

Pekka Alitalo, Frédéric Bongard, Jean-Francois Zürcher, Juan Mosig, and Sergei Tretyakov. 2009. Experimental verification of broadband cloaking using a volumetric cloak composed of periodically stacked cylindrical transmission-line networks. *Applied Physics Letters*, volume 94, number 1, 014103.

© 2009 American Institute of Physics

Reprinted with permission.

Experimental verification of broadband cloaking using a volumetric cloak composed of periodically stacked cylindrical transmission-line networks

Pekka Alitalo,^{1,2,a)} Frédéric Bongard,² Jean-Francois Zürcher,² Juan Mosig,² and Sergei Tretyakov¹

¹*Department of Radio Science and Engineering/SMARAD Center of Excellence, TKK Helsinki University of Technology, P.O. Box 3000, FI-02015 TKK, Finland*

²*Laboratory of Electromagnetics and Acoustics (LEMA), Ecole Polytechnique Fédérale de Lausanne (EPFL), Bâtiment ELB, Station 11, CH-1015 Lausanne, Switzerland*

(Received 10 October 2008; accepted 17 December 2008; published online 9 January 2009)

Cloaking using a volumetric structure composed of stacked two-dimensional transmission-line networks is verified with numerical simulations and measurements. The measurements are done in a waveguide, in which an array of metal cylinders is inserted causing a short circuit in the waveguide. The metal cylinders are cloaked using the transmission-line structure, which “hides” the cylinders and thus enables wave propagation inside the waveguide. © 2009 American Institute of Physics. [DOI: 10.1063/1.3068749]

The reduction of an object’s total scattering cross section (SCS) from electromagnetic waves impinging on the object from arbitrary directions, often referred to as cloaking, has been the subject of many works in the recent literature after the publication of some seminal papers.^{1–3} The number of scientific papers devoted to the study of this phenomenon is already huge, and therefore we will not review all the various cloaking techniques here, but instead, we suggest the reader to peruse the recent review paper by Alù and Engheta,⁴ and the references therein. The cloaking phenomenon that is studied in this paper is achieved with the use of so-called transmission-line networks. This approach to cloaking has been studied analytically, numerically, and experimentally in some of our recent papers.^{5–9}

In this paper, we experimentally demonstrate the cloaking phenomenon using cylindrically shaped networks of transmission lines. The “cloak” is a volumetric structure, composed of several two-dimensional networks that are stacked on top of each other. Two versions of the cloak design that is used here have been recently presented and studied numerically.^{6–8} A waveguide environment has been chosen here for the measurements since it allows to address the broadband behavior of the considered cloak through the measurements of reflection and transmission coefficients as functions of the frequency.

The principle of operation of the cloak studied here is the following: The electromagnetic wave that impinges on the cloak is coupled into transmission-line networks inside which the wave travels through the cloak.⁵ As the fields are mainly confined inside the transmission lines, any object can be placed in the space between adjacent sections of transmission lines without significantly affecting wave propagation in the network (outside the transmission lines the field amplitude is ideally zero). As a result, the objects placed inside the networks appear to be invisible, or in other words, cloaked from the surrounding electromagnetic fields.⁵ The cloaked object can have any shape and size as long as it fits inside the

space between the adjacent sections of transmission lines. The physics behind this cloaking technique, as well as its benefits and drawbacks, are discussed in more detail in Ref. 5.

Because the electromagnetic fields impinging on the cloak need to be “squeezed” into the transmission lines, a transition layer coupling the waves between the cloak and the surrounding medium is required. A transition layer topology that is easily implemented in cloaks composed of parallel-strip transmission lines was proposed in Ref. 5. The transition layer is composed of gradually enlarging parallel strips that cover the whole interface between the cloak and the surrounding medium, effectively behaving as mode transformers.⁹ Here the same transition layer topology is used for a cylindrical cloak by connecting the transmission lines of this layer radially around the cylindrically shaped transmission-line network, as shown in Fig. 1(a). The cloaked object is a two-dimensional array of metallic rods having a circular cross section and a diameter of 2 mm, as shown in the inset of Fig. 1(b), but with the proposed cloak a three-dimensional mesh can be cloaked as well (but only for one polarization due to the topology of the transition layer).

