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Broadband cloaking of selected objects in the microwave regime with a volumetric cloak comprising layered networks of transmission lines

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Introduction

Cloaking has recently aroused a great interest in the electromagnetics community. The number of papers devoted to this topic is rapidly increasing, as researchers find new ways of making objects "invisible" to the impinging electromagnetic radiation [1–5]. Electromagnetic cloaking means, in this context, the reduction of the total scattering cross section of a given object. In this paper we study, with numerical simulations and experiments, a volumetric cloak composed of periodically stacked networks of transmission lines.

Cloaking principle

Cloaking with transmission-line networks has been recently proposed [6,7]. The principle of operation is that the electromagnetic waves impinging on the cloak device are squeezed into a volumetric structure composed of networks of transmission lines, and in the cloak, the waves travel inside these lines. In the space between the adjacent sections of transmission line the electromagnetic fields are effectively zero thus enabling "cloaking" of objects placed in this space [6]. As compared to some other cloaking techniques, this results in the limitation of the size and shape of the cloaked object, but the benefits are simple structure and wide operation bandwidth. Cloaking with various designs based on the transmission-line technique has been verified both numerically and experimentally [6,7].

A cloak is usually intended to work for arbitrary angles of incidence, although applications where the incidence angle is fixed and known can be also thought of. This is why most cloak designs studied in the recent literature employ either fully three-dimensional symmetric structures or (volumetric) two-dimensional simplifications, which operate for any incidence angle in a fixed plane [5]. In this paper we study a recently proposed cloak design [7] which is of the latter type, i.e., the cloak consists of two-dimensional transmission-line networks but can be made volumetric by stacking a set of these networks on top of another.

Simulation results

The studied cloak is composed of cylindrical two-dimensional transmission-line networks, see Fig. 1(a). The cloak operates for waves with the electric field parallel to the z-axis. To study the cloaking capability of this structure, we have simulated the far-field scattering cross sections of cloaked and uncloaked objects when they are placed in free space and are considered to be infinitely periodic in the vertical (z-) direction. For these simulations we have used Ansoft's HFSS full-wave simulation software. The cloaking effect can be

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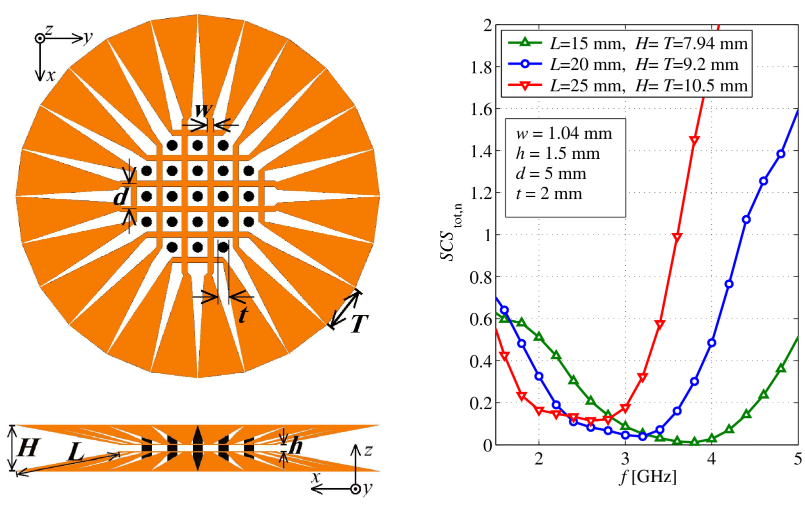
analyzed by illuminating the structures (cloaked and uncloaked objects) with plane waves at different frequencies and by calculating the scattering cross sections (SCSs) of both objects for all the angles in the xy-plane. The total SCSs can be obtained by integrating these results over the angle ϕ which lies in this plane. See Fig. 1(b) for the total SCS of the cloaked object which is normalized to the total SCS of the uncloaked object.

