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A microwave transmission-line network guiding electromagnetic fields through a dense array of metallic objects

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Abstract

We present measurements and simulations of a transmission-line network that has been designed for cloaking applications in the microwave region. Here the network is not used for cloaking but for channelling electromagnetic fields through an electrically dense array of metal objects, which alone is basically impenetrable to the impinging electromagnetic radiation. With the designed transmission-line network the waves emitted by a source placed in an air-filled waveguide are coupled into the network and guided through the array of metallic objects. Our goal is to illustrate the simple manufacturing, assembly, and the general feasibility of cloaking devices based on the transmission-line approach. Most importantly, we demonstrate both with measurements and with numerical simulations the excellent coupling of waves between the network and the surrounding medium.

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Keywords: Transmission-line network; Scattering cross section; Electromagnetic cloak

1. Introduction

The interest in different types of devices and materials capable of dramatic reduction of the total scattering cross sections of arbitrary or specific objects, has grown considerably upon publication of recent papers [1–4], although the subject of hiding objects or particles from the surrounding electromagnetic fields was studied earlier by many other groups, e.g., [5–9].

Recently, we have proposed an alternative approach to cloaking of objects composed of electrically dense arrays of small inclusions (in principle, these inclusions can be composed of arbitrary materials) [10–12]. This approach is based on the use of transmission-line networks that are coupled with the surrounding medium, e.g., free space. Since the objects “hidden” inside these networks can be two-dimensional or even three-dimensional interconnected meshes of e.g. metallic rods, practical applications of these types of cloaks include hiding strongly scattering objects such as support structures situated close to antennas, creating filters (a “wall” or a slab letting through only a part of the spectrum of the incoming field), etc. Also, as it has been recently proposed, these networks offer a simple way of creating new types of matched lenses especially for microwave applications [13].

The goal of this paper is to experimentally demonstrate the simple manufacturing and assembly of the previously proposed transmission-line structure, where

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the transmission lines composing the network are realized as parallel metal strips. By measurements we confirm the previously predicted matching of the network with free space, as well as a possibility of transmission of fields through an electrically dense mesh of metal objects.

The structure that is studied here is a two-dimensional transmission-line network having a square shape and therefore is not a "cloak" that can reduce an object's total scattering cross section, as the structures presented, e.g., in Refs. [11,12]. Instead, the structure presented here squeezes fields inside a network of transmission lines to enable wave propagation where it otherwise is not possible. Also, as discussed above, this approach can be used in creating walls or slabs that let part of the incident spectrum through themselves. The same approach can then be further applied to create symmetrical (cylindrical or spherical) cloaks, that indeed can reduce the scattering cross section of certain objects dramatically [11,12].

2. Transmission-line network

The transmission-line network that is used here is the same as designed in Ref. [10], with the optimal impedance matching with free space observed around the frequency of 5.5 GHz. For this design, the matching with free space and the cloaking phenomenon were verified with full-wave simulations [10]. In this paper we demonstrate the simple manufacturing and assembly of this type of structure with a two-dimensional periodic transmission-line network having a square shape and 16×16 unit cells in the network. The edges of the network are connected to a "transition layer" composed of parallel metal strips gradually enlarging from the ends of the network, as proposed in Ref. [10]. The function of this layer is to capture the fields propagating in free space and transform these modes to the propagating modes of the transmission-line network. Thus, the layer can be considered as a mode-transforming device.

By inserting the designed network inside a metallic parallel-plate waveguide (with the plates lying in the *xy*-plane), we effectively realize the same situation as would occur with an infinitely periodic array of networks with the periodicity along the *z*-axis, since here the electric fields are assumed to be normal to waveguide plates, as in the example case that was studied previously [10]. See Fig. 1 for an illustration of the transmission-line network.

The structure shown in Fig. 1 was manufactured by etching from a thin copper plate. The network can be simply assembled from two similar profiles (each profile as shown in Fig. 1a) just by placing them on top of each other, as shown in Fig. 1b. Ideally, the volume between these two metal objects should be free space [10]. Here, due to practical reasons, we have placed small pieces of styrofoam, with material properties very close to those of free space, between the metal strips. For assembly purposes, pieces of styrofoam are placed also on top and below the metal strips for support. These styrofoam pieces naturally do not affect the propagation properties of the transmission lines since the fields are mostly confined between the parallel strips.

