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Review

Electromagnetic cloaking with metamaterials

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Electromagnetic cloaking has aroused increasing interest in the scientific community, especially amongst researchers who are developing so-called metamaterials - artificial composites having exotic electromagnetic properties. In this paper we review the basic principles of metamaterials, especially those for cloaking applications, and describe the recent developments in the field of electromagnetic cloaking. Attention is given also to the recently proposed cloaking technique which is based on networks of transmission lines.

Previous Next

The idea of a device which makes objects invisible to the eye has a very long history, starting from folklore of many nationalities: we all have heard about various "invisibility hats" or "invisibility cloaks", such as the cloak of Harry Potter, a character in J. K. Rowling's novels, but can such a device be practically realized, at least in some limited frequency range? Can a finite-size physical body be made invisible for electromagnetic radiation? Scientists have been thinking about these questions for a long time. Dollin published a paper in 1961, where he described an inhomogeneous and anisotropic magneto-dielectric structure, such that a plane wave falling from infinity on this body "passes through it without distortions[1]". Apparently independent from that early work, similar structures were more recently described in a series of papers by Leonhardt, Pendry, Greenleaf, et al.2, 3, 4, 5. **As another example, Kerker published a paper entitled "Invisible bodies" in 1975[6], and that was a precursor of another recent series of publications by Alù and Engheta on invisible structures based on cancellation of scattering**7, 8, 9.

Here we will review cloaking techniques based on scattering cancellation, on coordinate transformations, and on the use of artificial materials realized as dense meshes of transmission lines[10]. There are some other techniques, like the use of artificial electromagnetic surfaces, which allow to hide objects of certain special shapes for a single direction of illumination[11] or the use of plasmonic resonant structures[12], which unfortunately can be only briefly touched in this paper.

At the very core of cloaking techniques is the use of materials with very specific and often quite exotic properties. Because nature does not provide us with ready-to-use materials with the necessary properties, the only possibility is to realize them as artificial materials (metamaterials).

Metamaterials

The European Virtual Institute for Artificial Electromagnetic Materials and Metamaterials[13] defines the metamaterial as "an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties". If certain electromagnetic properties of a material (usually measured in terms of its permittivity ε and permeability μ) are needed for an application in a certain range of the wavelengths of electromagnetic radiation, this material should appear homogeneous at the scale of this wavelength. This means that the size of its molecules as well as the distance between molecules should be much smaller than the wavelength. If the application is, for instance, in the microwave frequency range, where the wavelength is of the order of centimeters, the size of a single "molecule" can be of the order of millimeters, and it can be engineered and manufactured from ordinary materials consisting of usual, negligibly small at this wavelength scale, molecules. This is one of the origins of the term "metamaterial": it is an artificial material with unusual properties made of usual materials with usual properties[14, 15]. Of course, if the desired application is at very high frequencies, such as in the visible range, the size of these artificial molecules should be of the order of tens of nanometers or even smaller, which makes the actual realization a serious technological challenge.

The effective properties of metamaterials are defined by the (ordinary) materials from which the metamaterial inclusions are made, by their shape, mutual orientation and concentration of inclusions, and so on. This means that there are very many degrees of freedom in the design of the desired electromagnetic response, allowing for realization of artificial media with quite exotic and extreme properties[16], such as required for realization of cloaking devices. Although the metamaterial research activities started only quite recently, the results have been already covered in a number of monographs[17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27].

What is cloaking and invisibility

What is an electromagnetic cloak? This is a device which makes an object "invisible" for electromagnetic radiation in a certain frequency range. Of course, the most exciting applications can be envisaged for cloaks working in the visible part of the spectrum. An object is invisible if it does not reflect waves back to the source and in addition, it does not scatter waves in other directions, and, furthermore, it does not create any shadow (the last means that there is no scattering in the forward direction). From these conditions it follows that the object should not absorb any power. Put in other words, the object should not disturb the fields existing outside the object.

