Experimental study of the subwavelength imaging by a wire medium slab

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An experimental investigation of subwavelength imaging by a wire medium slab is performed. A complex-shaped near field source is used in order to test imaging performance of the device. It is demonstrated that the ultimate bandwidth of operation of the constructed imaging device is 4.5% that coincides with theoretical predictions [P. A. Belov and M. G. Silveirinha, Phys. Rev. E **73**, 056607 (2006)]. Within this band the wire medium slab is capable of transmitting images with $\lambda/15$ resolution irrespective of the shape and complexity of the source. Actual bandwidth of operation for particular near-field sources can be larger than the ultimate value, but it strongly depends on the configuration of the source. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2424557]

An original concept of imaging with resolution smaller than the wavelength (subwavelength imaging) has been recently proposed in Ref. 1. It has been demonstrated that a regular array of parallel conducting wires [see Fig. 1(a)] is capable of transporting images with subwavelength details from one planar interface to another. The principle of operation of this device (see Ref. 2) is based on the idea of transforming the whole spatial spectrum of the subwavelength source to the propagating modes inside of a metamaterial formed by the array of wires, also called as the wire medium.[3] In such a way, the evanescent waves which carry subwavelength information and normally decay in free space can be transformed into the propagating modes inside of the wire medium and transported to significant distances.

The initial experimental investigation of the subwavelength imaging capability of the wire medium slab has been performed recently in Ref. 1. The antenna in the form of letter "P" was used as a subwavelength source. The clear images of the source were detected at the back interface of the transmission device, and resolution of $\lambda/15$ was demonstrated for 18% operation bandwidth. The extensive theoretical studies[4] based on the analysis of transmission and reflection coefficients predict that the subwavelength imaging should be observed for at least 4.5% bandwidth for any kind of the source. However, in practice, for certain sources the imaging can be observed within larger frequency bandwidths. The complexity of the near field produced by the source and the interaction between the source and the transmission device play crucial roles in determining the imaging performance of the whole system. At the frequencies outside of the theoretical minimum band of operation, the strong reflections from the wire medium slab are expected in accordance to Ref. 4. That is why the sensitivity of the source with respect to external fields becomes an issue. If the source is very complex and contains a lot of subwavelength details, then its near-field distribution can be easily deformed by harmful reflections from the interface of the transmission device and no proper subwavelength imaging can be observed at the frequencies outside of the theoretical minimum band of operation. However, if the source is simple and does not contain many subwavelength details, then the source is immune from reflections and the image can be transported to the back interface even at some frequencies outside of the minimum band of operation, as it was observed in Ref. 1, for example.

In order to investigate the imaging capability of the wire medium slab in detail, we have performed an experiment with the meander-line antenna printed on 2 mm thick slab of Duroid with relative permittivity $\varepsilon=2.33$ [see Fig. 1(b) for other dimensions], which intentionally has much more complex near-field distribution as compared to the P antenna used in Ref. 1, see Fig. 2. The return loss (S_{11} parameter) within the frequency band from 840 to 1060 MHz for the meander-line antenna in the free space was compared with the return loss of the same antenna but placed close to the front interface of the wire medium slab, see Fig. 1(a). The results of the comparison are presented in Fig. 3 and clearly demonstrate that the wire medium slab does not affect the meander-line antenna at the frequency band from 915 to 955 MHz, see the shaded area in Fig. 3. It means that within 915–955 MHz frequency range, the meander-line antenna practically does not suffer from reflections from the wire medium slab. The slab is practically transparent at these frequencies and this fact was predicted theoretically in Ref. 4 where unprecedentedly small values of reflection coefficient for all angles of incidence including evanescent waves have been demonstrated.

