Transmission of images with subwavelength resolution to distances of several wavelengths in the microwave range

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We report experimental results that demonstrate transmission of a microwave image by means of an array of parallel metallic rods over a distance that is 3.5 times greater than the wavelength. The resolution of such an imaging device is 15 times less than the wavelength. The magnifying, demagnifying, and repeating properties of the lenses formed by the long metallic rods provide a unique solution for subwavelength imaging at the microwave range. The resolution of such lenses is mainly determined by the characteristic period, which is only limited by the fabrication capability rather than by any physical constraints. The lenses can be scaled down to operate at terahertz and midinfrared frequencies.

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Lens-based imaging devices, such as microscopes, for instance, cannot provide a resolution better than the half-wavelength of radiation. This restriction, which is known as the diffraction limit, takes hold irrespective of the frequency of operation—from microwave frequencies up to the visible range. Conventional lenses operate only with the far field of the source, which is formed by propagating spatial harmonics. The information related to the near field of the source is transported by evanescent spatial harmonics, which exhibit exponential decay in all natural materials as well as in free space. For this reason, the subwavelength details of the near field are not directly accessible with conventional imaging systems.

By transforming the evanescent harmonics into propagating waves inside a metamaterial, it is possible to transport an arbitrary field distribution through such a material with no loss of resolution provided that all the spatial harmonics propagate with the same phase velocity along a fixed direction. Lenses formed by slabs of such materials provide a unique opportunity to transmit the near field with super-resolution to a significant distance from the source that cannot be achieved by using other available imaging techniques. This phenomenon was suggested and named as canalization regime in our work.[1]

Media required for implementation of this regime are not directly available in nature. However, these materials may be synthesized as microstructured materials. In particular, an array of long thin parallel metallic wires has the necessary properties[2] in the microwave range.

A planar wire medium slab (Fig. 1) allows the transformation of the near field that is produced by a source placed in the vicinity of the slab into propagating transmission line modes. These modes propagate along the wires and transfer the distribution of electric field from the front interface of the lens to the back interface without distortion. Wire medium lenses operating in the microwave frequency range can be scaled down to the micrometer scale in order to provide a subwavelength imaging capability in the terahertz and even the midinfrared bands, as it was shown in Refs. 3–5.

A slab of a wire medium can also be regarded as a bundle of subwavelength waveguides that perform pixel to pixel imaging. Each wire plays the role of a waveguide delivering information from one side of the lens to the other. The waveguides are to some extent decoupled, which enables the propagation of waves along neighboring wires with negligibly small interaction. The imaging resolution is about two periods of the wire medium[6] and, in principle, can be made as small as required by a given application.

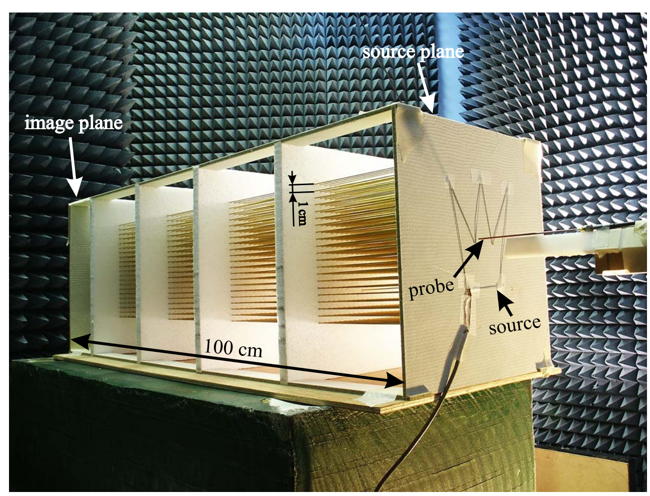

FIG. 1. (Color online) Photograph of the wire medium lens: 21×21 array of parallel 1-m long aluminum wires. The period of the array is 1 cm. The radius of the wires is 1 mm. The source in the form of a crown is adjacent to the front interface of the lens. The source is fed by a coaxial cable connected to a network analyzer. A small electric probe used for near field scan is shown together with the supporting arm.