In terms of the theory of scattering of electromagnetic waves (including light), to "cloak" an object means to reduce its total scattering cross section (SCS), ideally to zero, since the total scattering cross section is defined as the ratio of the total scattered power to the incident power density. Cloaking should not be confused with the stealth technology. Stealth technologies minimize only the power reflected back to the probing radar (the backscattering cross section or "radar cross section"). This can be done either by covering an object with an absorbing layer or by shaping the object so that the field scattered towards the illumination direction is minimized. Obviously, even an ideal stealth aircraft is visible if observed from the side or from the back. It can be shown that absorbing coverings and object shaping cannot reduce the total scattering cross section by more than 50%[28].

The concept of invisibility has been closely related to cloaking in recent literature, the difference is that invisibility means the reduction of the total scattering cross section of a specific object. This can be achieved for example by cancelling radiation from the induced dipole moments of the scatterer by introducing another object, in which dipole moments of the opposite direction are induced[7]. Thus, the combination of these objects scatters very little, whereas both objects independently scatter strongly. Some invisible structures can also be used as cloaks, if the object to be made invisible consists of, e.g., a perfectly conducting hollow enclosure, since inside this enclosure there are no fields[9].

Scattering cancellation technique

It has been known for a long time that scattering from an object can be mitigated by adding to the system another object, the scattering of which is complementary with respect to the principal scatterer6, 29, 30. This type of scattering minimization can be achieved for example with covering the main scattering object by single or multiple layers of dielectric materials6, 30, 31. The recent interest towards this technique has been aroused after the proposal of using plasmonic materials for transparency[7] and this technique has been developed further8, 9, 32, 33, 34, 35, 36, 37, 38.

Fig. 1 shows an illustration of the principle of scattering cancellation. Here a spherical dielectric object with permittivity larger than in the surrounding medium, is covered with a dielectric shell having the permittivity smaller than in the surrounding medium. The shell diameter can be chosen so that the scattering from the core and the shell cancel each other, since dipole moments of the opposite sign are induced in them. Of course, there may also exist higher modes in addition to the dipolar modes, but it has been shown that efficient invisibility can be achieved even with suppressing just the dipolar scattering[9]. It is possible to suppress also higher modes, but this obviously makes the design more complicated[9]. Cloaking of collections of particles and the extension of the scattering cancellation approach to infrared and optical frequencies have also been recently discussed33, 34, 35, 36, as well as the effects of material dispersion[37].

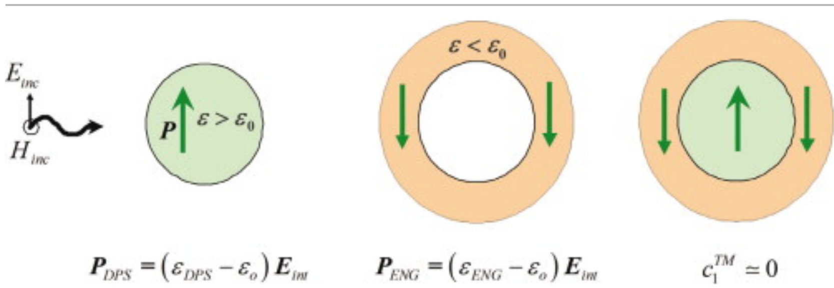

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Fig. 1. Illustration of the scattering cancellation technique[7]: the dipole moments induced in the object to be made invisible and in the shell covering this object cancel each other. Reproduced with permission from the American Physical Society.

The problems of utilizing cloaks based on the scattering cancellation technique relate to the realization of materials with the needed type of exotic material parameters (e.g., materials having the relative permittivity $\varepsilon_r < 1$). There are some materials readily available in nature that have the property of the desired low permittivity values at THz, infrared or optical frequencies (plasmonic materials such as silver and gold). The utilization of these plasmonic materials is limited by losses and by the fact that their material properties vary significantly as a function of the frequency. Moreover, at a specific frequency of interest there may not be a material with suitable properties available at all.

One recently suggested (practically possible) design of a scattering cancellation cloak consists of metallic parallel-plate implants placed radially around the cylindrical region where a dielectric object (to be made invisible) is located[32]. This structure is an example of a scattering cancellation device which is composed of an artificial metamaterial, see Fig. 2.