The near field scan has been performed for the frequencies within 840–1060 MHz frequency band which is signifi-

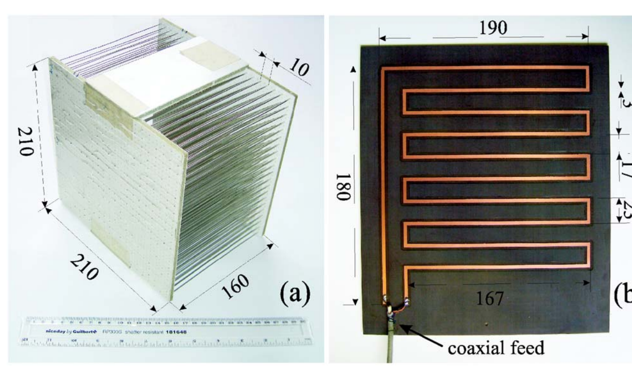

FIG. 1. (Color online) Geometries of the transmission device (a), a 21 ×21 array of wires with 1 mm radii, and the near-field source (b). All dimensions are in millimeters.

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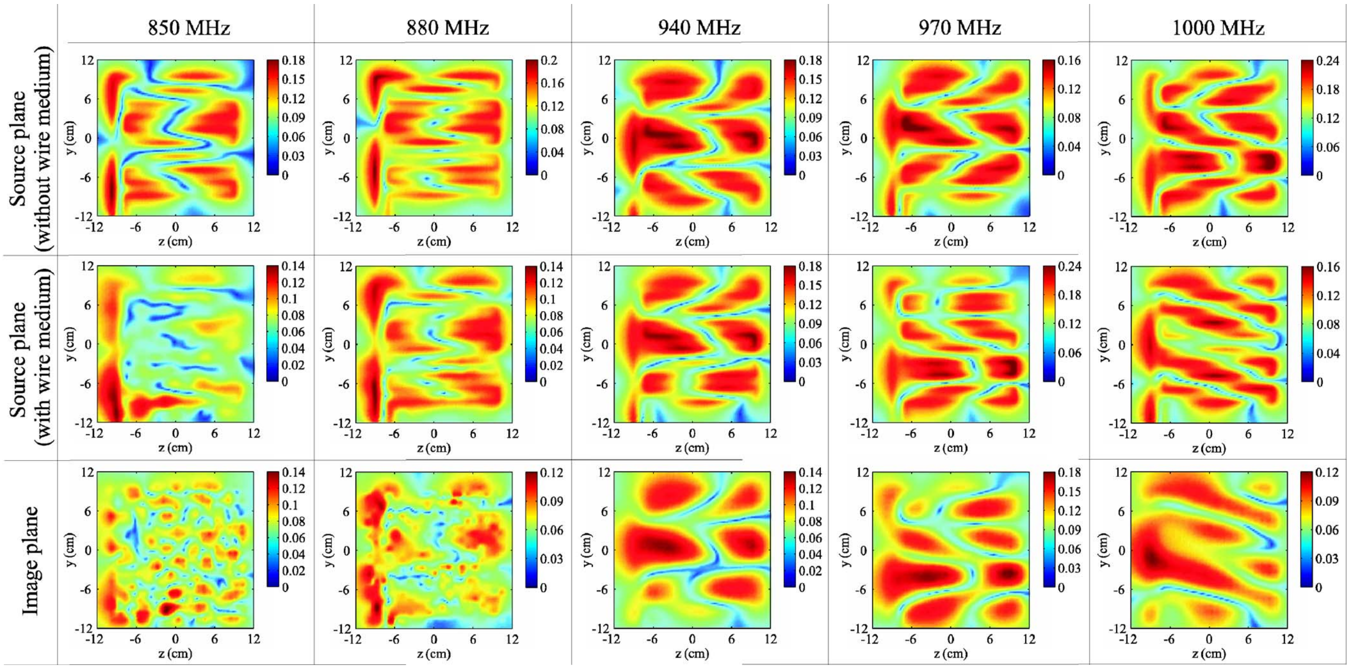