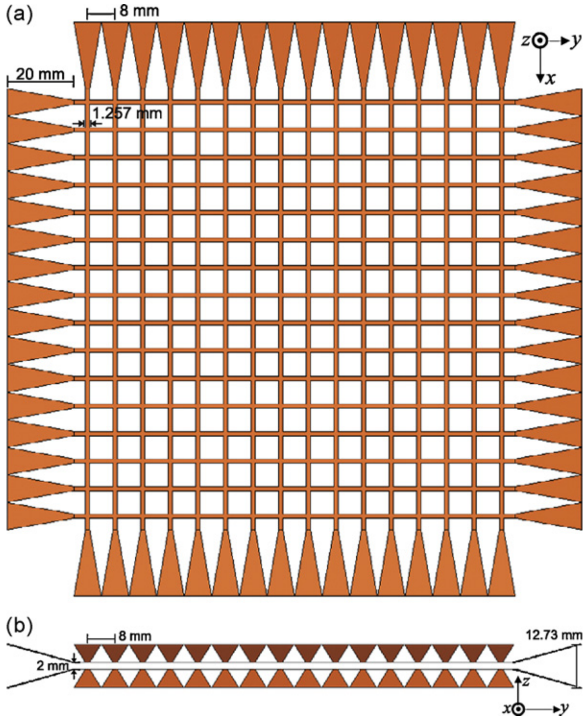

Fig. 1. Illustration of the designed transmission-line network. (a) Network in the *xy*-plane. (b) Network in the *yz*-plane.

In Ref. [10] the reference object, i.e., the object that we wanted to cloak (hide) from the surrounding electromagnetic fields, was an array of infinitely long perfectly conducting rods that fit inside the network of transmission lines. Here we use a similar periodic structure as a reference object through which we want to guide the fields. The individual inclusions of this reference object are metal cylinders (parallel to the *z*-axis) with the same height as the network (~13 mm). The diameter of these cylinders is 4 mm and there are a total of $15 \times 15 = 225$ cylinders in the array.

3. Measurement setup

The measurement setup that is used here is similar to the one presented in Ref. [4]. With our measurements we effectively simulate an infinitely periodic structure with the periodicity in the vertical (z-) direction, by introducing a measurement cell consisting of a parallel-plate waveguide with its metallic plates lying in the xy-plane. Because of the image principle (the electric fields are assumed to be parallel to the z-axis inside the waveguide), we can thus measure only one period of a volumetric structure. The difference between the measurement setup used here and the one in Ref. [4] is that here the upper plate of the waveguide is formed by a dense wire mesh, that lets through a fraction of the field inside the waveguide, instead of having a solid metallic upper plate with a hole for the probe, as was used in Ref. [4]. The mesh that we use here is the same as the one used in Ref. [14], i.e., the mesh is a thin copper plate, in which square holes of size 4 mm × 4 mm have been etched with the period of the holes being 5 mm. A small part of the field gets through this mesh and we can measure that field with a probe placed on top of the waveguide [14].

We excite a cylindrical wave in the waveguide with a coaxial feed probe placed inside the waveguide and measure the transmission from this probe to the measurement probe placed on top of the waveguide, with a vector network analyzer (VNA, Agilent E8363A). The use of the metal mesh as a part of the top plate of the waveguide, rather than using a probe inside the waveguide, ensures that the measurement probe does not disturb the fields inside the waveguide. The measurement probe on top of the waveguide is stationary, and the whole waveguide is moved with a PC-controlled scanner, synchronized with the VNA for precise measurements in the wanted coordinate positions. These points where the measurement of the complex S_{21}-parameter are taken with the VNA, can be arbitrarily chosen with the PC-program running the scanner. All the measurements presented in this paper were done with the steps of 5 mm. As the measured area is 240 mm × 100 mm, we will have the complex S_{21} measured at $49 \times 21 = 1029$ different points in the xy-plane.