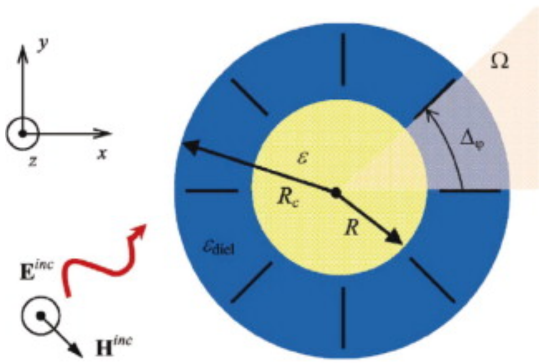

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Fig. 2. An example design of a scattering cancellation device[32], composed of metallic parallel plates embedded in a dielectric. The object to be made invisible is a dielectric cylinder. Reproduced with permission from the American Physical Society.

The benefits of the scattering cancellation technique are simple design and structure (assuming that materials with required properties are available) and the possibility to realize invisibility or cloaking with isotropic and homogeneous materials. The drawbacks, depending on what kind of object needs to be made invisible (penetrable or impenetrable object) are realization of metamaterials with required properties if plasmonic materials are not available, bandwidth limitations inherent to many realizable (resonant) metamaterials, and the fundamental limitation on the energy velocity when cloaking impenetrable objects in free space with passive cloaks (for ideal operation the energy of the electromagnetic wave should circle around the cloaked object faster than the speed of light).

Coordinate transformation technique

Cloaking with metamaterials that enable the creation of volumes with zero electromagnetic fields inside a device composed of such materials, has been recently described by Leonhardt[2] and Pendry *et al.*[3] Mathematical basis of the coordinate transformation required in such a method has been previously presented1, 4, 5. These techniques rely on the transformation of coordinates, e.g., a point in the electromagnetic space is transformed into a sphere in the physical space, thus leading to the creation of a spherical volume where electromagnetic fields do not exist, but are instead guided around this volume, see Fig. 3. There exist many possibilities to perform coordinate transformations, see recent literature related to the design and analysis of various types of cloaks based on the coordinate transformation technique2, 3, 4, 5, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65.

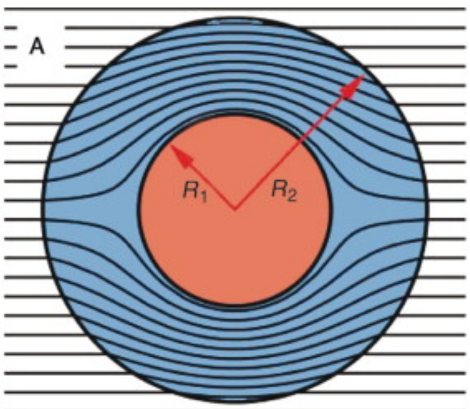

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Fig. 3. Illustration of the coordinate transformation technique[3]: the rays of electromagnetic field are guided inside the cloak device around the volume enclosed by the cloak. Reproduced with permission from the AAAS.

Cloaking objects in free space (or in a medium similar to free space) with the coordinate transformation technique necessarily requires the use of lossless anisotropic metamaterials with some components of the effective relative permittivity (ε_r) and/or permeability (μ_r) smaller than these values in free space[3].

The first realization of a coordinate transforming cloak, operating in the microwave region, has been recently presented[39] (Fig. 4). This structure is a two-dimensional simplification of the general case[3] and it operates as a cloak for one polarization only, for which the electric field is parallel to the axis of the cylindrical cloak (TE-polarization). The simplification of the cloaking device in terms of low dimensionality and single polarization relax the requirements on the metamaterial properties. Another two-dimensional simplification[40], working for the TM-polarization in the visible part of the electromagnetic spectrum, has also been proposed, but not yet realized.