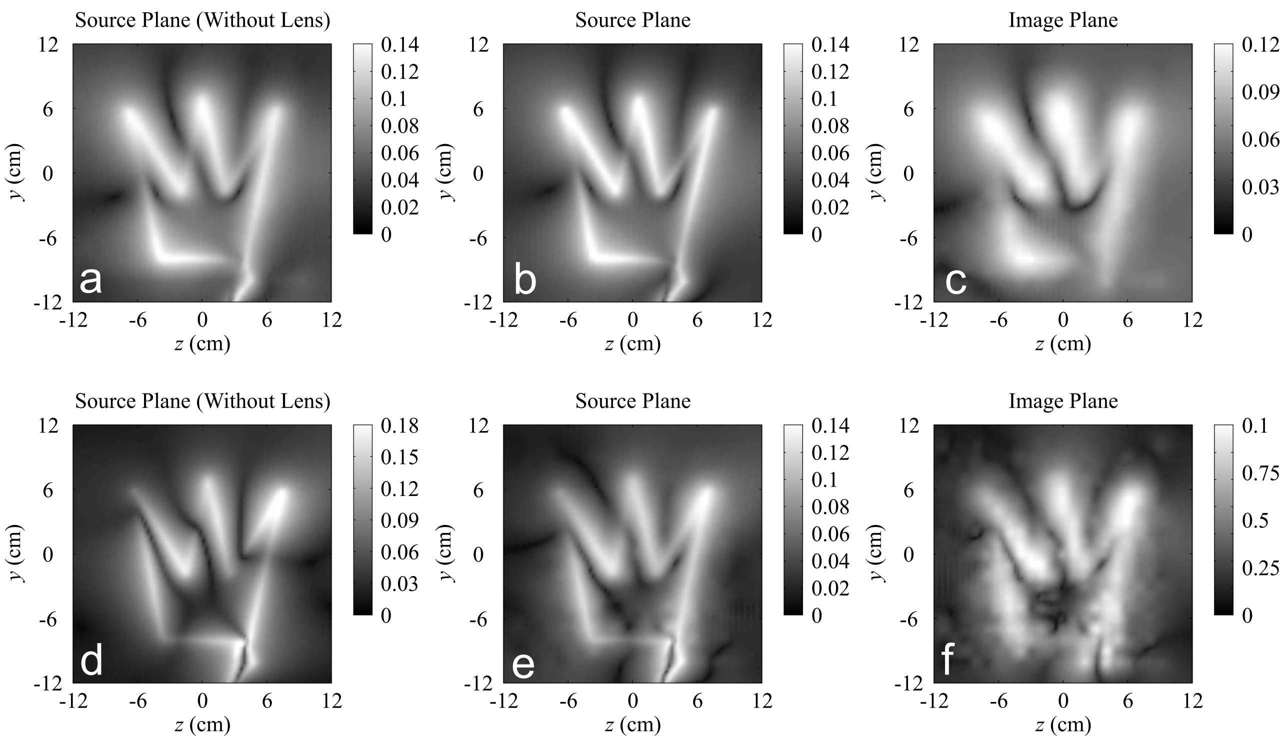

FIG. 2. Results of the near-field scan at the source plane (2 mm away from the front interface of the lens) without (a) and with (b) the wire medium lens and (c) at the image plane (2 mm away from the back interface of the lens) at 894 MHz. (d), (e), and (f) are the same as (a), (b), and (c) but at 1038 MHz.

In contrast to conventional lenses, near-field lenses have to be placed in the close vicinity of the source in order to capture evanescent waves. Thus, it is important to ensure that the lenses do not distort the source field distribution. An ideal near-field lens should not produce any reflections. The problem of possible harmful reflections from the lens can be eliminated by properly choosing its thickness so that it operates as a Fabry-Perot resonator. The thickness should be equal to an integer number of half-wavelengths inside the host material. In the case of a wire medium, the Fabry-Perot condition is simultaneously verified for all angles of incidence, including complex ones. This collective resonance makes the transmittance of the lens equal to unity for any propagating or evanescent waves. This outstanding property is justified by the fact that all transmission line modes travel across the slab with the same phase velocity, irrespective of the transverse wave vector. Thus, the total electrical length of the slab remains the same for all incidence angles.

