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Experimental verification of full reconstruction of the near-field with a metamaterial lens

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It is experimentally verified that a lens formed by tilted metallic wires enables the full reconstruction of the near-field, both in amplitude and phase. It is shown that since the electric field is measured at a significant electrical distance from the object under study the perturbation introduced by the measurement system may be less significant than in the case where the measurements are done in the immediate vicinity of the object, and thus the retrieved near-field may be more accurate. This suggests exciting applications for the tilted wire medium lens in near-field measurement. © *2010 American Institute of Physics*. [doi:10.1063/1.3495938]

In recent years, the manipulation of the near-field and the prospect of surpassing the constraints set by diffraction have stimulated the imagination of many researchers, and several novel imaging approaches based on metamaterial technology have been suggested.[1] An especially robust solution is based on an array of metallic wires that perform pixel to pixel subwavelength imaging.[2–4] In particular, recently it was shown that such "wire medium lens" retains its main properties even if the metallic wires are tilted with respect to the interface,[5] and that, consistent with the standard configuration,[2] it enables the transport of the electric field component parallel to the wires through an oblique projection. As a consequence, it is possible to retrieve the electric near-field components that are inaccessible with the usual setup,[2] such as the components parallel to the lens interface. Based on these findings, it was speculated in Ref. 5 that by mechanically rotating the metamaterial lens around the direction perpendicular to the interface plane, it could be possible to measure three linearly independent components of the electric field, and in this manner fully restore the near-field, independent of the wave polarization.

In order to confirm this result, we fabricated a prototype of the tilted wire medium lens [Fig. 1(a)] that consists of an array of 21×21 copper wires with radius $r_w = 0.5$ mm, length $L = 15$ cm, and arranged in a square lattice with period $a = 1$ cm. The angle between the wires and the direction perpendicular to the interface planes is $\alpha = 45°$. The wires are supported by thin styrofoam slabs with relative permittivity close to unity at the frequency of operation 1 GHz. A standard printed dipole antenna was taken as the near-field source. The printed antenna is fed by a coaxial cable through a balun and is placed at a distance $a/2$ from the front interface of the lens. A near-field scanner based on a robotic arm is used to measure the electric field at the source and image planes.

In our setup we found more convenient to rotate the printed dipole by 120° around the direction normal to the lens interface (z-direction), instead of rotating the lens as originally suggested in Ref. 5, but both approaches are in any case completely equivalent. The wire medium lens captures the component of the electric field parallel to the wires, E_α, and transports it to the image plane with nearly no distortions of amplitude or phase, provided the length of the wires is a multiple of $\lambda_0/2$.[5] In practice, it is possible to measure E_α simply by measuring the electric field component normal to the interface (E_z) at the image plane. This can be easily done using a very small metallic probe (≈ 1 mm long) directed along z. Indeed, even if the probe is not parallel to the wires its response is always proportional to E_α (calculated at the source plane), since that is the only component transported by the tilted wires lens.[5]

In order to explain the postprocessing of the experimental data, it is convenient to introduce a set of coordinates (x,y,z) attached to the lens and a set of coordinates $(x^{\mathrm{dip}}, y^{\mathrm{dip}}, z)$ attached to the dipole antenna. The coordinates $(x^{\mathrm{dip}}, y^{\mathrm{dip}})$ are such that x^{dip} runs along the direction parallel to the dipole arms, whereas the y^{dip} direction is perpendicular to the dipole arms [see Fig. 1(b)]. The rotation of the dipole is done in such a way that the center of the dipole is kept fixed with respect to the lens, and has coordinates $(x,y,z) = (0,0,0)$. Thus, the center of the dipole is imaged into the point $(x,y,z) = (0,0,-L\cos\alpha)$, independent of the orientation of the dipole. The result of each measurement, for a specific orientation of the dipole antenna ($i = 1,2,3$), at the output plane can be represented by a complex valued func-

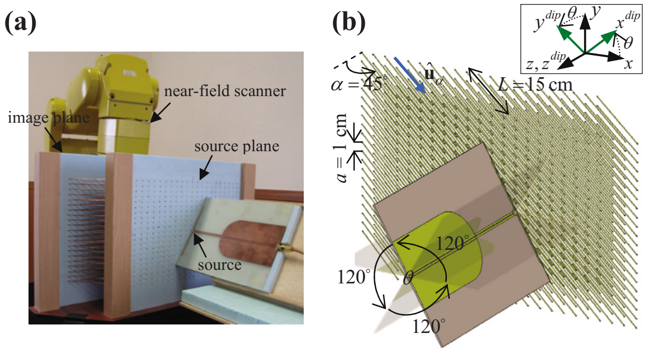

FIG. 1. (Color online) (a) Photo of the prototype of the tilted wire medium lens and of the printed dipole antenna (fed by a balun). (b) Illustration of the principle used to restore the near-field: the dipole antenna is sequentially rotated by 120° around the z-axis and the E_z component of the electric field is measured for each configuration at the image plane.