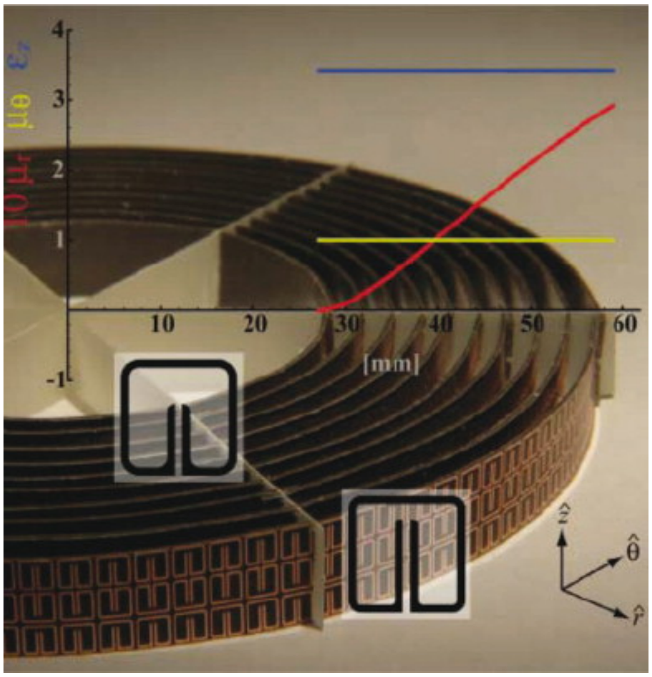

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Fig. 4. A realization of a cloak based on the coordinate transformation technique, composed of radially placed resonant particles[39]. The cloak is a two-dimensional simplification of a more general design[3] and it works only for TE-polarized waves. Reproduced with permission from the AAAS.

One of the big challenges in the realization of metamaterial cloaks working for arbitrary polarization of the incident fields is the need to design materials whose permittivity is equal to the permeability. As shown in[17], this may be possible with artificial chiral materials. In those media, the desired response is provided by electrically small but resonant inclusions (most commonly, metal helices). Since both electric and magnetic polarizations are provided by the same inclusions, their shape can be chosen so that the relative effective permittivity is the same as the permeability[66]. Chirality, which is not desired for the cloaking application, can be compensated using a racemic mixture of spirals. Recently, such chiral cloak has been proposed[43] and its performance demonstrated experimentally in the microwave frequency range[44].

In general, the operation of all these types of passive cloaks is limited mostly by the strongly dispersive (and also lossy) permittivity and/or permeability that are inherent to metamaterials needed for these types of cloaks[17], resulting in a very narrow bandwidth where the desired cloaking effect is possible to obtain58, 59, 60. Also, the introduction of simplifications to the ideal values of the permittivity and permeability inevitably deteriorates the cloaking performance61, 62.

A more fundamental design problem is related to causality restrictions of cloaking objects in free space: the wave that travels through the cloak must travel faster than the wave outside the cloak, as can be seen from Fig. 3 (the ray path is longer inside the cloak). This is not impossible to achieve for cloaking of e.g. acoustic waves63, 64, but becomes a serious problem when cloaking electromagnetic waves in air or free space since the wave outside the cloak travels with the speed of light[65]. The phase velocity of the electromagnetic wave can of course be faster than the speed of light, but the energy velocity in a passive system cannot. One solution is to include active elements in the material composing the cloak[57]. The latter option has the drawback of potential field instabilities and makes the design of the necessary types of metamaterials even more difficult and complicated[67].

Recent theoretical developments of the transformation-optics approach to cloaking include the use of non-linear coordinate transformations41, 42 and the idea of using different transformed spaces to the field strength tensor (electric field and magnetic induction) and to the excitation tensor (displacement field and magnetic field)[68]. Furthermore, an alternative approach to design of artificial materials which perform the desired transformation of distribution of electromagnetic fields in the volume occupied by materials has been proposed[69].

The benefits of the coordinate transformation technique are the simplicity of the theoretical design and the fact that it is fundamentally independent of the cloaked object's shape and/or constitutive material. The drawbacks are the difficulties in the realization of materials with suitable properties, especially when wide bandwidths and cloaking from signals (energy pulses) are required.