The cloak is periodic in the vertical direction (z -direction), with the dimensions of a single period as illustrated in Fig. 1(a). Thus, the cloak can be made volumetric by stacking structures as in Fig. 1(a) on top of another. The period d of the transmission-line network is 5 mm and the width and height of the parallel-strip transmission lines are shown in the figure. Due to the chosen transmission-line topology, this type of structure can cloak objects only from TE-polarized waves with electric field E parallel to the z -axis.

The dimensions of the cloak (width and height of the transmission lines, length of the transition layer) are found by optimizing the structure with the commercial simulation software ANSOFT HFSS (Ref. 10) to obtain a wide cloaking bandwidth with the center frequency around 3 GHz. The analytical expressions⁵ for the dispersion in transmission-line networks, such as here, are used to make sure that wave

^{a)}Author to whom correspondence should be addressed. Electronic mail: pekka.alitalo@tkk.fi.

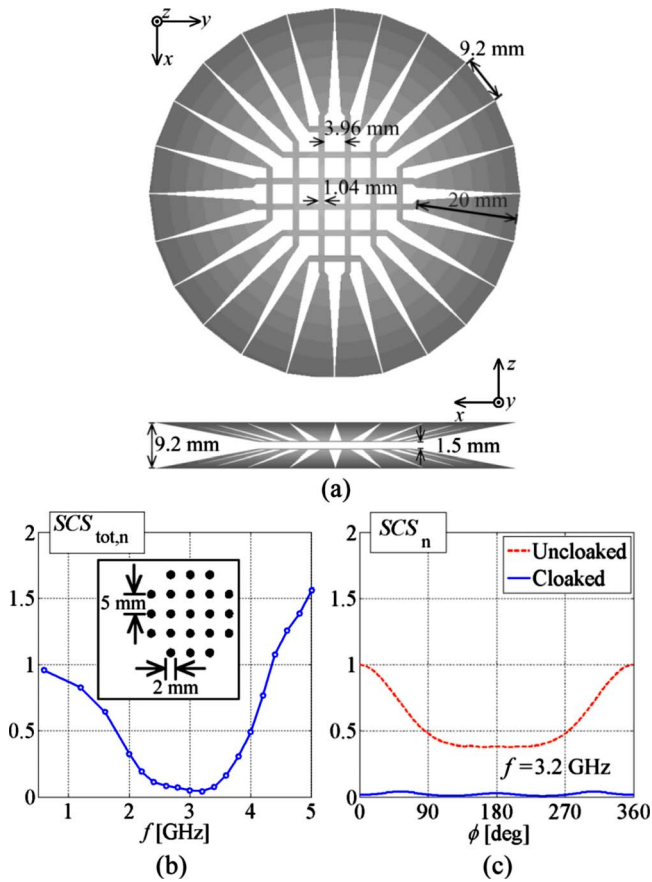


FIG. 1. (Color online) (a) Cloak structure and dimensions in the xy -plane (top) and in the xz -plane (bottom). (b) Full-wave simulated total SCS of the cloaked object, normalized to that of the uncloaked object. The inset shows the dimensions of the cloaked array of infinitely long metal rods in an xy -plane cut. (c) Full-wave simulated SCSs of uncloaked and cloaked objects at the frequency of 3.2 GHz. ϕ is the angle in the xy -plane, and the plane wave illuminating the cloak travels to the $+x$ -direction, i.e., in the direction $\phi=0$.

propagation inside the network is effectively isotropic, which is the case if the period of the network d is small enough at the operation frequency.⁵

For the cloak structure studied here, the cloaking phenomenon is first confirmed by conducting full-wave simulations¹⁰ of a cloaked and uncloaked object in free space and calculating the far-field SCSs for both cases. In the simulations the cloak and the cloaked object are considered to be periodically infinite along the z -direction. The simulations are conducted by exciting the cloaked and uncloaked objects with TE-polarized plane waves of different frequencies, and the SCS is calculated from the power scattered in all directions in the xy -plane. See Fig. 1(b) for the frequency dependence of the total SCS (SCS integrated over the angle ϕ) of the cloaked object, normalized to the total SCS of the uncloaked object. Figure 1(c) presents the angular dependence of the SCS of cloaked and uncloaked objects at the frequency of 3.2 GHz. The data presented in Fig. 1(c) are normalized to the maximum value of the uncloaked object's SCS. Figure 1(b) illustrates that at the optimal cloaking frequency of 3.2 GHz, the total SCS of the cloaked object is reduced by more than 96%, as compared to the uncloaked case. Figure 1(c) on the other hand shows that at that frequency, the cloak significantly reduces the scattering to all directions in the xy -plane.