In order to demonstrate the potentials of subwavelength imaging by slabs of wire media, a 1-m long wire medium lens with a 1 cm period was constructed and tested. The photograph of the lens located in the anechoic chamber together with the setup for near-field scan is presented in Fig. 1. The 1-m long lens operates at frequencies around $150n$ MHz corresponding to Fabry-Perot resonances of the nth order. The lens being tested is about seven times longer than the 15-cm long lens used for the preliminary experiments reported in Refs. 7 and 8. This allows us to demonstrate the transmission of subwavelength images to distances more than three times larger than the wavelength at frequencies around 900 and 1050 MHz, which correspond to Fabry-Perot resonances of the sixth and seventh orders, respectively. In the initial experiments,[7,8] the images were transmitted to a half-wavelength distance only.

A wire antenna shaped as a crown was taken as the near-field source. The source was placed near the front interface of the wire medium lens as shown in Fig. 1, and the near field at a 2 mm distance from the front and back interfaces of the lens (source and image planes) was scanned by using an automatic mechanical planar near-field scanner. The collected data were compared to the reference near-field distributions obtained by scanning the near field created by the source in free space. The comparison is necessary to confirm that the lens does not perturb or distort the near field of the source. The results of the near-field scan at 894 and 1038 MHz are presented in Fig. 2. A near-field distribution that reproduces the crown shape of the wire antenna is clearly visible at the image plane. It is practically indistinguishable from the distributions in the source plane both with and without the presence of the wire medium lens. The imaging resolution is about two periods of the wire medium (2 cm), which in terms of the wavelength corresponds to $\lambda/15$. This demonstrates subwavelength imaging with such a fine resolution over a distance much larger than the wavelength. The distance between the source and image planes at 894 and 1038 MHz is equal to 3 and 3.5 wavelengths, respectively. In the best experiment with a negative-index metamaterial based lens,[9] only a $\lambda/8$ resolution for a $\lambda/3$-thick lens was experimentally demonstrated, and thicker lenses with a better resolution cannot be created even theoretically because of the restriction dictated by losses that are inevitably present in any metamaterial due to its resonant nature.[10]