Transmission-line technique

Recently we have proposed a cloaking technique which is profoundly different from the ones discussed in the previous sections. This technique is based on the use of volumetric structures composed of two-dimensional or three-dimensional transmission-line networks[10]. In these structures, the electromagnetic fields propagate inside transmission lines, thus leaving the volume between these lines effectively cloaked. See Fig. 5 for an illustration of this cloaking principle.

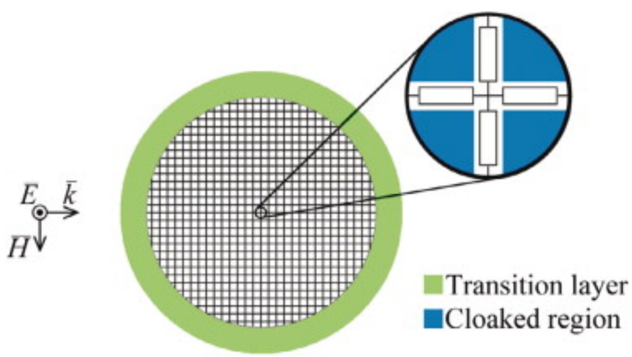

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Fig. 5. Illustration of the transmission-line technique for cloaking: an incident electromagnetic wave is coupled into a transmission-line network which leaves a volume inside the network (between the adjacent sections of transmission lines) cloaked. The cloaked object can have any size and shape as long as it fits inside the transmission-line network (array of smaller objects, interconnected mesh, etc).

Since the fields entering from the surrounding medium into the cloak need to be “squeezed” into the transmission lines, a coupling layer is needed to couple the fields between this medium and the network. In Fig. 5 this layer is described as a “transition layer”. We have proposed that in practice this layer can be realized e.g. with gradually enlarging parallel-strip transmission lines[10], that effectively work as mode transformers between the cloak and the surrounding medium. The operation of this practically realizable transition layer has been confirmed numerically and experimentally for various structures10, 70, 71, 72, 73.

Even though the main principle of cloaking with transmission-line networks is very simple, it cannot overcome the following fundamental limitation: for perfect cloaking of an object in free space, the wave velocity inside the transmission lines should exceed the speed of light[10]. This is because the network itself “slows” down the wave, since a single transmission line sees all the other transmission lines as periodic loads. It is possible to obtain ideal wavenumber in a network even when cloaking objects in free space by placing periodical reactive loads in such a network[10]. However, this solution has the inevitable drawbacks of design complexity and significant frequency dispersion. It has therefore been concluded that for practical applications that require large bandwidths and/or cloaking from signals, the use of simple unloaded transmission-line networks is preferable, even though the propagation velocity inside the cloak is not ideal[10]. This is illustrated here by conducting full-wave simulations of a homogeneous cylinder inside which the wave travels with the same wavenumber as in a cloak composed of two-dimensional transmission-line networks with free space filling the transmission lines. The scattering from this “cloak” is compared to the scattering from a two-dimensional array of perfectly conducting (PEC) rods (Fig. 6).

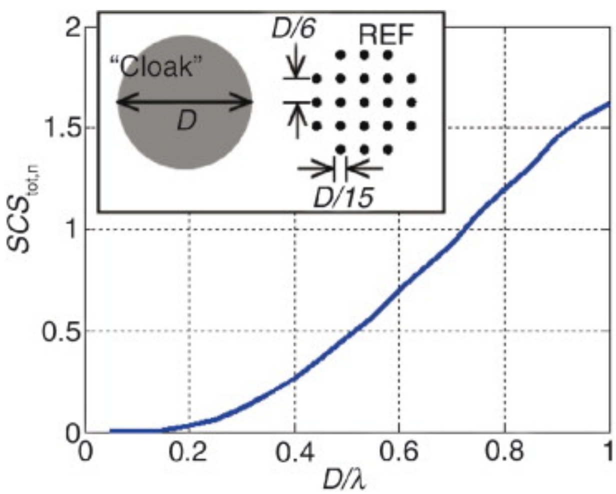

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Fig. 6. Full-wave simulated[74] total SCS of an infinitely long homogeneous cylindrical object (which is composed of a material with $\varepsilon_r = \mu_r = \sqrt{2}$, i.e., a material having the same wavenumber as a two-dimensional transmission-line network with free space filling the transmission lines), normalized to the total SCS of a two-dimensional array of infinitely long PEC rods. The dimensions of the “cloak” cylinder and of the PEC array are shown in the inset. The incident electric field is parallel to the axis of the cylinder.

