On electromagnetic cloaking – general principles, problems and recent advances using the transmission-line approach

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Abstract

Principles, historical background and recent developments on the subject of electromagnetic cloaking are discussed. The problems related to the propagation of energy inside some previously proposed cloak structures are explained. One recently proposed approach to achieve cloaking, namely, the use of transmission-line networks, is presented in more detail and the principles of this approach are compared to other cloaking methods.

1. Introduction

The subject of cloaking objects from arbitrary electromagnetic fields propagating e.g. in free space, has aroused a lot of interest after the publication of the recent work by Greenleaf et al. [1], Leonhardt [2], Pendry et al. [3] and the research groups of Engheta [4–6] and Smith [3,7]. In [1–7] two different methods aimed for the reduction of an object's total scattering cross section were discussed. In [4–6] a way of making objects invisible using a specific material cover to cancel the dipolar scattered fields of the object to be made invisible, is presented. In [1–3,7] the cloak material cover is designed in such a way that the electromagnetic fields are zero in the cloaked region, i.e., the fields are guided around the cloaked object. Although the method introduced in [4–6] in principle differs significantly from cloaking (by cloaking we mean reduction of the scattering from an arbitrary object), this method can also be used for similar cloaking purposes as in e.g. [2,3,7], if the object to be made invisible is placed inside an enclosure made of a perfectly conducting material. The approach proposed in [2,3] and designed for TE polarization in [7] has been developed also for TM polarization [8] and for operation for both polarizations simultaneously [9]. In addition, there has been recently a lot of work done to estimate feasibility and scattering properties of such cloaks, see, e.g., [10]. An alternative approach, as compared to [2,3], aimed to obtain arbitrary field transforms by starting directly from the required field distributions, has been recently presented [11].

Although the subject of cloaking (or invisibility) has aroused huge amount of interest after the publication of e.g. [1–4], it was, in fact, studied already a few decades ago [12,13], when a similar method as suggested in [4] was used to cancel the scattering from spherical and ellipsoidal objects. Also in [14] the scattering properties of multilayered spheres were studied. The use of hard surfaces for reducing the scattering from antenna struts was thoroughly studied already some time ago, see, e.g., [15]. Although the design proposed in [15] is somewhat limited in view of the generality of the cloaking phenomenon (this approach is strongly anisotropic since scattering of an object can be significantly reduced only for waves with a fixed direction of arrival), it is still to this date the only approach to cloaking which has been shown to work in practice for a specific application. Recently, also other alternative approaches to cloaking have been suggested. In [16] it is shown that line or dipole sources positioned near to a so called superlens (a material slab with effectively negative permittivity and permeability) are cloaked due to localized resonance effects. Although this approach is very interesting in the scientific sense, it seems to be even more difficult in view of realization, as compared to e.g. [2–4].

Recently, the use of transmission-line networks matched with the surrounding medium (e.g., free space), has been suggested for cloaking objects made of 2D or 3D meshes composed of an arbitrary material [17–19]. This cloaking method differs significantly from the previously discussed methods since it is based on enabling the incoming electromagnetic wave to go through the object instead of going around it (or cancelling the induced dipole moments) in a very simple way just by coupling the incoming wave to a network of transmission lines. This approach has the clear drawback of limiting the object to be cloaked to a mesh or an array of small objects, but the advantage obtained is a very simple structure and the ease of manufacturing. Also, as shown and discussed in [18,19], in certain cases the operational relative bandwidth (where cloaking is achieved) can be up to 40 percent or more, which is considerably more than what can be obtained by using materials composed of resonant inclusions [7].

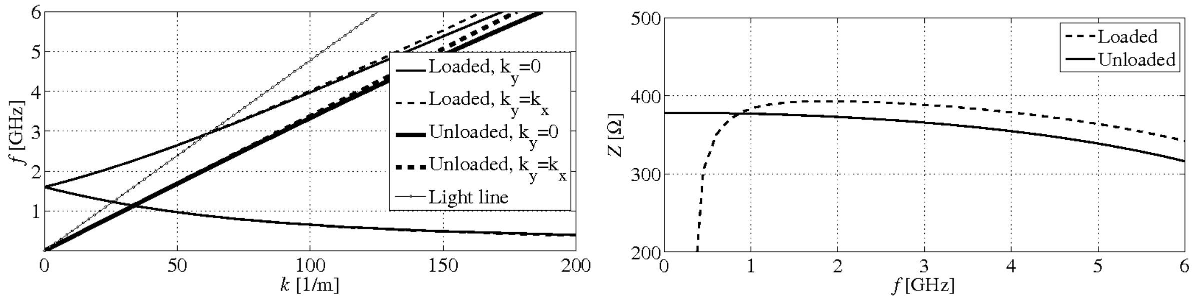
2. Energy velocity in cloaks composed of passive inclusions