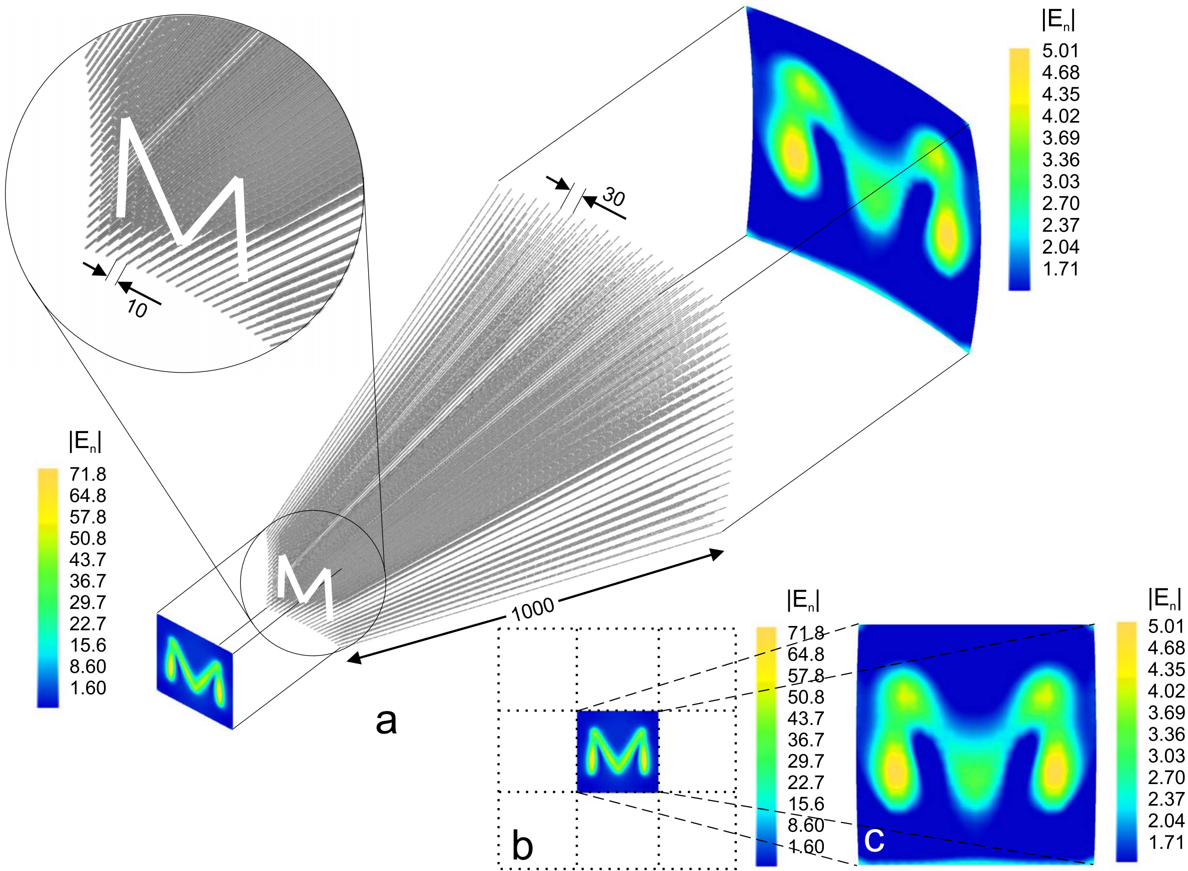

FIG. 3. (Color online) (a) Geometry of the magnifying wire medium lens excited by the planar near-field source in the form of the letter M. The distance between the source and the center of the front interface is 13 mm. All dimensions in the figure are given in millimeters. Calculated distributions of the normal component of electric field: (b) on a plane surface 8 mm from the source in the direction away from the lens, which is (13+8) mm from the center of the lens input surface and (c) on a spherical surface 15 mm from the output surface. The frequency of operation is 910 MHz.

In principle, the resolution of a wire medium lens can be made as fine as required by a specific application by just using materials with smaller periods. For example, instead of using a lens with a 1 cm period and wires with a 1 mm radius (as in Fig. 1), which provides resolution of $\lambda/15$, one can manufacture a structure with a 1 mm period and 100 μm radius wires, which could provide a resolution of $\lambda/150$, and so on. Basically, the minimum achievable resolution is limited only by the manufacturing capabilities and requirement that the radii of wires should be greater than the skin depth of the metal.[3]

The measurement results for the ranges 890–910 MHz and 1030–1042 MHz with a 2 MHz step are presented in Ref. 11. These results enable us to clarify how the resolution of the wire medium lens depends on the frequency of operation. As it was shown in Ref. 6, the best imaging is achieved at a frequency slightly below that corresponding to the Fabry-Perot condition. At higher frequencies, subwavelength imaging is still observed but with worse resolution. This can be clearly seen in Ref. 11: the widths of the lines at the image plane become wider above the Fabry-Perot resonance. Also, the amount of reflection provided by the wire medium slab increases with the frequency. In Ref. 11, the difference between the source plane distributions with and without the presence of the lens is more pronounced as the frequency increases. At frequencies below the Fabry-Perot resonance, the imaging is disturbed by the excitation of the surface waves at both the front and back interfaces of the lens. This effect can be clearly seen in Ref. 11, wherein the image and the source plane field distributions in the presence of the lens at frequencies below Fabry-Perot resonance are completely distorted by the ripples caused by the excitation of surface waves. These properties are typical of wire medium lenses.[6,8]