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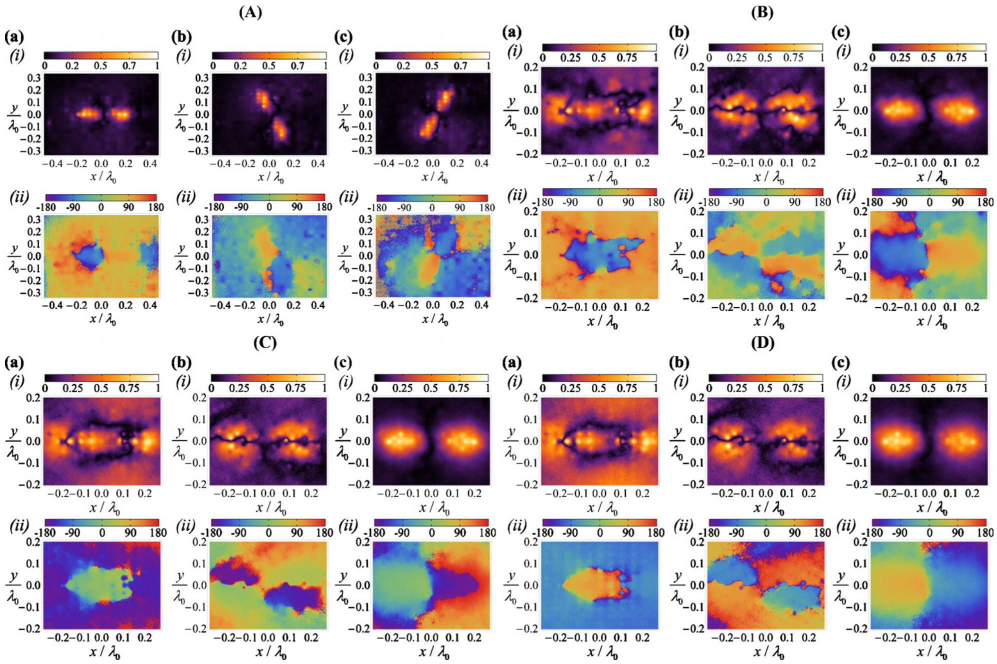

FIG. 2. (Color online) Panel (A): Normalized amplitudes (i) and phases (in degrees) (ii) of the three near-field scan measurements for the frequency of operation of 1 GHz at the image plane. (a) The arms of the dipole are along the x-axis (parallel to the planes of the wires of the lens). [(b) and (c)] The dipole is rotated by 120° and 240° relatively to first position, respectively. Panels (B), (C), and (D): retrieved normalized amplitude (i) and phase (in degrees) (ii) of all components of the electric field of the dipole antenna. (B) $f=1$ GHz; (C) $f=1.025$ GHz; and (D) $f=1.05$ GHz. (a), (b), and (c) represent the x, y, and z components, respectively.

tion $F_0^i(x,y)$ proportional to E_α.[6] Then, using simple trigonometric relations for the two sets of coordinates, (x,y,z) and $(x^{\mathrm{dip}},y^{\mathrm{dip}},z)$, and taking into account that at the design frequency the lens transports the component of the electric field parallel to the wires with negligible distortion, it follows that the electric field components in the reference frame of the dipole satisfy the 3×3 linear system,

$$E_x' \cos\theta^i \sin\alpha + E_y'(-\sin\alpha \sin\theta^i) + E_z' \cos\alpha = F_0^i\big|_{(x^{\mathrm{dip}}\cos\theta^i - y^{\mathrm{dip}}\sin\theta^i,\; x^{\mathrm{dip}}\sin\theta^i + y^{\mathrm{dip}}\cos\theta^i)}, \qquad (1)$$

where $\theta^i = 0°, 120°, 240°$ for $i=1,2,3$, respectively, and the prime indicates that the electric components are defined with respect to the dipole coordinate system. By solving this linear system with respect to $\{E_x', E_y', E_z'\}$, we can retrieve both the amplitude and phase of the near-field.