FIG. 2. (Color online) Results of the near field scan at 850 MHz, 880 MHz, 940 MHz, and 1 GHz (in arbitrary units): the amplitude of the component of electric field normal to the interface at 2 mm distance from the meander antenna in the free space (source plane without wire medium), the same but when the antenna is placed at the front interface of the transmission device (source plane with wire medium) and at 2 mm distance from the back interface of the wire medium slab (image plane).

cantly wider than the band of 915–955 MHz where perfect imaging is expected in order to verify the general behavior of the imaging system. We used an automatic mechanical near-field scanning device and a 2 mm long monopole probe made from the central core of a coaxial cable with 2 mm diameter. The scan area was $24\times 24\ \mathrm{cm}^2$ with 75 steps in both directions. The probe was oriented normally with respect to the interfaces of both the meander antenna and the transmission device. So, it detected only the normal component of electrical field. The wire medium slab is capable of imaging only the electromagnetic waves with transverse magnetic polarization[1] and only the normal component of electric field is completely restored at the back interface. The other two components contain contribution of electromagnetic waves with transverse electric polarization, which are not transferred by the wire medium slab.

The slab of wire medium is a transmission device, not a usual lens. It transports electric field from its front interface to the back interface and does not involve any focusing effects. The electric field at 2 mm distance from the front interface of the meander-line antenna located in free space (without the wire medium) was scanned and regarded as the source field. After that the meander-line antenna was placed at the front interface of the wire medium slab and the field at 2 mm distance from the front interface of the antenna was scanned once gain. This allows us to detect the difference between the field created by antenna with and without the presence of wire medium. The image field was scanned at 2 mm distance away from the back interface of the slab in order to avoid touching of the probe and the transmission device. Results of the near-field scan at 23 frequencies from 840 to 1060 MHz with 10 MHz step are presented in the multimedia file.[5] The same results, but only for 850 MHz, 880 MHz, 940 MHz, and 1 GHz, are shown in Fig. 2. At 910–960 MHz the fields at the source plane with and without presence of antenna are practically identical (see Ref. 5 or Fig. 2 for the result at 940 MHz). This confirms that the wire medium slab practically does not introduce reflections at theses frequencies. At the same time the field in the image plane repeats the source field with an accuracy about 2 cm.

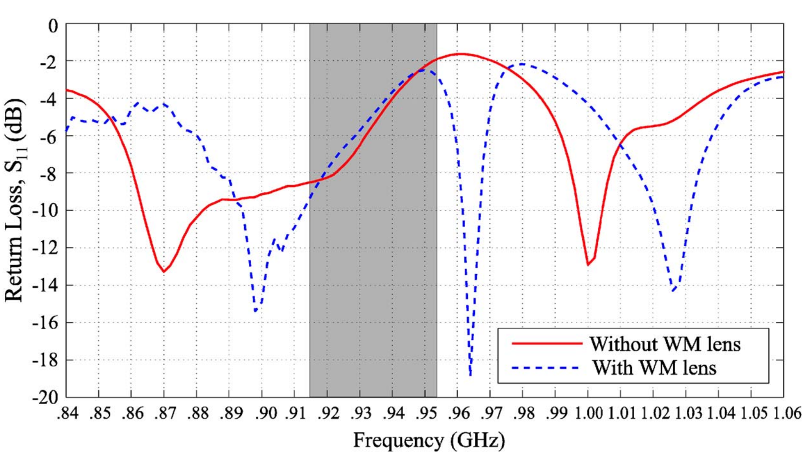

FIG. 3. (Color online) Return loss (S_{11} parameter) as function of frequency for the meander-line antenna in the free space and at the interface of the wire medium slab.

This confirms that the resolution of the imaging device at this frequencies is about $\lambda/15$.