Despite the described dependency of the resolution on frequency, the resolving capabilities of wire medium lenses are reasonably wide band. The actual bandwidth of operation depends on the complexity of the near-field source and on its sensitivity to external fields,[8] but it cannot be smaller than the fundamental theoretical limit formulated in Ref. 6. In practice, we observed a bandwidth on the order of a few percents: 4.5% in Ref. 8 for a half-wavelength thick lens with a complex meanderlike source, and 2% in the current experiment with a three-wavelength thick lens with a crown-shaped source. For less complex sources, the same lenses may provide a much better bandwidth. For example, in Ref. 7, the bandwidth was 18% for a half-wavelength thick lens with a source shaped in the form of the letter “P.”

The processing of subwavelength images, such as magnification or demagnification, can be performed by tapering the array of wires. Thus, by gradually increasing (decreasing) the spacing between wires from the front interface to the back interface, it is possible to magnify (demagnify) the subwavelength details of an image.

A numerical simulation of the tapered version of the 1-m lens described in the previous section was performed by using a commercial electromagnetic simulator based on the method of moments (MoM).[12] The geometry of the structure is presented in Fig. 3(a). The spacing between the wires at the front interface is 1 cm (as in Fig. 1) and it gradually increases up to 3 cm at the back interface. The front and back interfaces of the lens are spherical surfaces with 50 and 150 cm radii, respectively. The lens is excited by a planar center-fed wire antenna in the form of the letter "M," which is placed in the close vicinity of the front interface. The frequency of operation (910 MHz) is chosen to be slightly higher than the Fabry-Perot resonance of the sixth order (900 MHz) in order to achieve the best quality of imaging.[13]

This structure enables a threefold magnification of the source. This fact is clearly seen in Figs. 3(b) and 3(c), wherein the distributions of the normal (with respect to the interface) component of electric field at an 8 mm distance from the source and a 15 mm distance from the back interface are plotted. The distance between the source and the image is about three wavelengths. In Figs. 3(b) and 3(c), a sharp near-field distribution in the form of the letter M is visible, but the image is magnified three times compared to the original.

The magnifying lenses will find immediate application in near-field microscopy as near-field to far-field transformers since they allow mapping field distributions with subwavelength details into images with details larger than the wavelength, which can be processed by using conventional diffraction-limited imaging techniques.[14,15] Also, the tapered lenses can be used for demagnification of images if the source and image interfaces of the magnifying lens are interchanged. The demagnifying lenses allow the creation of complex near-field distributions on demand from their enlarged copies created in the far field.

The tapered wire medium lenses can be seen as multipixel endoscopes capable of performing direct and inverse manipulations with the electromagnetic fields in the subwavelength spatial scale: capturing an electromagnetic field profile created by deeply subwavelength objects at the endoscope's tip and magnifying it for observation, or projecting of a large mask at the endoscope's base onto a much smaller image at the tip.[4]

In the microwave range, the tapered lenses can be readily applied to improve magnetic resonance imaging (MRI) systems[16] or to increase the aperture efficiency of impulse radiating antennas.[17] Also, the tapered wire medium lenses can be used to enhance the performance of mechanical near-field microwave scanners.

In conclusion, in this Brief Report, we have both experimentally and numerically demonstrated the possibility of using dense arrays of metallic wires to magnify, demagnify, and transmit images with a deeply subwavelength resolution to significant distances in terms of the wavelength at microwave frequencies. In particular, the transmission of an image with a $\lambda/15$ resolution to a distance that is as large as 3.5λ was experimentally shown. The resolution of the proposed imaging systems is ultimately determined by the granularity of the artificial material, which can be made as small as required by a particular application. We anticipate that such near-field lenses may find applications in near-field microscopy and in medical imaging, starting from MRI systems that operate at low microwave frequencies and completing with a new generation of terahertz and infrared imaging devices.

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