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Subwavelength microwave imaging using an array of parallel conducting wires as a lens

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An original realization of a lens capable of transmitting images with subwavelength resolution is proposed. The lens is formed by an array of parallel conducting wires and effectively operates as a telegraph which captures a distribution of the electric field at the front interface of the lens and transmits it to the back side without distortions. This regime of operation is called canalization and is inherent in flat lenses formed by electromagnetic crystals. The theoretical estimations are supported by numerical simulations and experimental verification. The subwavelength resolution of $\lambda/15$ and 18% bandwidth of operation are demonstrated at gigahertz frequencies. The proposed lens is capable of transporting subwavelength images without distortion to nearly unlimited distances since the influence of losses to the lens operation is negligibly small.

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The resolution of common imaging systems is restricted by the so-called diffraction limit, since these systems operate only with propagating spatial harmonics emitted by the source. The conventional lenses cannot transport evanescent harmonics which carry subwavelength information, since these waves exhibit exponential decay in natural materials and even in free space. In order to overcome the diffraction limit it is required to engineer an artificial material (metamaterial) with electromagnetic properties which dramatically differ from those of materials available in nature.[1] One of the options was suggested by Pendry in his seminal paper.[2] Pendry proposed using left-handed materials, isotropic media with both negative permittivity and permeability.[3] A planar slab of such a metamaterial provides unique opportunities to restore and even amplify amplitudes of evanescent modes. This becomes possible due to resonant excitation of surface plasmons at the interfaces of the slab. However, the promising theoretical predictions meets numerous practical difficulties in the development of left-handed metamaterials. On the one hand, the major problem is to create the materials possessing magnetic properties at optical and tetrahertz frequencies.[4,5] On the other hand, the issues related to losses play a very important role as well. The enumerated problems are closely related with the fundamental restrictions and can be hardly overcome. There are other options to reach the subwavelength resolution, for example,[6,7] or an idea suggested by Wiltshire.[8,9] The last idea is based on the use of an array of magnetic wires, so-called Swiss rolls[10] in order to transfer subwavelength information directly from the source to the image plane (pixel-to-pixel imaging principle). The lens formed by the Swiss rolls have to be placed in the near field of the source since it is capable of transporting rather than amplifying evanescent harmonics. This realization of subwavelength imaging experiences similar problems as those in the development of left-handed medium; it is essential to obtain a metamaterial with magnetic properties and also keep the losses small.

In the present paper we suggest an alternative approach to constructing the subwavelength lens which does not require magnetic properties. The imaging device is formed by an array of parallel conducting wires, so-called wire medium,[11–14] see Fig. 1. At first sight it seems that this structure is an electrical analog of Wiltshire's system. An array of Swiss rolls, being similar to magnetic wires, is capable of transmitting s-polarized [transverse electric (TE)] spatial harmonics of the source spectrum. An array of wires operates in the same manner, but for p-polarized [transverse magnetic (TM)] waves. In other words, an array of Swiss rolls restores at the back interface normal components of magnetic field produced by the source. An array of wires restores normal components of the electric field. At the same time, there is a serious difference between the Wiltshire's system and the slab of wire medium. The Swiss rolls are artificial resonant structures which behave as magnetic wires only at the frequencies in the vicinity of the resonance. This fact restricts the Swiss rolls to be narrow-band and very lossy. However, the conducting wires in this sense are natural electrical wires. It means that they are wide-band and practically lossless. The absence of strong losses (inherent in Swiss rolls) in ordinary wires lifts the restriction on the lens thickness. It allows us to create subwavelength lenses of nearly arbitrary thickness and deliver images with subwavelength resolution into the far-field region of the source and beyond. The imaging system effectively works as a telegraph formed by a multiconductor transmission line.