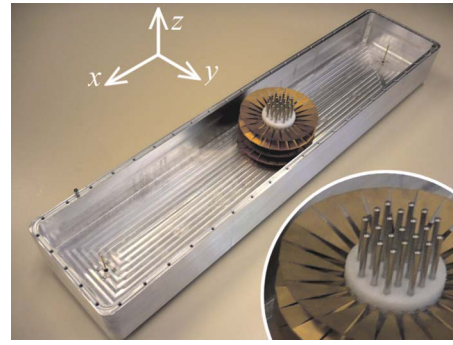


FIG. 2. (Color online) Photograph of the waveguide with the cloaked object and the cloak inside. The top wall of the waveguide is removed for clarity. The inset shows a magnification of the cloaked object (an array of metallic rods) enclosed by the cloak.

The cloak shown in Fig. 1(a) was manufactured by etching from 200 μm thick metal sheets composed of an alloy of bronze and beryllium. For stacking the cloak parts on top of each other, we use layers of dielectric foam (Rohacell) with relative permittivity $\epsilon_r \approx 1.05$. The measurements are conducted with a modified aluminum WR-340 waveguide, with the inner dimensions of $435 \times 86.36 \times 36.8$ mm³ (length \times width \times height). The height is determined by the fact that it must be a multiple of the cloak period in the vertical (z -) direction. In this case we use four networks on top of each other, i.e., 4×9.2 mm = 36.8 mm. Transmission through the waveguide is measured with standard coaxial probes with the distance from the waveguide (front and back) walls being 23 mm. The height of the probes also equals 23 mm. These values, with which good matching between the probes and the waveguide is obtained, were found with full-wave simulations of the empty waveguide.

The object that is supposed to be cloaked is the same as that studied numerically above, i.e., a two-dimensional array of metallic rods that fits inside the cloak structure. The rods are connected with the bottom and top walls of the waveguide to create a short circuit inside the waveguide. See Fig. 2 for a photograph of the waveguide with the cloak and the metal cylinders inside.

The measured reflection and transmission for the empty waveguide are shown in Fig. 3, demonstrating that the empty waveguide section has low reflectance and high transmittance at the frequencies of interest, i.e., around 3 GHz, where the cloak is supposed to work the best. With the uncloaked object inside the waveguide, the transmission (S_{21}) is less than -15 dB around this frequency. With the cloaked object, the measured transmission and reflection agree well with those of the empty waveguide, especially in the frequency band from 2.5 to 4 GHz.

The measurement results are in good agreement with the previous simulations of the cloak, experimentally confirming the broadband cloaking phenomenon also for real structures. As the fundamental mode inside the waveguide can be considered to be a sum of two plane waves with the incidence angles varying as functions of the frequency, these results also give further confirmation of the isotropy of the cloak. For comparison, full-wave simulation results for cloaked and uncloaked objects inside the waveguide are also shown in Fig. 3(b), showing very good agreement with the measurement results.