The results can be interpreted in the following way: since the “cloak” is perfectly matched to the surrounding free-space environment, only forward scattering can occur. This forward scattering becomes stronger as the electrical size of the cloak is increased, as expected. From Fig. 6 we can conclude that even with a cloak having the diameter of 0.4λ, the total scattering cross section of the PEC array can in principle be lowered by 75%. There are also other regions where efficient cloaking can be achieved, depending on the cloak's electrical size which can be even several wavelengths[10]. It is clear that the cloaking effect will be inevitably less broadband in these cases10, 72.

A cylindrical cloak as shown in Fig. 7a, b has been recently studied numerically71, 72, 73. To obtain the total SCS of the cloaked and uncloaked objects, we illuminate the model in Fig. 7 (cloaked object), and the same model without the cloak, i.e., the PEC array alone, with plane waves having the electric field parallel to the z-axis. From the resulting simulation data, we extract the power scattered to all directions in the xy-plane and compute the total scattering cross section in both cases. To present the cloaking efficiency, we normalize the computed total SCS of the cloaked object to the total SCS of the uncloaked object, similar to the case of the homogeneous "cloak" studied above. The resulting normalized total SCS is presented in Fig. 7c. The relative bandwidth where a reasonable cloaking effect ($SCS_{tot,n} < 0.5$, i.e., reduction of the total scattering cross section by more than 50%) is achieved, is more than 75% with the center frequency at 2.9GHz. At the optimal cloaking frequency of 3.2GHz, the total SCS of the cloaked object is reduced by more than 96 %, as compared to the uncloaked object.

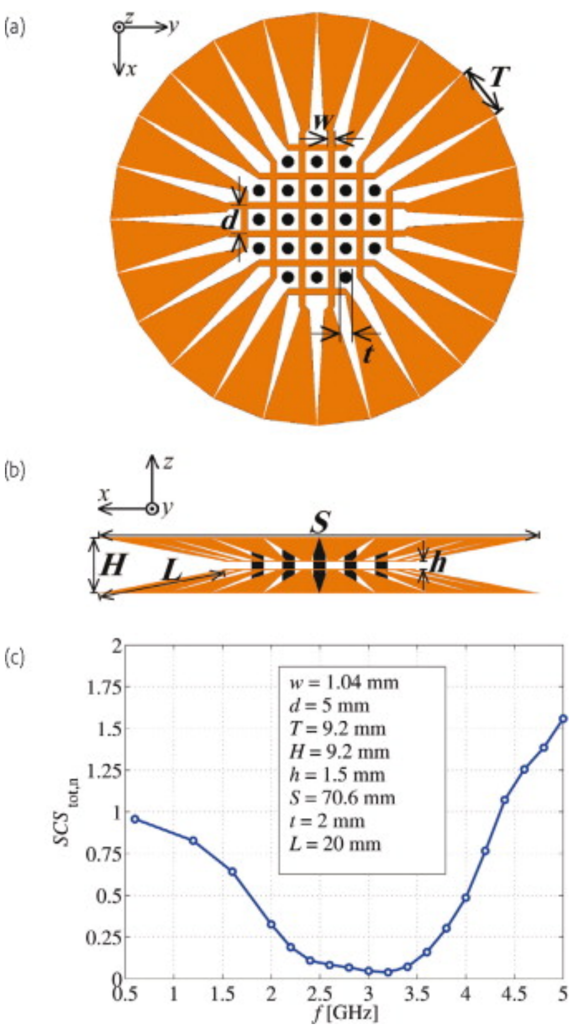

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Fig. 7. A design of a cylindrical volumetric cloak[72, 73] (periodic in the z-direction) in xy- (a) and xz-plane (b) cuts. The cloak structure (shown in orange) works for any incidence angle in the xy-plane for the TE-polarization, i.e., for waves with the electric field parallel to the z-axis. The cloaked object is a two-dimensional array of PEC rods and it is illustrated in black. (c) Full-wave simulated[74] total scattering cross section of the cloaked object, normalized to that of the uncloaked object. Dimensions of the simulated cloak and object are illustrated in the inset of (c).

