Experimental demonstration of multiwire endoscopes capable of manipulating near-fields with subwavelength resolution

Pavel A. Belov,[1,2] George K. Palikaras,[1] Yan Zhao,[3,a)] Atiqur Rahman,[1] Constantin R. Simovski,[2,4] Yang Hao,[1] and Clive Parini[1]
[1]School of Electronic Engineering and Computer Science, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
[2]St. Petersburg State University of Information Technologies, Mechanics and Optics, Sablinskaya Street 14, 197101 Saint Petersburg, Russia
[3]International School of Engineering, Faculty of Engineering, Chulalongkorn University, Phayathai Road, Pathumwan, Bangkok 10330, Thailand
[4]Department of Radio Science and Engineering, School of Science and Technology, Aalto University, P.O. Box 13000, FI-00076 Aalto, Finland

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Endoscopes formed by arrays of metallic wires can transmit, magnify, and demagnify near-field distributions with subwavelength resolution. Our experiments demonstrate that despite their small apertures, the parallel multiwire endoscopes can be used to transmit near-field distributions with a resolution of five thousandths of a wavelength to a distance of a half-wavelength in the microwave frequency range, and tapered multiwire endoscopes with flat input and output interfaces provide threefold image magnification and demagnification. © *2010 American Institute of Physics*.
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Conventional dielectric lenses suffer from two major drawbacks: their resolution is limited to a half-wavelength ($\lambda/2$) of the electromagnetic radiation and their transverse dimensions are required to be significantly larger than the wavelength in order to avoid aberrations. However, both limitations can be overcome by using devices made of materials with extreme anisotropy.[1–3] Electromagnetic waves in these media do not experience cutoff and travel strictly along the axis of anisotropy without any diffraction effects. Such waveguiding property allows one to construct endoscope devices with thickness up to several wavelengths for subwavelength imaging applications.

Structures with extreme optical anisotropy in microwave, terahertz,[4] and infrared[5–7] frequencies can be constructed using arrays of metallic rods. It has been demonstrated in literature that endoscopes formed by arrays of parallel metallic rods are capable of transferring images with subwavelength resolutions.[5,6,8–11] The principle of operation is based on the transformation of the complete spectrum of spatial harmonics generated by the source, including evanescent waves, into propagating eigenmodes of the metallic array. Previous experimental works have demonstrated the transmission of images with $\lambda/15$ resolution over a short distance of $\lambda/2$ and a long distance of 3λ.[8–10] Applications of such endoscopes range from magnetic resonance imaging (MRI),[12,13] to biomedical imaging,[14] to near-field microscopy.

In this letter, we report on the experimental results of image transmission using an endoscope formed by an array of parallel metallic wires, followed by the results of image magnification and demagnification using an endoscope formed by an array of tapered metallic wires. Arrays of parallel wires operate in the so-called "canalization" principle;[1] therefore, they are capable of transmitting field patterns comprising TM-polarized incident waves with *any* transverse components of the wave vector. The canalization principle requires the thickness of the wire medium to be $n\lambda/2$, $n=1,2,\ldots$, to satisfy the Fabry–Pérot resonant condition.

In this work, an endoscope device formed by an array of 21×21 parallel brass wires with an equal length of 1 m and a radius of 1 mm is fabricated. A crown-shaped loop source printed on a 2 mm thick Duroid substrate with $\varepsilon_r=2.33$ is used as the near-field source. The detailed dimensions of the source can be found in Fig. 1(a).

An automatic mechanical near-field scanning device is used in the experiment. The scanned area is 180×240 mm^2 at both the source and image planes [see Fig.

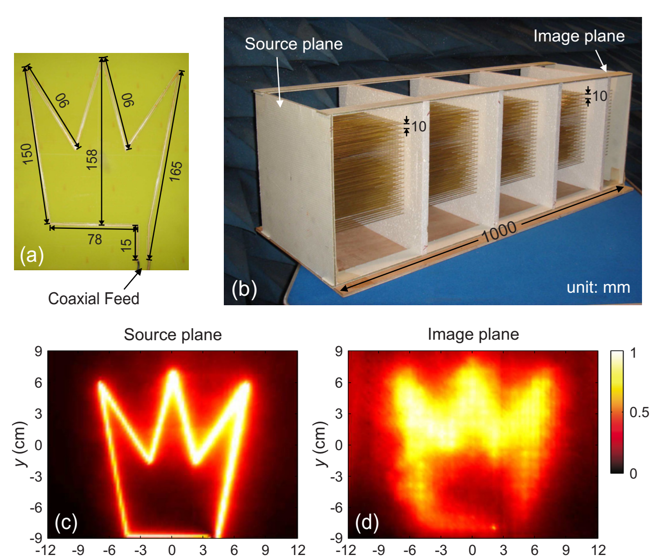

FIG. 1. (Color online) (a) A crown-shaped near-field source and (b) an endoscope formed by a parallel array of brass wires used in the experiment at a frequency of 150 MHz. Distributions of electric field amplitude in (c) source and (d) image planes.

a)Author to whom correspondence should be addressed. Electronic mail: yan.z@chula.ac.th.