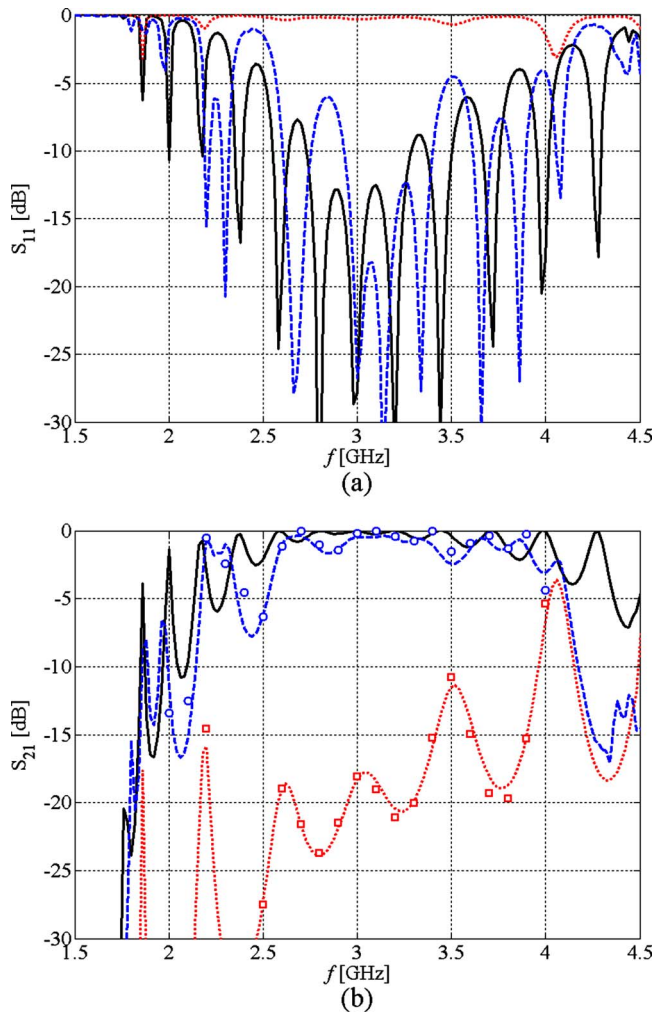


FIG. 3. (Color online) Measured (a) reflection and (b) transmission for the empty waveguide (solid line), waveguide with the uncloaked object inside (dotted line), and waveguide with the cloaked object inside (dashed line). For comparison the full-wave simulated transmission corresponding to the uncloaked (squares) and cloaked (circles) cases are also shown in (b).

The phase of the measured S_{21} in the empty waveguide and the cloaked case are obviously different. For example, in

the frequency range from 2.5 to 3.3 GHz, the absolute value of the phase difference between these two cases varies between 0° and 45° . The envelope of the phase difference curve grows in magnitude with increasing frequency. This phase difference is due to the fact that the wave number inside the cloak differs from that in free space, by a factor of $\sqrt{2}$, as has been previously reported.⁵ As discussed in Ref. 5 and also demonstrated by Figs. 1(b) and 1(c), this nonideality does not prevent efficient cloaking in many practical situations.

We have presented a waveguide-based measurement procedure, with which we can, in a convenient way, study the cloaking phenomenon of certain types of cloaks. In this paper we have studied the performance of a volumetric microwave cloak composed of layered two-dimensional transmission-line networks. The broadband cloaking phenomenon, which has been studied before with numerical simulations, is now confirmed with measurements.

This work has been partially funded by the Academy of Finland and TEKES through the Center-of-Excellence program. During this work P.A. was an invited researcher at EPFL-Switzerland. P.A. acknowledges financial support by GETA, the Emil Aaltonen Foundation, and the Nokia Foundation.

¹A. Alù and N. Engheta, *Phys. Rev. E* **72**, 016623 (2005).

²U. Leonhardt, *Science* **312**, 1777 (2006).

³J.B. Pendry, D. Schurig, and D.R. Smith, *Science* **312**, 1780 (2006).

⁴A. Alù and N. Engheta, *J. Opt. A, Pure Appl. Opt.* **10**, 093002 (2008).

⁵P. Alitalo, O. Luukkonen, L. Jylhä, J. Vernerio, and S. A. Tretyakov, *IEEE Trans. Antennas Propag.* **56**, 416 (2008).

⁶P. Alitalo and S. Tretyakov, Proceedings of the 2008 IEEE International Workshop on Antenna Technology, Chiba, Japan, 4–6 March 2008, p. 147.

⁷P. Alitalo and S. Tretyakov, Proceedings of the XXIX URSI General Assembly, Chicago, USA, 7–16 August 2008, p. B01.9.

⁸P. Alitalo and S. Tretyakov, Proceedings of the 2nd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, Pamplona, Spain, 21–26 September 2008, p. 392.

⁹P. Alitalo, S. Ranvier, J. Vehmas, and S. Tretyakov, *Metamaterials* **2**, 206 (2008).

¹⁰The homepage of Ansoft corporation, <http://www.ansoft.com/>.