One significant problem with the cloaking approach introduced in [2,3] is the fact that the electromagnetic wave must go around the object (or the region which is supposed to be cloaked) in a way that the wave on both sides of the cloak is left undisturbed by the cloak/cloaked object. This requires that the wave propagation velocity inside the cloak is faster than outside the cloak. For the phase velocity at a single frequency point this is not a problem, as it was demonstrated e.g. in [7], but for the energy propagation velocity (group velocity) this requirement is impossible to achieve when using cloaks composed of passive components and materials. The negative effect of the inevitable phase and group velocity mismatch on the cloaking phenomenon strongly depends on the type of the pulse (signal) that impinges on the cloak. If the pulse is very narrow in the frequency, it is clear that the mismatch effect is not very strong and cloaking can be achieved, at least to some extent. On the other hand, cloaking with realizations as suggested e.g. in [7,8] is inherently restricted to a very narrow frequency band since the cloak materials are composed of strongly resonant inclusions. The cloaking methods based on the cancellation of the dipole scattering [4–6,12–14] are also expected to have similar problems when the object to be cloaked is placed inside a perfectly conducting enclosure, which in turn is made invisible by the cloak material cover, since also in this case energy cannot go along a straight line but it must go around the cloaked object.

As discussed in [17,18], the transmission-line approach to cloaking has the benefit of fairly simple design and manufacturing, and in certain cloak designs (unloaded networks), the group velocity is actually equal to the phase velocity. On the other hand, when the group velocity equals the phase velocity, the problem is that they obviously cannot be ideal when cloaking objects situated in free space [18]. It must also be noted that since inside a transmission-line cloak only waves of voltages and currents propagate, the so called matching layer between the network and the surrounding medium dictates for which polarization cloaking can be achieved. At the moment, no feasible realization for a transmission-line cloak operating for two orthogonal polarizations has been suggested.

3. Operation of the transmission-line cloak

The principle of operation of the transmission-line cloak is thoroughly explained in [18]. The main idea is that a network of transmission lines is designed in such a way that at the operating frequency the wave propagation (voltages and currents) is isotropic or at least very close to isotropic. This means that the period of the network must be much smaller than the wavelength at the operational frequency. If a wave in free space could be coupled into this network, the space between the transmission lines of the network would be ideally cloaked from this wave since in the network the wave travels only inside the sections of transmission line. In order to have perfect cloaking effect, the wave propagation inside the network must be identical to the wave propagation in the surrounding medium. As shown in [18], this is impossible to achieve with a simple (unloaded) transmission-line network when the surrounding medium is free space. This is due to the fact that inside the network, the waves propagate slightly slower than in the material which is filling the individual sections of transmission line. One way to get past this problem is to use a loaded transmission-line network [17,18]. This choice has the drawback of resulting in a difference between the phase (v_p) and the group (v_g) velocities ($v_p = c_0$, $v_g < c_0$, where c_0 is the speed of light). Thus, with the loaded transmission-line cloak we end up with a similar problem regarding the energy propagation, as e.g. with the cloaks discussed in [2,3]. See Fig. 1 for the dispersion and impedance in two example networks, a loaded and an unloaded one. The unloaded network has the same parameters as in [18], but the loaded network is periodically loaded by series capacitors ($C = 0.67$ pF) and also by shunt inductors ($L = 101.3$ nH), as opposed to the capacitively loaded network in [18]. The impedance of the lines in the loaded network is 550 Ω. From Fig. 1a we see that the loaded network has the ideal phase velocity at two frequencies (1.25 GHz and 3 GHz in the studied example case). Also, the impedance of both networks can be tuned to be very close to the ideal value of 120π Ω on a relatively large bandwidth, as can be seen from Fig. 1b.



(a)

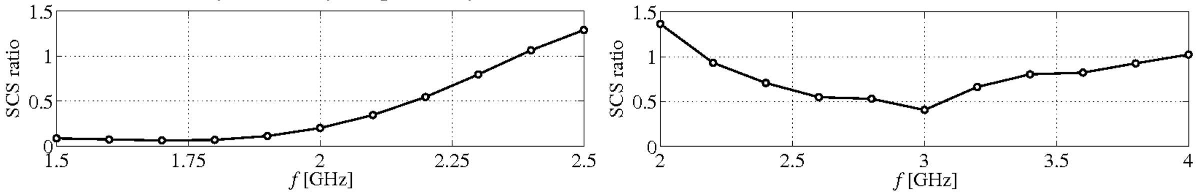
(b)

Figure 1: (a) Dispersion and (b) impedance for the studied networks. The period d of both networks is equal to 8 mm [18]. The total wavenumber in the networks is $k = \sqrt{k_x^2 + k_y^2}$.