Different spatial harmonics incident to the front interface

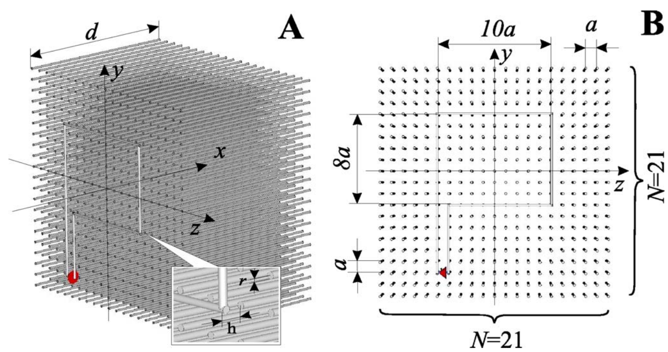

FIG. 1. (Color online) Geometry of the flat lens formed by the wire medium and the source of the form of the letter P. (A) Perspective view. (B) Front view. Parameters: $a=10$ mm, $r=1$ mm, $d=150$ mm, $h=5$ mm, $f=1$ GHz.

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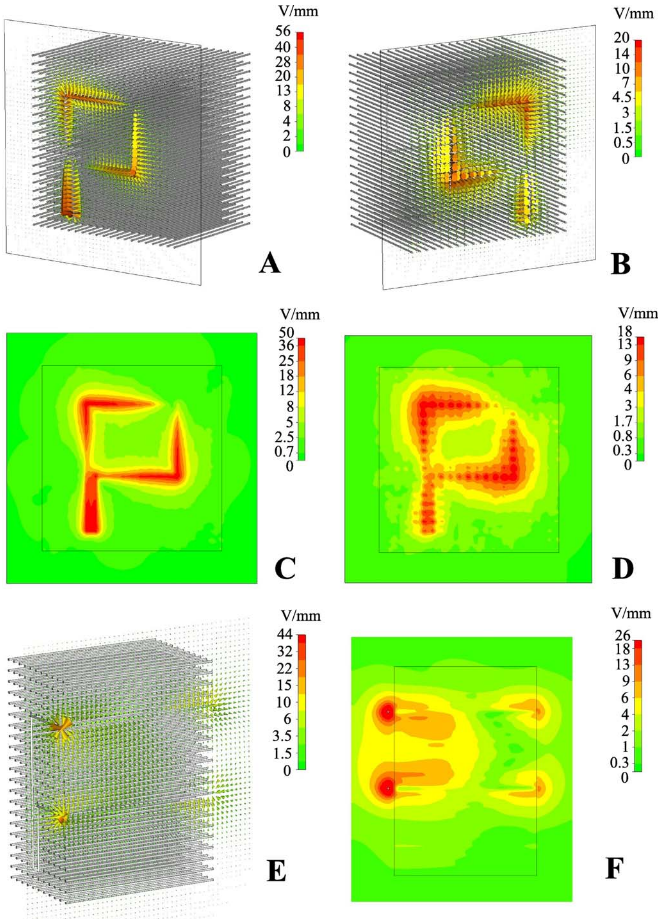

FIG. 2. (Color online) Distribution of electric field and its absolute value: (A),(C) in the vicinity of the source (at 2.5 mm distance from the front interface); (B),(D) in the image plane (at 2.5 mm distance from the back interface); (E),(F) in the transverse plane.

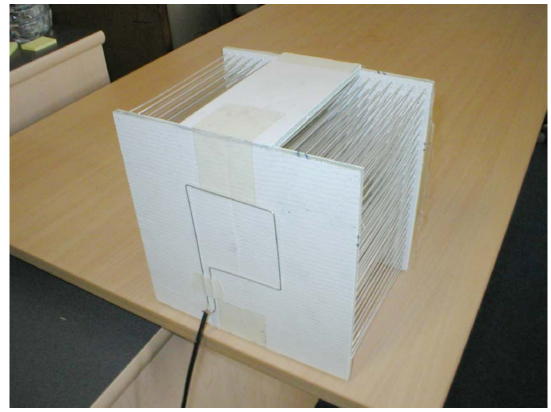

FIG. 3. (Color online) Photo of wire medium lens used in the experiment.