The measurement probe that we use here is a monopole oriented along the z-axis and positioned approximately at 3 mm on top of the metal mesh. The probe is intentionally poorly matched at the frequencies of interest (5–6 GHz) in order to make sure that the measurement probe does not disturb the fields inside

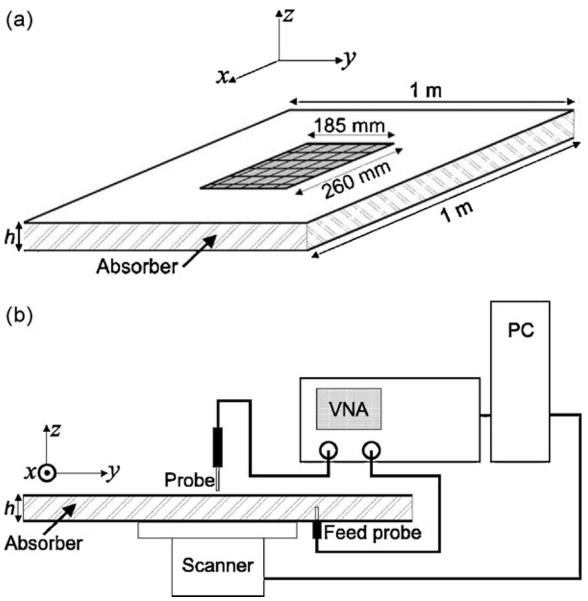

Fig. 2. Illustration of the measurement setup. (a) Waveguide with a metal mesh in the upper plate. (b) Measurement system with a VNA connected to the feed and measurement probes (the measurement probe is stationary) and a PC controlling the scanner which moves the waveguide in x- and y-directions.

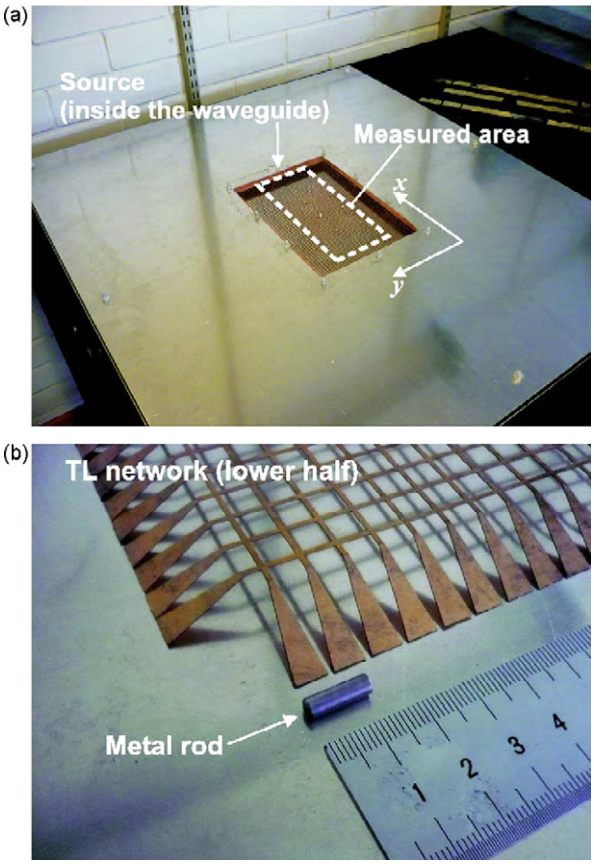

Fig. 3. (a) Photograph of the measurement setup, showing the aluminium parallel-plate waveguide and a copper mesh placed in the center of the top plate of the waveguide. (b) Photograph of the lower half of the TL network together with one metallic rod of the reference object.

the waveguide. The high dynamic range of the VNA makes sure that we can measure the electric field distribution inside the waveguide even with this poorly matched probe.