4. Cloaking metal meshes with cylindrically shaped transmission-line networks

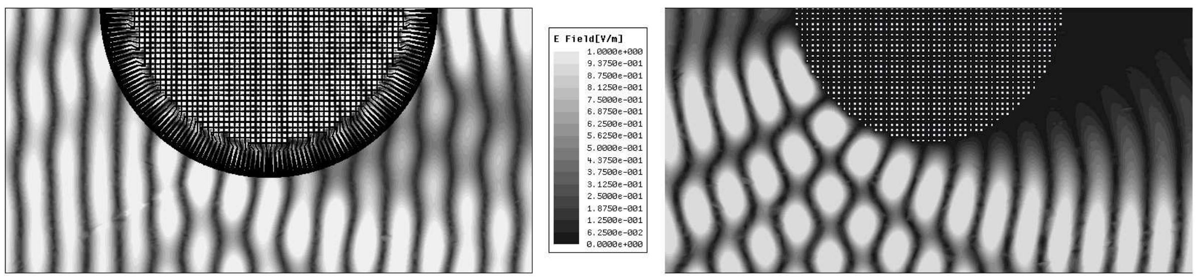
The most practical transmission-line cloak is clearly the simplest unloaded one, since in that case the phase and group velocities are equal, and the obtainable operation bands are the largest [18]. The drawback in this structure is that when cloaking objects in free space, the phase and group velocities differ slightly from c_0. As was discovered in [18,19], a cylindrical cloak like this still scatters very little (as compared to a metallic, uncloaked object), when its diameter is small compared to the wavelength (e.g., smaller than a half wavelengths). Also, it was found that for a cloak with a fixed diameter, there are other, higher frequency ranges, where the cloak scattering is greatly reduced. These points occur at the frequencies where the cloak's diameter is simultaneously close to a multiple of the wavelength inside and outside the cloak [18].

Here we reproduce the results for a small cylindrical cloak presented in [19] (diameter equal to $0.32\lambda_0$ at the design frequency of 2 GHz) and use the same network design for creating a cloak which is large compared to the wavelength. To obtain an electrically large cloak, we simply increase the diameter of the small cylindrical cloak, while keeping the period and other dimensions of the transmission lines similar to those used in [19]. With the help of the scattering simulations done for a homogenized cloak in [18], we have estimated a suitable diameter of the electrically large cloak to be $52d$ (d is the network period and here $d = 8$ mm) for a cloak operating around 2...3 GHz. For the simulation of the large cylindrical cloak, we cut the model in half with a PMC boundary inserted in the middle of the cylinder. The transition layer, as in [19], is designed in such a way that basically the whole surface around the cloak is covered by the "antennas" that are composed of gradually enlarging parallel strip transmission lines (with equal width and separation). For the large cylindrical cloak, the separation between the "antenna" strips and their width are both equal to 7.73 mm (at the interface with free space). The length of the "antennas" is equal to 40 mm [19]. See Fig. 2 for the ratios of the simulated total scattering cross sections of the both cloaks and the corresponding reference cases, and Fig. 3 for snapshots of the simulated electric field distributions in the large cylindrical cloak ($52d \approx 4\lambda_0$ at 3 GHz) and its reference case. For both cloaks the reference cases are cylindrically shaped arrays of PEC rods that fit inside the cloaks [17–19].



(a) (b)

Figure 2: Ratios of the HFSS-simulated total scattering cross sections. (a) Electrically small cylindrical cloak as presented in [19]. (b) Electrically large cylindrical cloak. When the ratio is less than 1, the cloak's (with reference object inside) total scattering cross section is less than that of the uncloaked reference object's.



(a) (b)

Figure 3: Snapshots of the HFSS-simulated total electric field distributions at 3 GHz for (a) cloak (metal strips illustrated as black) with the reference object inside and (b) bare reference object (the PEC rods illustrated as white squares). A plane wave with electric field normal to the figure plane travels from left to right.

5. Conclusion

We have discussed the basic principles and problems of cloaking related to the various cloaking methods presented in the literature. It is clear that regarding cloaking of pulses (waves carrying energy and information), there are some problems that are bound to limit the applicability of some suggested cloak structures. The mismatch of the phase and group velocities, inherent to certain types of (passive) cloaks, clearly needs more study before the reduction of the cloaking effect can be fully understood. We have also discussed a recent alternative approach to cloaking, namely, the use of transmission-line networks. This approach has some severe limitations regarding the size and shape of the objects that can be cloaked, but on the other hand, it offers a very simple structure and ease of manufacturing, as well as relatively large operation bandwidth.

6. Acknowledgments

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