The benefits of the transmission-line technique are the simple structure, ease of manufacturing and assembly, and wide-band operation. The most significant drawback of this approach, especially when compared to the previously discussed techniques, is the limitation on the size and shape of the cloaked object.

Experimental results on cloaking with volumetric transmission-line cloaks

As the realization of metamaterials, and especially those needed for coordinate-transformation cloaks or for scattering cancellation, is rather difficult, there have been very few experimental results related to these cloaking techniques[39, 44]. The transmission-line approach on the other hand offers a way of obtaining efficient cloaking with very simple structures. We have recently studied how a realization of the transition layer, based on extending parallel strip transmission lines, works with the unavoidable non-idealities that are related to manufacturing and assembly[70]. In this case a two-dimensional transmission-line network having a square shape was studied and the goal of the study was to demonstrate excellent coupling of waves between free space and an easily realizable cloaking network. The good coupling of TE-polarized electromagnetic waves, emitted by a cylindrical source placed close to the network, was verified with numerical simulations and measurements[70].

We have also experimentally demonstrated the cloaking phenomenon with a cylindrical volumetric cloak as that shown in Fig. 7[73]. Such a cloak was manufactured by etching from sheets of 200μm thick metal (alloy of Bronze and Beryllium). Four layers of the structure of Fig. 7 were stacked on top of each other creating a volumetric cloak. For measuring the frequency response of the cloak, the measurements were done in a waveguide environment[73]. The cloaked object is a two-dimensional array of vertical metallic rods (as that shown in Fig. 7), which causes a short-circuit in the waveguide.

Here we have modified the cloaked object to be a fully three-dimensional object, connecting metallic cylinders periodically to the array of metallic rods. Fig. 8a shows a photograph of the cloak, enclosing the cloaked object, placed in the measurement waveguide. Fig. 8b illustrates the cloaked object alone. Between the transmission lines of the cloak and the metallic cloaked object, dielectric foam having the relative permittivity $\varepsilon_r \approx 1.05$ is placed to ensure good insulation.