of the lens formed by a wire medium experience different reflection/transmission properties. It happens due to impedance mismatch between air and wire medium. The wire medium has a surface impedance for *p*-polarization which is independent of incidence angles in contrast to the air which the surface impedance varies for different angles of incidence. The reflections from the thin slabs are negligibly small, but become significant for thick layers. This problem can be solved by choosing an appropriate thickness of the slab in order to fulfill conditions for the Fabry-Perot resonance and reduce reflections. Actually, the reflections can be eliminated completely in the present case in contrast to those in the classical Fabry-Perot resonator where nonzero reflections are inevitable for oblique incidences. For any incidence angle the wire medium supports propagating modes, so-called transmission line modes,[14] which travel across the slab with the same phase velocity equal to the speed of light. If the slab thickness is chosen to be an integer number of half-wavelengths, then the Fabry-Perot condition holds for any incidence angle (including complex ones) and hence such a slab experiences total wave transmission. This phenomenon of collective reduction of reflections for all angles of incidence together with the fact that the waves are allowed to transfer energy only across the slab (along the wires) with a fixed phase velocity is called a canalization regime.[15] This regime can be observed in various electromagnetic crystals which possess flat isofrequency contours at certain frequencies.[16–18] The wire medium is a unique example of electromagnetic crystals with such properties observed at very long wavelengths as compared to the period of the crystal, which opens up the possibility of obtaining a nearly unlimited resolution of subwavelength imaging. Resolution of the lens formed by a wire medium is restricted only by its period which can be made as small as it is necessary for certain applications. In the present case the resolution is equal to the double period of the lattice; two different objects can be distinguished if they are located close to two different wires, but their location within one elementary cell cannot be determined. It means that the wire medium lens has the best possible resolution among other periodical structures since in Ref. 19 it has been shown that a double period of the lattice is an ultimate limit for resolution of superlenses formed by electromagnetic crystals.

In order to verify the concept described above, numerical simulations of the structure presented in Fig. 1 were performed using the CST Microwave Studio package. The lens consisting of an array of 21×21 aluminum wires excited by a source in the form of a P letter was modelled. The operating frequency f is 1 GHz, the length of the wires (thickness of slab) d is 15 cm (a half wavelength in the free space), the period of the lattice a is 1 cm, the radius of the wires r is 1 mm. The source in the form of a P letter is placed at $h=5$ mm distance from the front interface of the lens and fed by a point current source $I=1$ A. Results of the simulation are presented in Fig. 2. The source produces subwavelength distribution of the electric field at the front interface of the slab, see Fig. 2(A). The *p*-polarized contribution of the field is canalized from the front interface to the back interface and forms an image, see Fig. 2(B). The quality of the imaging can be clearly seen in Figs. 2(C) and 2(D), where absolute values of electric field in the vicinity of the front and back interfaces are plotted. The local maximums of the field intensity produced by terminations of the wires are visible in Fig. 2(D). The resolution of the imaging system can be evaluated as a radius of spot at a half of field intensity level. In the present case the resolution is equal to 2 cm (double period of the structure), which is one-fifteenth of the wavelength ($\lambda/15$).

The canalization principle can be easily illustrated with the help of Figs. 2(E) and 2(F), where distribution of electric field in transverse plane is presented. Two sources [visible at the left sides of Figs. 2(E) and 2(F)] produce both *s*- and *p*-polarized spatial harmonics. The *s*-polarized harmonics practically do not interact with the wire medium since they have electric fields perpendicular to the thin wires. The lens behave nearly as an air for such waves. Therefore, the *s*-polarized evanescent harmonics decay with the distance and practically disappear at the center of the slab; their contribution is visible only in vicinity of the front interface. In contrast to these waves, the *p*-polarized harmonics are guided by wires and canalized from the front interface to the back one. The trace of their propagation is visible inside the slab. This waves form an image at the back interface [right-hand sides of Figs. 2(E) and 2(F)].