See Fig. 2 for an illustration of the measurement setup. The parallel-plate waveguide has the width and length of 1 m, and the height $h = 13$ mm. Ideally h should be equal to 12.73 mm [10], but the height was chosen to be exactly 13 mm because of assembly issues. A part of the solid upper plate is removed from the center for the placing of the metal mesh (the area above which we want to measure the field distributions). The area of this mesh is 260 mm × 185 mm. The measurable area is further restricted by the scanners moving the waveguide. We have used two scanners, one with the movement limited to 300 mm (x-axis) and one with the movement limited to 100 mm (y-axis). The area to be measured has been decided to be 240 mm × 100 mm, centered in the mesh area. The feed probe is positioned in the center of the mesh along the y-direction and just outside the measured area in the x-direction, in order to have more space between the measured area and the feed. The feed probe coordinates are therefore decided to be $x = 250$ mm, $y = 50$ mm, with the origin of this coordinate system being in one corner of the measured area. See Fig. 3 for a photograph of the measurement setup, taken from the direction of the positive z-axis, showing the empty waveguide and the metal mesh inserted as a part of the upper plate. The feed probe position and the measured area are also illustrated in the figure.

The volume between the waveguide plates, surrounding the metal mesh, is filled by a microwave absorber. A large size of the waveguide ensures that the reflections from the waveguide edges are minimized. The absorber thickness in the x- and y-directions is approximately five wavelengths or more at the frequency of 5 GHz.

4. Measurement results

Three different measurements were conducted: (1) an empty waveguide, (2) the reference object (array of 15 × 15 metal cylinders) inside the waveguide, and (3) the reference object *and* the transmission-line network inside the waveguide, with the inclusions of the reference object placed in the space between the transmission lines of the network. All the measurements were conducted in the frequency range from 1 GHz to 10 GHz, with the step of 0.025 GHz.

In the first case (empty waveguide), the results showed an expected result: at higher frequencies, i.e., at 5 GHz and above, the waveform inside the waveguide is close to the waveform produced by a line source. At lower frequencies, where the waveguide is electrically smaller, the reflections from the edges start to affect the field distributions, making them more complicated. See Fig. 4a for a snapshot of the measured time-harmonic electric field distribution at the frequency 5.85 GHz. Some reflections naturally still occur (mainly from the absorbers), but it is clear that the wave inside the waveguide resembles a cylindrical wave emanating from the point $x = 250$ mm, $y = 50$ mm.

In the second case (reference object inside the waveguide), the results were again as expected: at the higher frequencies, where it makes sense to compare the field distributions, the wavefronts emanating from the source are strongly reflected at the front boundary of the refer-

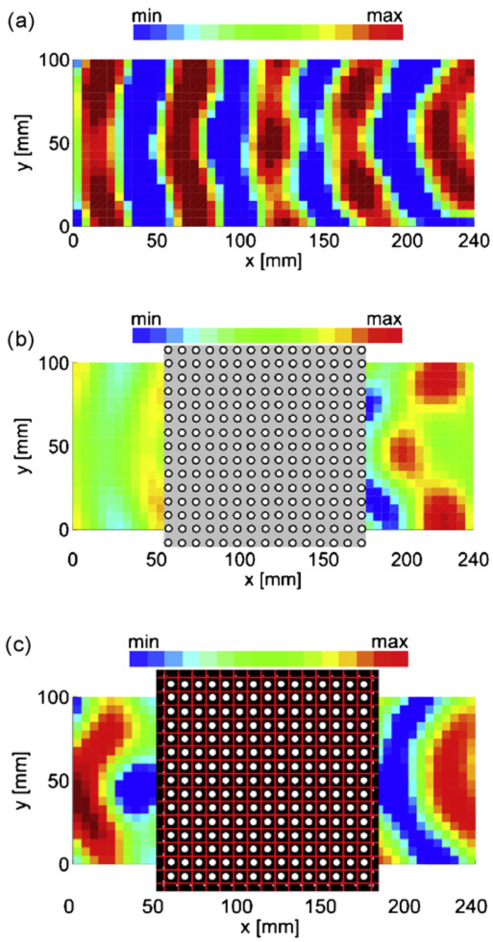

Fig. 4. Snapshots of the measured time-harmonic electric field distributions at 5.85 GHz: (a) empty waveguide, (b) reference object inside the waveguide, (c) reference object and the transmission-line network inside the waveguide. The "transition layer" connected to the network is not shown in (c) for clarity.