At frequencies lower than 920 MHz (up to 870 MHz), the fields in the source plane with and without wire medium slab remain practically identical. However, the image is distorted by sharp maxima (see Ref. 5 or Fig. 2 for the result at 880 MHz). These maxima are caused by surface waves excited at the interfaces of the wire medium and were predicted theoretically in Ref. 4. We can say that at these frequencies the transmission device maintains the capability of subwavelength imaging, but with reduced resolution. At frequencies lower than 870 MHz the surface waves completely degrade the image and simultaneously provide strong reflections which make distribution in the source and image planes different.

At frequencies higher than 960 MHz the imaging performance of the transmission device also degrades, but this happens because of other reasons. At 970 MHz the distributions at the source plane with and without wire medium already become significantly different. It can be explained by strong reflections from the slab which change the distribution of currents in the antenna. In this case reflections are much more prominent than those at lower frequencies and are caused by the fact that the slab does not fulfill the Fabry-Pérot resonance condition anymore. Following the theoretical studies,[4] at lower frequencies the reflection coefficient is large only for spatial harmonics with wave vectors close to the wave vector of the surface wave. That is why while the wave vector of the surface wave is large (870–920 MHz) we observe only sharp maxima in the image plane and no significant changes between fields in the source plane with and without wire medium. As the wave vector of the surface wave decreases (<870 MHz), the reflections experienced by the antenna from the wire medium increase and completely destroy the imaging. In the case of high frequencies (>960 MHz) there are no surface waves, but the reflection increases and this increase happens simultaneously for all spatial harmonics. That is why we observe strong difference between fields in the source plane with and without wire medium at these frequencies. However, it is interesting to note that the distributions in the source and image planes of the transmission device remain practically identical (see Ref. 5 or Fig. 2 for the result at 970 MHz and 1 GHz). The difference is practically negligible at 960–1060 MHz. The resolution remains the same (2 cm, about $\lambda/15$) as at lower frequencies. Following the theoretical predictions[4] the resolution should slightly degrade with an increase of frequency; however, within the tested frequency range, we were not able to detect any significant degradation of resolution.

Thus, we can conclude that the wire medium slab has good subwavelength imaging properties even at frequencies higher than the frequency of Fabry-Pérot resonance, but the large level of reflections from the wire medium slab is an issue. If the subwavelength source is sensitive to external field (for example, the meander-line antenna whose current distribution changes in an external field), then the wire medium slab cannot be used for its imaging. However, if the source field is not sensitive to external fields (for example, an array of small antennas fed by fixed current sources), then it remains unaffected by reflections from the transmission device and the wire medium slab can be used for imaging of this source with very good subwavelength resolution. The antenna in the form of P letter used in Ref. 1 is insensitive to reflections from the wire medium slab and that is why the subwavelength imaging with $\lambda/15$ resolution was reported in Ref. 1 for the range from 920 MHz to 1.1 GHz.

In conclusion, in this letter the minimum operation bandwidth of the wire medium slab as the subwavelength imaging device, theoretically predicted in Ref. 4 was confirmed experimentally. We would like to stress that the actual bandwidth of operation significantly depends on the complexity and sensitivity of the source to reflections from the wire medium slab. For sources which are not sensitive to external fields, the subwavelength imaging can be performed within significantly wide frequency range. However, for an arbitrary source, the imaging can be guaranteed only within the minimum bandwidth. We would like to remind[1,4] that the wire medium slabs are able to transmit images to any long distances specified by a particular application. The only restriction is that the length of the transmission device should be equal to an integer number of half wavelengths in order to fulfill Fabry-Pérot condition and eliminate unwanted reflections. The resolution of the wire medium slab is ultimately defined by its period. That is why in the microwave frequency range practically any fine subwavelength resolution can be obtained if the wire medium with the sufficiently small period can be manufactured.

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[5] See EPAPS Document No. E-APPLAB-89-228652 for results of the near-field scan at 23 frequencies from 840 to 106 MHz with 10 MHz step. This document can be reached via a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html).