Figure 2(A) depicts the raw data $F_0^i(x,y)$ obtained from the measurements at the image plane for each angle of rotation at $f=1$ GHz. The subwavelength imaging properties of the wire medium lens are quite evident from Fig. 2(A). The resolution is determined by the spacing between the wires and is roughly $a/\cos\alpha = 1.4a$ along the x-direction, and a along the y-direction. The near-field of the dipole antenna is obtained from the raw data by solving Eq. (1). Figures 2(B)–2(D) depict the retrieved amplitude and phase of the x, y, and z components of the electric field (relative to the coordinate system attached to the dipole) for frequencies in the interval 1–1.05 GHz. In order to have a benchmark for the experimental results, we depict in Fig. 3 the near-field of the printed dipole when it stands alone in free-space, calculated using the electromagnetic solver CST Microwave Studio 2010.

It is clear from Fig. 2(B), which corresponds to the Fabry–Perot resonance ($L=\lambda_0/2$), that the near-field distributions of all Cartesian components of the electric field reproduce accurately the theoretical field distributions (Fig. 3). Particularly, consistent with Fig. 3(a)(i), Fig. 2(B)(a)(i) shows three maxima for $|E_x|$ at both dipole arm ends and at the center of the dipole (i.e., at the feeding point). The phase of E_x also follows closely the theoretical results [Fig. 3(a)(ii)], varying 90° from the center of the dipole to the arms ends. We note that in the raw data [Fig. 2(A)] the position corresponding to the center of the dipole corresponds invariably to a minimum, and thus it is quite remarkable that the extraction algorithm is, indeed, able to reconstruct the fine features of the near-field. In the same manner, the reconstructed E_y is also completely consistent with the simulations [Fig. 3(b)], being the four lobes and the null in the plane of symmetry $y=0$ accurately predicted, as well as the behavior of the phase that alternates by 180° between the top and bottom lobes and the left and right lobes. As could be expected, E_z is the component more accurately restored, since besides being normal to the lens interface it has the highest

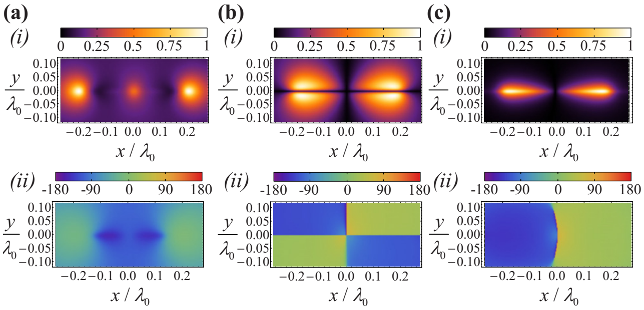

FIG. 3. (Color online) Normalized amplitude and phase (in degrees) of the near-field components of the electric field of the printed dipole antenna when it stands alone in free-space, obtained using CST Microwave Studio. The frequency of operation is 1 GHz and the rest of the legend is as in Fig. 2(B).

amplitude. The two lobes associated with the left and right arms of the dipole, as well as the corresponding 180° phase-shift, are clearly seen in Fig. 2(B)c, consistent with the simulations [Fig. 3(c)].

At higher frequencies, e.g., 1.025 and 1.05 GHz [Figs. 2(C) and 2(D)], the near-field is still well retrieved. However, for frequencies larger than 1.05 GHz the results may be less accurate, because the wire medium lens introduces amplitude and phase distortions in the transmitted image,[5] and we cannot assume anymore that E_α at the image and source planes are proportional, as we did in the derivation of Eq. (1). Nevertheless, in principle it is possible to include the effect of these distortions in the extraction algorithm, and this may improve even more the bandwidth of the proposed system. We will explore these refinements in future work. As shown in the supporting material,[7] at frequencies a few percent lower than 1 GHz, it is impossible to reconstruct the near-field because of the excitation of the surface waves that completely corrupt the transmitted field.[2,4,5]

The reconstructed fields may reproduce even more closely the theoretical results (Fig. 3) if the density of the wires is increased, because the resolution of the wires lens is only limited by the period of the structure. Moreover, by properly scaling the structure, and provided it is possible to measure both the amplitude and phase of the fields, it is in principle feasible to fully reconstruct the near-field up to terahertz frequencies.[3] It is important to underline that such procedure is out of reach of the standard configuration with wires normal to the interface.[2]