The simulations have been conducted for three different lengths of the transition layer (L) that surrounds the transmission-line network. The dimensions H and T, i.e., the height and width of the transmission lines at the interface between the transition layer and free space, are changed accordingly to cover the whole interface. In the previously published design [7] the length $L = 20$ mm was chosen so that the center of the frequency band where cloaking is achieved, was approximately 3 GHz. As demonstrated by Fig. 1(b), the cloak operation can be changed in terms of bandwidth and center frequency by tuning L. Of course, all the dimensions of the cloak can also be scaled in order to obtain the same cloaking effect at any frequency region of interest.

It is also clear that in the design of this type of cloak, the dimensions of the transition layer actually play a larger role than the impedance of the network itself: we have numerically tested the operation of the cloak discussed here varying the impedance of the network between 170 Ω and 140 Ω (by changing the width w of the transmission lines). This variation results in a very minor shift of the optimal cloaking frequency (less than 0.1 GHz) and also the effect on the cloaking bandwidth is minimal. Thus, it is clear that when the dimensions of the transition layer are properly chosen, for example using numerical optimization, the network impedance does not have to be matched to the wave impedance of the surrounding medium in order to achieve efficient cloaking. The simulated electric field distributions for cloaked and uncloaked objects at 3 GHz (for the case $L = 20$ mm) are shown in Fig. 2, demonstrating that the plane-wave field impinging on these objects is almost perfectly preserved in the cloaked case.



(a) (b)

Figure 1: (a) Cloak structure and dimensions in a xy-plane cut (top) and in a xz-plane cut (bottom). The cloaked object, which is an array of metallic rods, is illustrated as black. (b) Simulated total SCS of the cloaked object, normalized to the total SCS of the uncloaked object. Three different values of L are studied.

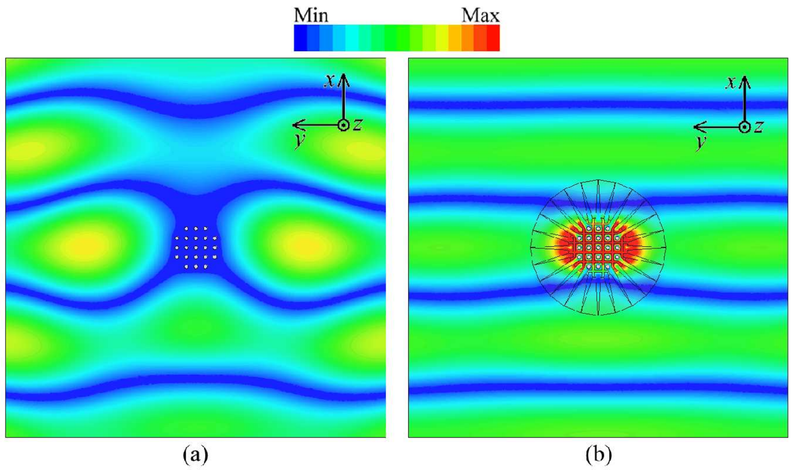


Figure 2: Electric field distributions at 3 GHz for (a) uncloaked and (b) cloaked objects.

Waveguide measurement

A waveguide measurement is suitable for testing a cloak such as studied here, due to the simple analysis of the results: the broadband operation of the cloak can be easily verified by conducting reflection and transmission measurements for a waveguide which encompasses cloaked and uncloaked objects. A waveguide, designed for this purpose was recently presented, see [7] for details and dimensions. The cloak and the object that is "hidden" with the cloak, are the same as shown in Fig. 1 (with $L = 20$ mm). The measured transmission magnitude and phase are shown in Fig. 3. The simulated electric field distributions inside the waveguide, corresponding to the various cases that were measured, are shown in Fig. 4.