TABLE I. Recorded parameters from experiments of subwavelength image transmission through an array of parallel wires.

Frequency (MHz)	Resolution	Aperture	Thickness
150	$\lambda/200$	$(\lambda/10)^2$	0.5λ
300	$\lambda/100$	$(\lambda/5)^2$	λ
450	$\lambda/70$	$(\lambda/3.5)^2$	1.5λ
600	$\lambda/50$	$(\lambda/2.5)^2$	2λ
750	$\lambda/40$	$(\lambda/2)^2$	2.5λ
900	$\lambda/35$	$(\lambda/1.75)^2$	3λ
1050	$\lambda/30$	$(\lambda/1.5)^2$	3.5λ

1(b)]. The measured near-field distributions at a frequency of 150 MHz are shown in Figs. 1(c) and 1(d), respectively. It is clearly illustrated that a field distribution with a resolution of approximately $\lambda/200$ is resolved at the image plane, while the aperture size and length of the device are $(\lambda/10)^2$ and $\lambda/2$, respectively. Similar measurements have been performed using the same device, and various parameters in the experiment are listed in Table I.

The above results demonstrate the advantage of the proposed structure over negative-index material (NIM) based endoscope devices: extremely high resolutions can be obtained using an array of parallel metallic wires with a large length and a small aperture size. So far, only images with a resolution of $\lambda/8$ using a NIM lens with $\lambda/3$ thickness have been reported.[15] Furthermore, higher resolution and larger thicknesses of NIM lenses cannot be achieved due to the lossy nature of the material.[16]

Recently, there is a growing interest in the development of structures that are capable of magnifying subwavelength field distributions in the visible frequency range.[17–20] These structures allow source details to be transferred to a certain distance, while maintaining the same patterns with a linearly magnified or enlarged scale.

The capability of tapered arrays of wires to transmit, magnify, and demagnify images with subwavelength details has been reported in literature.[6,10,14,21] However, the previously proposed device has spherical input and output interfaces,[21] which is unsuited for many near-field imaging applications. Here, we report on the experimental results using a tapered array of wires with planar interfaces. Hence, phase distortions are introduced by the unequal length of wires in such a tapered array—the difference in physical length between the longest wires at four corners and the shortest wire at the center is approximately 10.05 mm. At the lowest operating frequency of 150 MHz where the length of the longest wires is equal to a half-wavelength ($\lambda/2$), the maximum phase distortion can be estimated as $k\Delta l_{\max} = (2\pi/\lambda)\Delta l_{\max} = 0.032$ rad. Previous studies demonstrate that the operating bandwidth of parallel endoscopes highly depends on the complexity of source distributions and is at least 5% for an arbitrary type of source with image resolution above $\lambda/15$.[9] The phase distortion introduced by tapering of wires reduces the bandwidth of operation considerably to around 3%, estimated from our experimental results. The bandwidth issue of magnifying and demagnifying endoscopes will be studied further and reported in a subsequent publication. It suffices to state that phase distortions can be eliminated using a dielectric phase compensator to adjust the electrical lengths of wires.[22]

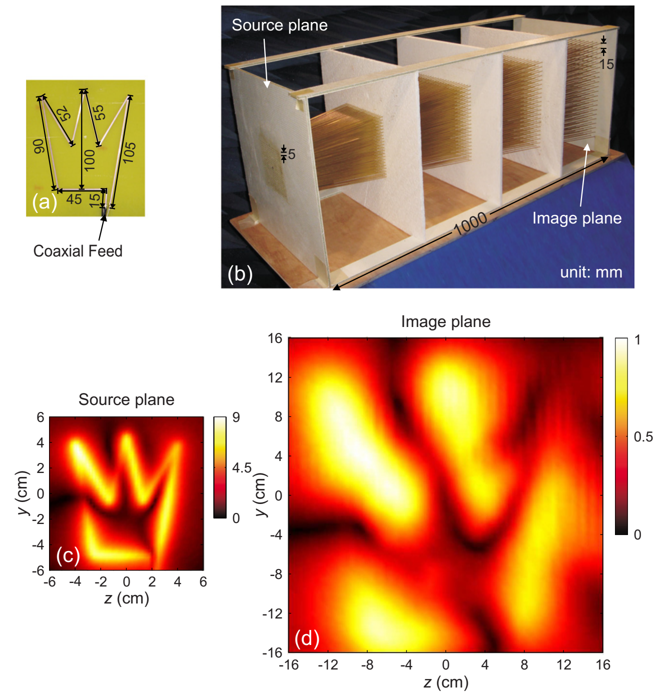

FIG. 2. (Color online) (a) A crown-shaped near-field source and (b) an endoscope formed by a tapered array of brass wires used in the magnification experiment at 1047 MHz. Distributions of electric field amplitude in (c) source and (d) image planes.