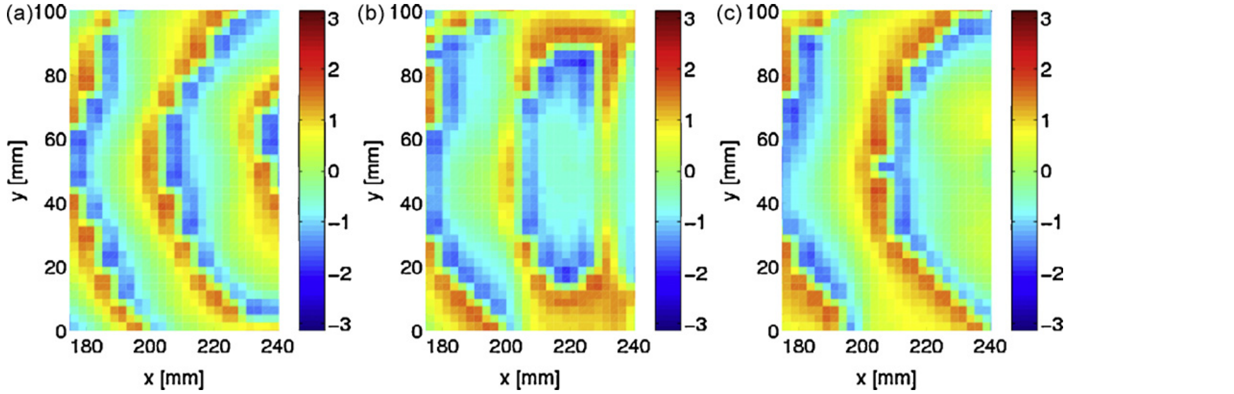

Fig. 5. Phase of the measured electric field distribution at 5.85 GHz: (a) empty waveguide, (b) reference object inside the waveguide, (c) reference object and the transmission-line network inside the waveguide. The phase distributions in each figure are interpolated from the corresponding measurement data for clarity.

ence object. The field is seen to "split" in the center and move up or down along the reference object side. See Fig. 4b for a snapshot of the measured time-harmonic electric field distribution at the frequency 5.85 GHz.

In the third case (the reference object and the transmission-line network inside the waveguide) the field pattern on the source side is seen to be well preserved, as compared to Fig. 4a, in a certain frequency band around 5.85 GHz. Also, at the backside of the network some field is propagating. At the position of the network, which encompasses the reference object, no field is measured, since the fields are confined inside the transmission lines. See Fig. 4c for a snapshot of the measured time-harmonic electric field distribution at the frequency 5.85 GHz.

To further study the differences between the situations with and without the network, the phase distributions, calculated from the measured complex field data, are shown in Fig. 5. The phase distributions are plotted in the area between the reference object/network and the feed probe, i.e., in the area $x = 175$ mm . . . $x = 240$ mm. As compared to the empty waveguide, i.e., Fig. 5a, the case with the bare reference object, Fig. 5b, looks very different. This is due to the strong reflections from the front edge of the reference object. When the transmission-line network is placed inside the waveguide, together with the reference object, we see that the resulting phase distribution again is close to the one in Fig. 5a.

A more illustrative measure for the operation of the network is to compare the absolute value of the field *behind* the reference object with and without the network in place (i.e., in the area $x = 0$ mm . . . $x = 50$ mm). These results are shown in Fig. 6a and b, for the case without the network and with the network, respectively. As demonstrated by Fig. 6a, the field amplitude behind the reference object is strongly suppressed, as compared to the field amplitude in front of this object. With the transmission-line network in place, the field amplitude behind the reference object/network is practically the same as in front, see Fig. 6b.