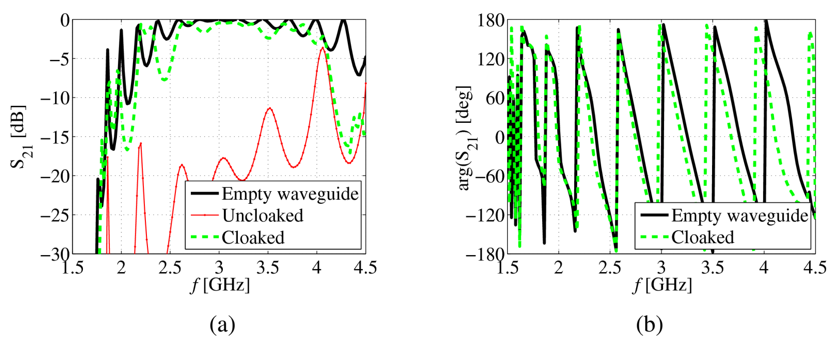


Figure 3: Measured transmission magnitude (a) and phase (b) for the cloak and cloaked object shown in Fig. 4.

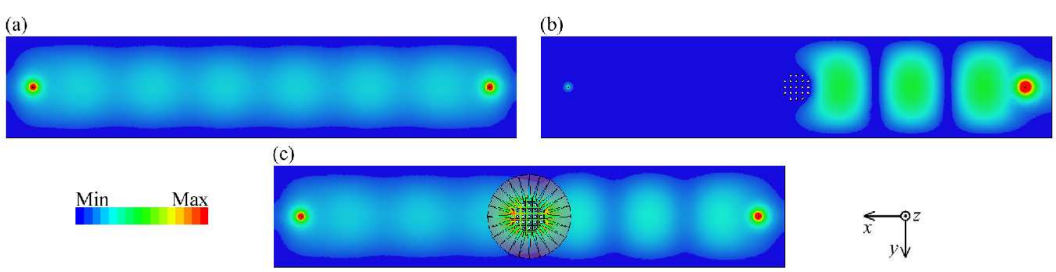
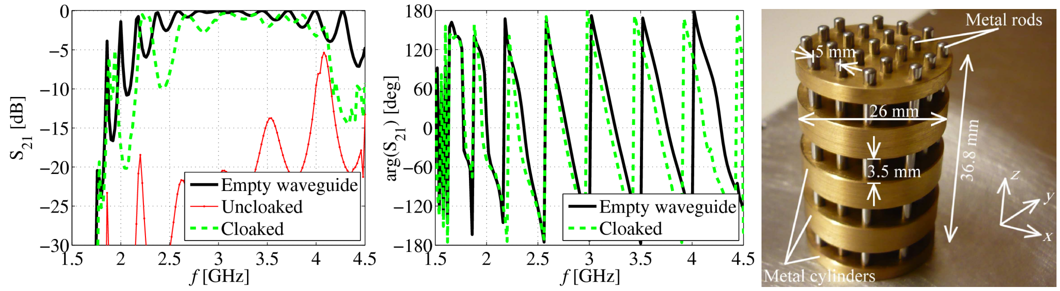


Figure 4: Simulated electric field magnitude at 3 GHz. (a) Empty waveguide. (b) Uncloaked object inside the waveguide. (c) Cloaked object inside the waveguide.



(a) (b) (c)

Figure 5: Measured transmission magnitude (a) and phase (b). A photograph of the cloaked object, which comprises an array of metal rods and a set of metal cylinders interconnecting these rods, is shown in (c).

We have modified the cloaked object to make it fully three-dimensional by adding metal cylinders to the array of metal rods, as shown in Fig. 5(c). The measured transmission magnitude and phase for this object are shown in Figs. 5(a) and 5(b). The cloak and the measurement waveguide are the same as in the previous case. The results demonstrate that the transmission properties are almost the same for both types of cloaked objects that are studied here.

Conclusions

A volumetric cloak composed of cylindrical two-dimensional transmission-line networks, has been studied with numerical simulations and measurements. The broadband cloaking effect obtained with this structure is confirmed for two different metallic objects.

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