Excellent correspondence between theoretical predictions and numerical simulations proves validity of the canalization regime. Further confirmation is also achieved by experimental verification. A slab of wire media with the same parameters as in Fig. 1 was constructed. A photo of the lens is available in Fig. 3. The wires are fixed by thin slabs of foam which have relative permittivity close to unity at frequencies around 1 GHz. The source is an antenna in the form of the P letter directly fed by a coaxial cable and located at the surface of the foam (approximately 3 mm away from the terminations of wires). The mechanical near-field scanning device was used for measurements of electric field distribution in the source plane (5–7 mm from the source and front interface of the lens) and image plane (4–6 mm from the back interface of the lens). A short piece of wire (1 cm long) connected to the central conductor of a coaxial cable was used as a probe. The measurements have been done for *x*-, *y*-, and *z*-orientations of the probe (see Fig. 1 for orientation of axes). The best quality of imaging was observed at 980 MHz. This frequency corresponds to the Fabry-Perot resonance and it is slightly lower than the theoretical value of 1 GHz due to the tolerance of sample construction. The measurement results are presented in Fig. 4. The *x*-component of the electric field (normal to the interface) is nearly completely restored at the back interface, but some parts of *y*- and *z*-components, which have *s*-polarization are lost during the imaging. The absolute values of measured electric fields in source and image planes are plotted in Figs. 4(G) and 4(H) for comparison with results of numerical simulation presented in Figs. 2(C) and 2(D). The probe used for the measurements does not allow us to determine an exact value of the local field; it actually provides an averaged value by a volume of about 1 cm × 1 cm × 1 cm around the probe. That is why the maxima visible at Fig. 2(D) related to the terminations of the wires cannot be observed at Fig. 4(H). In spite of that the general behavior of the measured field and distribution predicted by numerical simulations are identical.

The experimental studies show that the imaging with 2 cm resolution is observed at 980 MHz. Further experiments demonstrate that the subwavelength imaging keeps within 920 MHz–1.1 GHz frequency range. It means the

