffices to illustrate the importance of $\epsilon < 0$. Consider Fig. 2, which illustrates a

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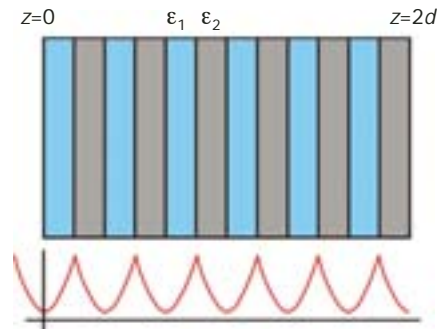


Figure 2. (Top) Simple metamaterial comprising alternate layers of a metal, such as silver, and a dielectric. The layers are presumed to be very thin, much less than the wavelength of light. (Bottom) Schematic electric field intensity in the metamaterial showing how a chain of surface plasmon excitations conveys the field from one end of the material to the other.

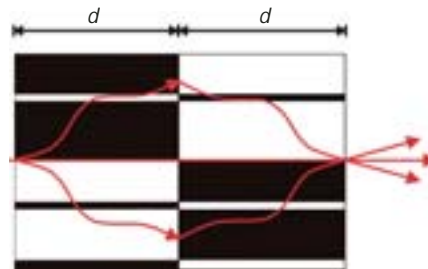


Figure 3. Two media annihilate one another in an optical sense if ϵ, μ in one is the negative mirror image of ϵ, μ in the other. Here we show the trajectory of an electromagnetic ray with the second medium correcting for the diversion created by the first.

metamaterial comprising alternate layers of silver, permittivity ϵ_1 , and a dielectric with permittivity ϵ_2 . The layers are presumed very thin and of equal thickness so that as far as light is concerned, the composite is homogeneous but anisotropic. Next, we choose to work at a frequency such that,

$$\epsilon_1 = -\epsilon_2 + i\delta,$$

where $i\delta$ represents the losses in silver. By considering the average electric field we can calculate the effective permittivity for fields perpendicular to the layers,

$$\epsilon_{\perp eff}^{-1} = \frac{1}{2} (\epsilon_1^{-1} + \epsilon_2^{-1}) \approx -\frac{1}{2} i\delta,$$

so that $\epsilon_{\perp eff}$ is large and imaginary, as is the case with a good conductor. Parallel to the layers,

$$\epsilon_{\parallel eff} = \frac{1}{2} (\epsilon_1 + \epsilon_2) = +\frac{1}{2} i\delta,$$

so that $\epsilon_{\parallel eff}$ takes a small imaginary value, as in the case of an insulator with low losses.

Evidently this system is mimicking a set of highly conducting wires aligned perpendicular to the sheets and separated by insulating material. As in the case of any system of wires, it will function as an endoscope: electrical fields at one end will be captured by the wires and relayed faithfully to the other end of the system. It does not matter whether the electrical fields are near or far, the wires simply grab them and regurgitate them at the far end. The lower part of Fig. 2 shows the schematic electric field intensity which comprises a series of surface plasmon excitations at each of the interfaces, handing the fields down from one layer to the next.

In some sense, the layers of alternating sign of ϵ are annihilating one another so that, optically speaking, the two ends of the system are one and the same entity. In our example, of course, this only works for the electric field, but a rigorous theoretical generalization states that if two slabs of material meet at a plane, they optically annihilate if ϵ, μ in one system is the negative of the corresponding point in the second system, mirrored in the plane that joins them.³ Figure 3 makes this point and since both the electric and