The size of the network in this example case is comparable to the wavelength, so the inherent difference of the phase velocities between the wave propagating inside the network and the wave in free space, results in a change, or distortion of the impinging cylindrical waveform, as can be seen from Fig. 6b. The reasons for this difference in the phase velocity are discussed in Ref. [10]. Also, as the sharp edges of the square-shaped network are close to the measured area, scattering from these edges distorts the waveform. Note that the previously simulated "cloak slab" [10] was much wider and also thinner than the network measured here.

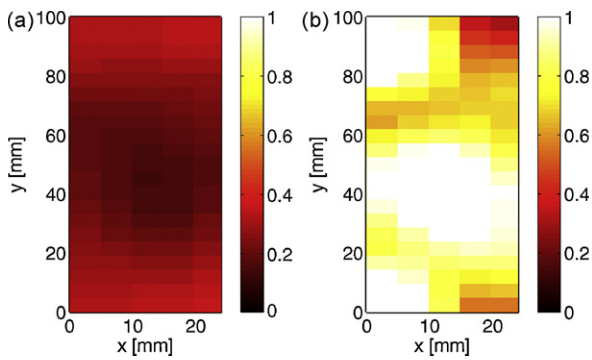

Fig. 6. Absolute value of the measured electric field distribution at 5.85 GHz, normalized to the maximum field value measured in front of the reference object/network (in the region $x = 175$ mm . . . $x = 240$ mm): (a) reference object inside the waveguide, (b) reference object and the transmission-line network inside the waveguide.

To obtain efficient cloaking, i.e., to preserve the waveform of the incident wave both in front and behind the object (to reduce the total scattering cross section), one clearly needs to use a cloak which is electrically small enough and which does not have strong irregularities in its shape, not to cause significant forward scattering. It is also possible to use an electrically large cloak, dimensions of which are properly designed for a specific frequency range so that the desired reduction of the forward scattering is achieved [12]. When the incidence angle of the impinging radiation is not known, the cloak also needs to be symmetric, i.e., cylindrical in the two-dimensional case or spherical in the three-dimensional case [10–12]. Also, what is important in the case when the angle of the incident radiation is not known, the transmission-line network needs to be isotropic in the frequency range where most efficient cloaking is needed, i.e., the network period must be small enough as compared to the wavelength, as e.g. in the cylindrical cloaks studied in Refs. [11,12].

5. Numerical results

To provide further verification for the efficient coupling of fields between the transmission-line network and free space, we have conducted full-wave simulations with the Ansoft HFSS software http://www.ansoft.com/. The simulation model includes the same network and