The experimental results confirm that the tilted wire medium lens can be used to access the near-field of a certain object at a significant distance from its location, independent of the wave polarization. As discussed next, this property may be an actual advantage of the proposed system, at least as long as one uses an extraction algorithm similar to the one reported here based on three different independent measurements of the near-field. In fact, in order that Eq. (1) makes sense it is necessary that the field radiated by the antenna is independent of the measurement. However, in practice the antenna is always somehow perturbed by the measurement system, especially if the scanning probe is in its immediate vicinity. This may change the antenna near-field in an unpredictable manner. Quite differently, for a wire medium lens operating close to the Fabry–Perot resonance ($L=\lambda_0/2$) the reflected field may be relatively weak,[5] and thus the introduced perturbation may be less significant. In order to confirm these theoretical considerations we have measured the near-field of the same dipole antenna directly at the source plane (without the metamaterial lens). In this configuration, the scanning probe is tilted so that it makes an angle $\alpha=45°$ with the z direction, and as before, the dipole antenna is successively rotated by 120°. The reconstructed near-field is depicted in Fig. 4. Notwithstanding the fact that in this scenario the resolution of the images is only limited by the step of the near-field scanner (1 mm), Fig. 4 undoubtedly shows a much coarser agreement with the theoretical results (Fig. 3) than the results obtained with tilted wires lens [Fig. 2(B)], particularly for the E_x and E_y field components. In order to verify that such result is indeed due to an increased perturbation of the antenna by the measurement system, we measured the S_{11} of the antenna as a function of the position of the sensor in the two following scenarios: (i) near-field measurements in the presence of the lens; (ii) the same without lens. The experimental results show that the standard deviation of the S_{11} in scenario (ii) is larger than in scenario (i) by a factor of 10%. It is also worth noting that when using the tilted wires lens the component of the electric field required for the reconstruction process is effectively isolated by the lens before the actual measurement is done, whereas when the field is measured in the vicinity of the printed dipole there are other electric field components which may also induce undesired currents in the sensor.

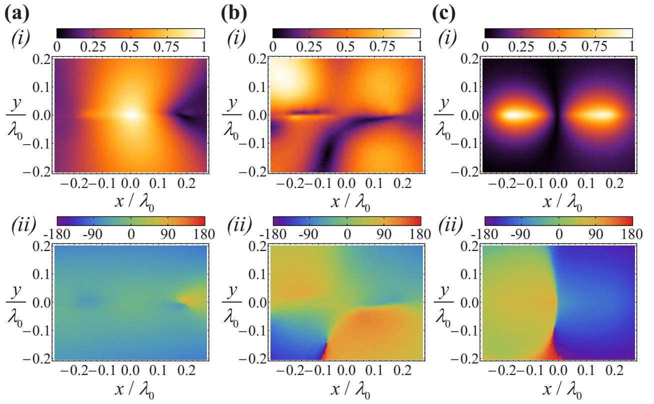

FIG. 4. (Color online) Normalized amplitude and phase (in degrees) of the near-field of the dipole-type antenna at the source plane and when the near-field scanning is performed directly at the source plane (without the lens). The frequency of operation is $f=1$ GHz, and the rest of the legend is as in Fig. 2(B).

In conclusion, we have experimentally verified the total reconstruction of the near-field using a tilted wire medium lens. It was theoretically argued and experimentally verified that the retrieved near-field may be more accurate if obtained using the metamaterial lens, than by a direct measurement at the source plane. Such exciting property, the relatively robust bandwidth of the lens, and the simplicity of the measurement process suggest promising applications for the tilted wire medium lens in near-field measurement in a broad spectral range that includes microwaves and terahertz frequencies.

[1] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000); N. Fang, H. Lee, C. Sun, and X. Zhang, Science **308**, 534 (2005); A. Salandrino and N. Engheta, Phys. Rev. B **74**, 075103 (2006); I. I. Smolyaninov, Y. J. Hung, and C. C. Davis, Science **315**, 1699 (2007); M. J. Freire, R. Marques, and L. Jelinek, Appl. Phys. Lett. **93**, 231108 (2008).

[2] P. A. Belov, Y. Hao, and S. Sudhakaran, Phys. Rev. B **73**, 033108 (2006).

[3] M. G. Silveirinha, P. A. Belov, and C. R. Simovski, Opt. Lett. **33**, 1726 (2008).

[4] P. A. Belov, Y. Zhao, S. Tse, P. Ikonen, M. G. Silveirinha, C. R. Simovski, S. Tretyakov, Y. Hao, and C. Parini, Phys. Rev. B **77**, 193108 (2008).

[5] T. A. Morgado and M. G. Silveirinha, New J. Phys. **11**, 083023 (2009).

[6] In our setup both the near-field scanner probe and the dipole antenna are connected to a R&S ZVB20 VNA; apart from the multiplication of an irrelevant constant, E_α is determined by the S_{21} parameter.

[7] See supplementary material at http://dx.doi.org/10.1063/1.3495938 for the retrieved electric field of the dipole antenna at the frequency $f=975$ MHz.