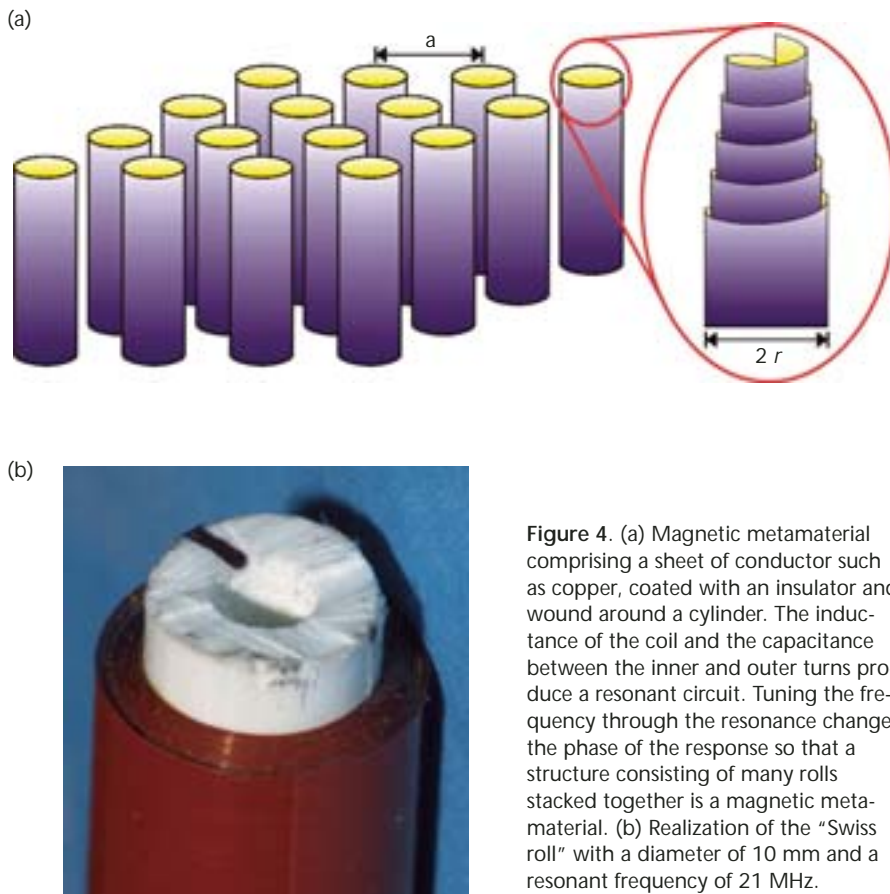


Figure 4. (a) Magnetic metamaterial comprising a sheet of conductor such as copper, coated with an insulator and wound around a cylinder. The inductance of the coil and the capacitance between the inner and outer turns produce a resonant circuit. Tuning the frequency through the resonance changes the phase of the response so that a structure consisting of many rolls stacked together is a magnetic metamaterial. (b) Realization of the “Swiss roll” with a diameter of 10 mm and a resonant frequency of 21 MHz.

magnetic fields are now included in the theorem, both the radiative and near field components are brought back to the same state. In effect, the system acts as a perfect lens, reproducing exactly the fields at one end of the system at the other.⁴ Of course, there is always some loss in real materials which prevents the requirements of the theorem being met precisely; the price paid is that the resolution is never perfect. Nevertheless, here is a system in which both the near and far fields contribute to image formation and therefore one in which the resolution can exceed the wavelength limit of conventional imaging systems.

The cancellation is perfect, at least in so far as the requirements of the theorem are met, and that is where we return to the question of metamaterials. In our first example, the electric fields alone were controlled by the metamaterial; to control the entire electromagnetic field requires materials that respond to the

magnetic as well as to the electric field, and in particular require both ϵ and μ to be simultaneously negative. No such materials are found in nature and therefore all our theorems concerning these systems are useless until we can engineer a metamaterial with the appropriate responses.

A loop of wire has a magnetic response to an external magnetic field because of the currents induced. Unfortunately the phase of the currents is such that only a diamagnetic response is seen. To create the more interesting responses, which produce negative values of μ , we must change the phase of the induced current. We do this by arranging for the conductors to be part of a resonant system. One of the first such systems devised⁵ was the so called “Swiss roll” structure (or “jelly roll” structure, depending on which side of the Atlantic you do your cookery on). Figure 4 shows a schematic of this magnetic metamate-

rial, which consists of an insulated metal sheet wound around a cylinder. The inductance of the coil and the capacitance between the inner and outer turns produce a resonance so that the response to a magnetic field is strongly paramagnetic just below the resonant frequency, $\mu \gg 0$, and above the resonant frequency $\mu \ll 0$. On resonance the permeability is purely imaginary, taking a large positive value dictated by the losses in the system, and the rolls behave like magnetic wires.

Mike Wiltshire⁶ has exploited this property to perform subwavelength imaging of a magnetic field. Figure 5 shows details of his experiment, in which the object is a set of coils formed into the shape of the letter “M.” The frequency employed was 21 MHz and the wavelength around 15 m. Since the dimensions of the experiment are of the order of 100 mm and the details to be resolved are approximately 10 mm, we are working in the extreme near field limit. A stack of rolls 60 mm thick was placed underneath the object coil and the magnetic field emerging from the far side was detected with a probe coil. The resulting scan, shown in Fig. 5 (b), clearly resolves details of the object on a 10-mm scale: $1/1,000^{\text{th}}$ the wavelength. In the absence of the rolls, details of the image are blurred by approximately the separation from the object, which is 60 mm.

This particular metamaterial is designed to manipulate the RF field in a magnetic resonance imaging machine in which the powerful DC fields require that any material has zero response to a static magnetic field.⁷

Another magnetic design replaces the conducting sheets with split rings of conductors⁵ which work on the same principle: just as before, the circulation of current around the ring and the capacitance across the split make a resonant circuit, so that an array of rings gives a magnetic response but in this case at a much higher frequency than the Swiss rolls: typically 10 GHz. The split ring design has been combined with an array of thin wires to produce a metamaterial with a negative magnetic and electric response. Smith and Schultz^{8,9} have used this design to confirm the existence of a negative refractive index, a property predicted many years ago¹⁰ by Veselago in

materials where ϵ and μ are simultaneously negative. At the beginning of this article there is a photograph of a structure similar to the one used by Smith and Schultz in their experiment. This demonstration sparked renewed interest in negative refraction and the split ring design has been something of a workhorse for the several proof of principle experiments and computations which have been made.¹¹⁻¹⁴

The split ring design has already been demonstrated to give magnetism in the THz region of the spectrum¹⁵ and it is believed that the concept can be extended into the infrared, bringing us close to the realization of magnetism at optical frequencies. Indeed, there has already been speculation that silver nanorods could be used to produce magnetic effects in the visible region.¹⁶ Ultimately the design is limited by losses in the metallic components, losses which become severe as we attempt to extend the design to optical frequencies.