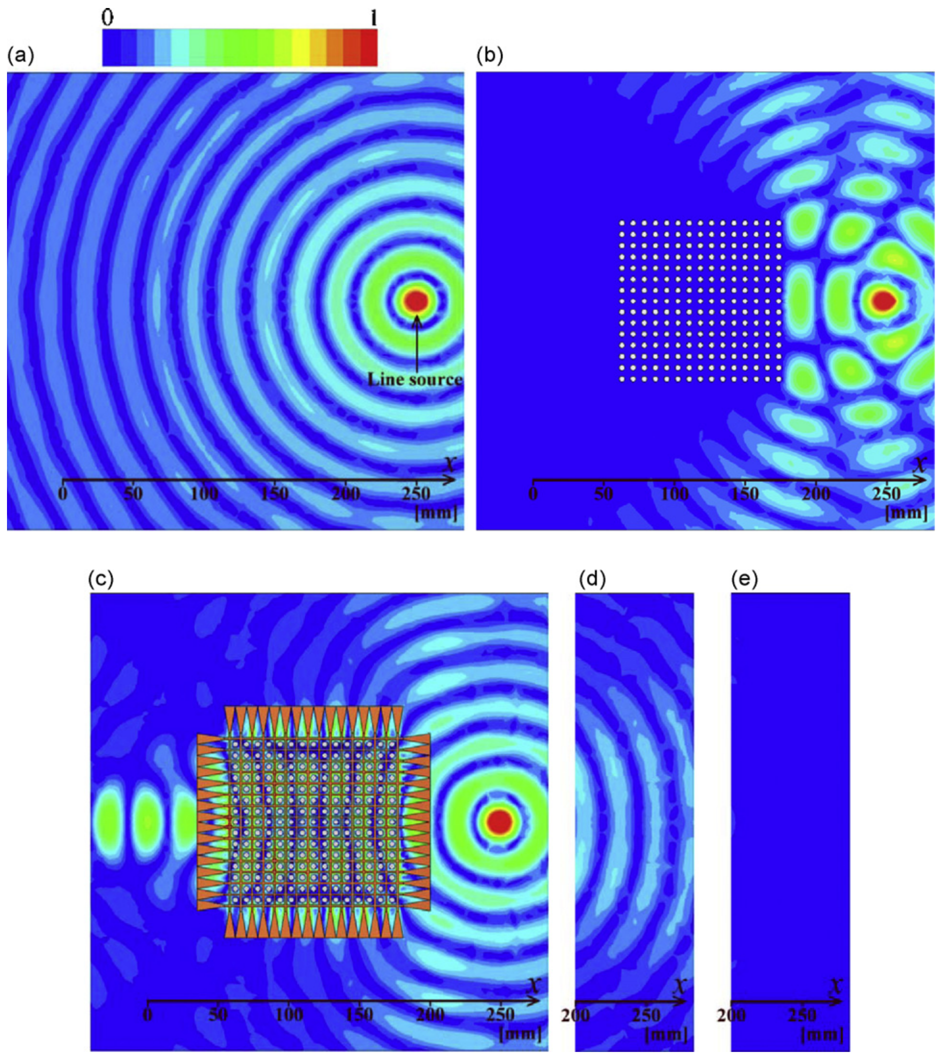

Fig. 7. Snapshots of the simulated electric field distributions at 5.85 GHz (absolute value of the real part). The fields are plotted in the *xy*-plane situated in the center between the parallel strips of the transmission lines. All plots are normalized to the same value. (a) Incident field. (b) Total field with reference object only. (c) Total field with reference object and the transmission-line network. (d) Scattered field in front of the reference object. (e) Scattered field in front of the reference object enclosed by the transmission-line network.

reference object as studied in the previous sections, placed in an infinitely large parallel-plate waveguide with height $h = 12.73$ mm. To reduce the simulation complexity, a perfect magnetic conductor wall is placed in the *xz*-plane in the center of the model, i.e., we simulate only one half of the space due to the symmetry. The transmission-line network as well as the reference object are modelled as perfect electric conductors, with the thickness of the strips of the transmission lines equal to zero. A line source is placed at the same distance away from the reference object/transmission-line network as was in the measured case, i.e., the line source is located at $x = 250$ mm, $y = 0$ mm.

The results of the simulations, for the frequency of 5.85 GHz, are presented in Fig. 7. As can be observed from Fig. 7a–c, that show snapshots of the time-harmonic electric field in the simulated model, the backscattering from the transmission-line network enclosing the reference object is minimal, whereas the reference object alone lets practically no field through itself and therefore scatters most of the power back towards the source. With the transmission-line network in place, the incoming field clearly gets through the reference object, travelling inside the transmission lines. The reduction of the scattering is even more clear from Fig. 7d and e, where only the scattered fields (difference between the total field and the incident field) are plotted, with and without the transmission-line network in place.

When comparing the results of Fig. 7 to the ones in Fig. 4, the reader should note that in Fig. 7 the absolute value of the real part of the electric field is plotted, whereas in Fig. 4, it is the real part (having both negative and positive values).

6. Conclusions

We have presented an experimental demonstration of a previously proposed transmission-line network, originally designed for cloaking purposes. In this paper we have demonstrated the benefits of this approach, such as the simple manufacturing, and confirm by measurements the predicted coupling of fields between the network and free space. Also the field propagation through such a network, with a periodic array of metallic rods placed between the transmission lines of the network, is demonstrated. The results are validated through comparison to the measurements on an empty cell and the measurements of the periodic array of metallic rods, effectively behaving as an impenetrable wall at the frequencies of interest. The results are further supported with numerical simulations.

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