The fabricated tapered array consists of 21×21 brass wires with their radius equal to 1 mm. The dimensions of the tapered array are shown in Fig. 2(b).

A small crown-shaped loop source similar to the one used in the previous experiment is designed and fabricated. Detailed dimensions of the source can be found in Fig. 2(a). The same experimental setup as in the previous case is used and a series of measurements at frequencies around 1050 MHz is performed (the thickness of the tapered array is approximately 3.5λ). The scanned areas are 120×120 and 320×320 mm^2 in the source and image planes, respectively. The optimum result is obtained at 1047 MHz and shown in Figs. 2(c) and 2(d). The slight frequency deviation from the theoretical Fabry–Pérot resonance is caused by the gradually enlarged spacing between wires and the influence of slight manufacturing errors. Despite the frequency shift, the field distribution is satisfactorily reproduced at the image plane, with magnified characteristic dimensions by a factor of 3. As indicated by the scales of color bars in Figs. 2(c) and 2(d), the amplitude of the electric field in the image plane is approximately nine times lower than the source plane, which is caused by the ninefold increase in the distribution area. It is important to note that when the Fabry–Pérot resonant condition is met, it is not required to maintain a uniform transmission line characteristic impedance along the device[23] (e.g., by altering the radius of wires[6]), which eases practical implementations of the device significantly.

The magnification of images with subwavelength resolutions allows one to enlarge source details smaller than the wavelength up to the scale that can be detected using conventional diffraction-limited imaging systems. Moreover, the inverse operation is also possible: the tapered arrays are capable of *demagnifying* electromagnetic field distributions, through which, one may be able to obtain highly confined subwavelength distributions of arbitrary shapes required by a

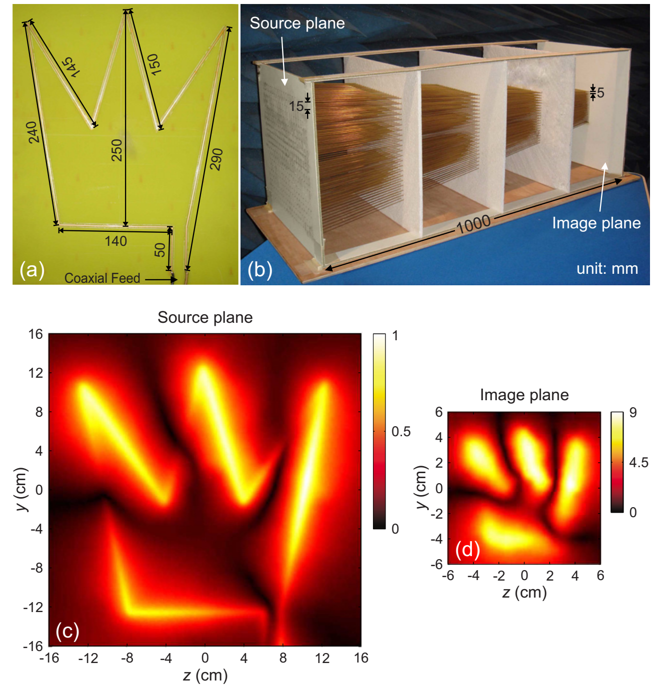

FIG. 3. (Color online) (a) A crown-shaped near-field source and (b) an endoscope formed by a tapered array of brass wires used in the demagnification experiment at 455 MHz. Distributions of electric field amplitude in (c) source and (d) image planes.

particular application. In order to demonstrate the demagnification capability of the tapered array of wires, we interchange the source and image planes of the device, as illustrated in Fig. 3(b).

A large crown-shaped loop source is designed and used in the demagnification experiment. The source is placed in front of the larger interface of the tapered array and near-field scanning is performed at several frequencies around 450 MHz. The scanned results at 455 MHz are chosen and presented in Figs. 3(c) and 3(d). It is clearly shown that the distribution in the image plane reproduces the entire source details and has three times smaller dimensions.

In conclusion, we have experimentally demonstrated the possibility of using dense arrays of metallic wires to transfer, magnify, and demagnify images with deep subwavelength resolution to significant distances at microwave frequencies. In particular, the transmission of an image with a resolution of $\lambda/200$ to an electrical distance of $\lambda/2$ is shown. A threefold image magnification with subwavelength resolution is demonstrated using a tapered array of metallic wires. Besides, the proposed device can be utilized in the opposite way to achieve image demagnification: electrically large source distributions can be "concentrated" to a confined area. Such near-field devices may find their applications in near-field microscopy and medical imaging, ranging from MRI operating at low microwave frequencies to terahertz and infrared imaging.

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