Metamaterials open new doors for us in electromagnetism, giving access to material parameters not available in nature, including negative values of ϵ and μ . In particular we can now make material with a magnetic response at much higher frequencies than before. THz magnetism has been demonstrated and the infrared cannot be far behind. Where ϵ , μ are simultaneously negative, the refractive index is also negative. Internal resonances are associated with these negative parameters, which couple strongly to the near field and can be used to control and manipulate the near field in ways not previously thought possible.

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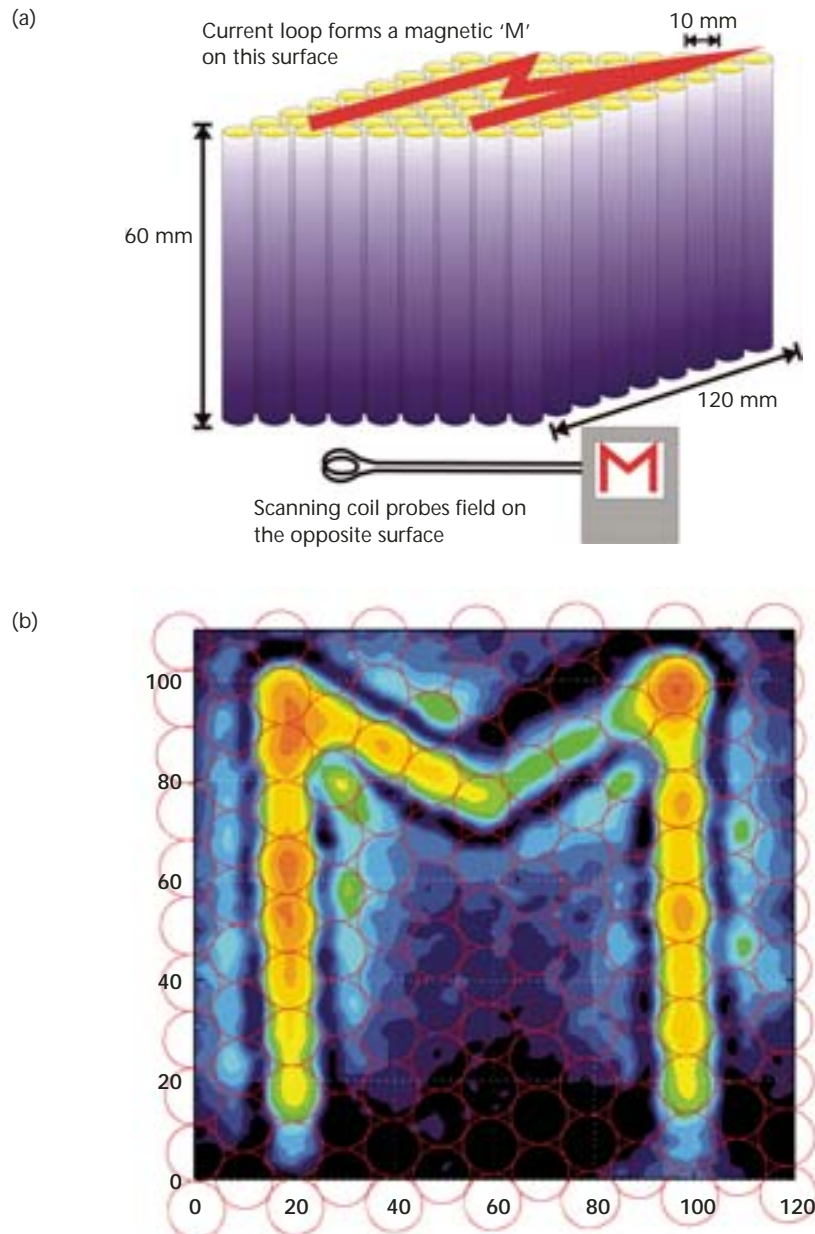


Figure 5. (a) Stack of 10-mm diameter Swiss rolls on resonance at 21 MHz behaves like a set of "magnetic wires" conducting magnetic field lines just as a normal electric wire conducts electric field lines. Current loops in the form of an "M" were placed at one end of the sample and the transmitted field measured by a probe coil. (b) Experimental results of a scan by a probe coil (dimensions marked in mm). The wavelength at 21 MHz is 15 m and therefore we are in the extreme near field limit, imaging details on a scale less than 1/1,000th the wavelength.

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