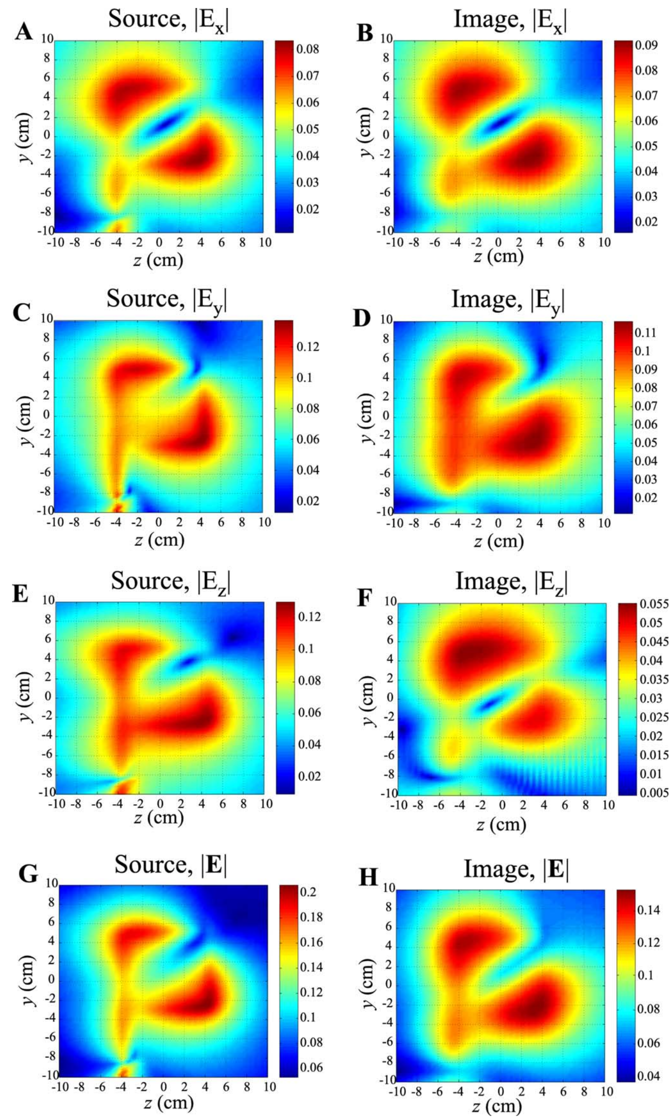

FIG. 4. (Color online) Results of near field scan measurements: absolute values of *x*-, *y*-, and *z*-electric field components and total field in arbitrary units: (A,C,E,G) in the source plane and (B,D,F,H) in the image plane, respectively.

bandwidth of the wire medium lens is about 18% which is incomparably wider than the bandwidth of operation for the Swiss rolls. The similar imaging effects are also experimentally observed within 1.9–2.1 GHz frequency range. It corresponds to the Fabry-Perot resonance appearing when the thickness of the slab is equal to the whole wavelength. This confirms that the imaging exists when the thickness of slab becomes equal to the integer number of half-wavelengths and that the observed effects are well described by the canalization regime. Therefore, the lens can be made arbitrarily thick and no distortions will appear. The Ohmic losses caused by the currents in the wires do not disturb the imaging quality. These losses only reduce field intensity of the image, in the same manner as that in long multiconductor transmission lines.

In conclusion, it is necessary to note that in the present paper we proposed the lens formed by conducting wires capable of transmitting images with subwavelength resolution for long distances as compared to the wavelength. The lens operates in the canalization regime when any incident spatial harmonics transform inside the crystal into the plane waves which deliver images from one interface to another. The plane waves in the crystal travel with the same phase velocity which allows us to tune the thickness of the slab to fulfill the Fabry-Perot condition for any incident angle and achieve total transmission. This imaging effect was verified both numerically and experimentally at gigahertz frequencies. The subwavelength resolution of $\lambda/15$ and 18% bandwidth of operation are demonstrated. It is shown that the system is not sensitive to the losses in the wires. All listed effects become possible only due to the presence of transmission line modes in the wire medium and strong spatial dispersion.[14] The wire medium effectively becomes an anisotropic dielectric with an infinite permittivity along the anisotropy axis and it is caused not by the frequency resonance as in the case of Swiss rolls but by strong spatial dispersion effect. Following Ref. 14, the component of the wire medium permittivity tensor corresponding to the direction along the wires in the spectral region has the form,

$$\varepsilon_{\parallel}(\omega,q) = \varepsilon_0\left(1 - \frac{k_0^2}{k^2 - q^2}\right),$$

where ω is frequency, q is the component of the wave vector along wires, $k=\omega/c$ is the wave number, c is the speed of light, and k_0 is the wave number corresponding to the plasma frequency. The transmission line modes travel along wires and have $q=k$. It means, that for such modes the wire medium effectively has infinite permittivity. The losses in wires influence to the plasma frequency, make it complex[20] and thus do not affect the value of permittivity corresponding to transmission line modes.

The present realization of the canalization regime with the help of a wire medium is advantageous at microwave frequencies, but it cannot be realized at an optical range where metals lose their conducting properties. It does not mean that implementation of the canalization regime in optical range is impossible. This regime can be realized using photonic crystals,[15,21,22] but resolution of such lenses will be restricted by the period of the crystals which cannot be reduced too much due to the absence of high-contrast lossless materials at the optical range. The other possibility is to construct uniaxial material with infinite permittivity along the anisotropy axis. It can be done using lattices of resonant uniaxial nanoparticles or multilayered structures.[23,24]

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