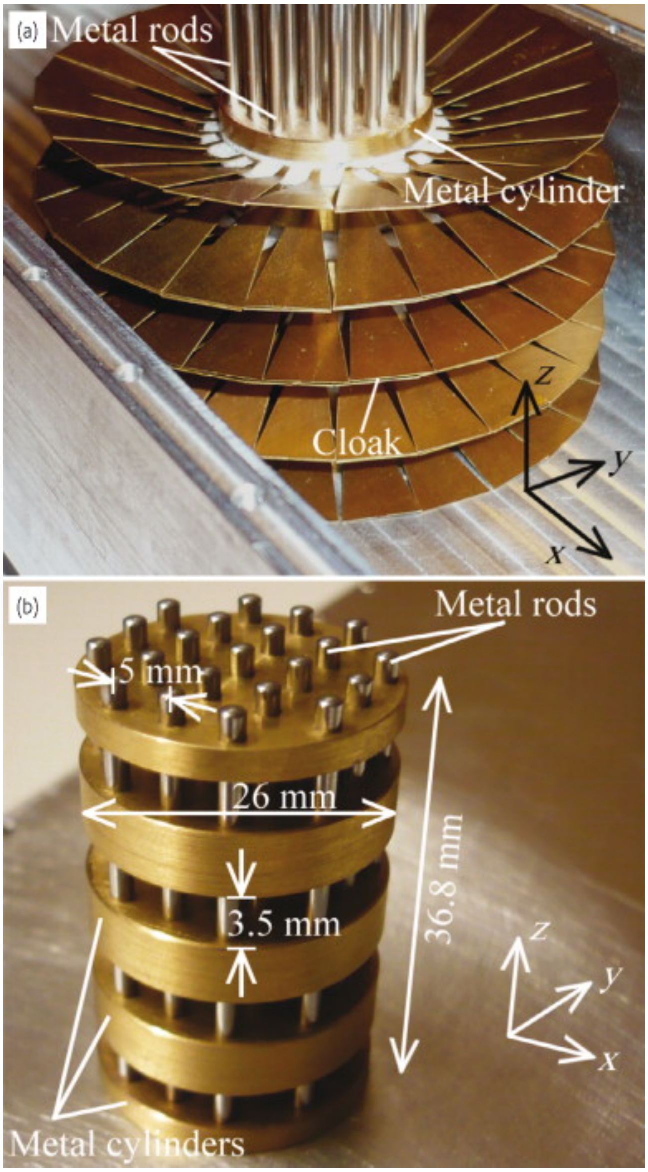

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Fig. 8. (a) Photograph of the transmission-line cloak enclosing the cloaked metallic object (the top wall of the waveguide is removed for clarity). (b) Cloaked object alone.

The transmission through the waveguide was measured in three cases: 1) empty waveguide, 2) waveguide with the uncloaked metallic object inside, and 3) waveguide with the cloaked object inside. Fig. 9 shows the results of magnitude and phase of the transmission (S_{21}) through the waveguide. The magnitudes of the transmission in the cloaked case and the empty case are very much alike, whereas in the uncloaked case, almost no power is transmitted through the waveguide. The results indicate that the cloak works as expected, even in a realistic scenario where all the manufacturing errors, errors due to manual assembly etc., are present. The slight difference in the phase of S_{21}, shown in Fig 9b, is due to the non-ideal wavenumber inside the cloak[10]. This non-ideality will not prevent efficient cloaking, as long as the electrical size of the cloak is sufficiently small as compared to the wavelength, see Fig. 6, Fig. 7.

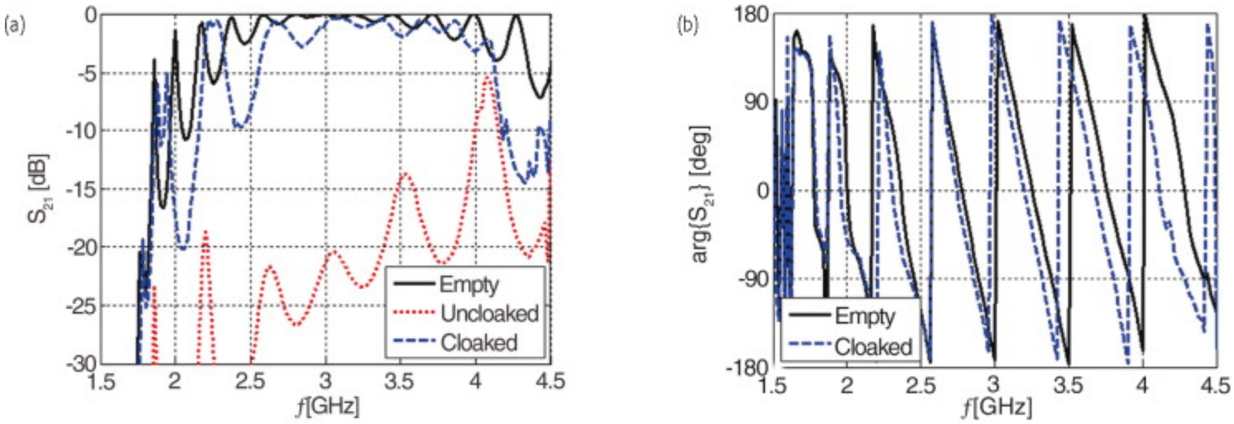

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Fig. 9. (a) Measured transmission magnitude for the empty waveguide, waveguide with the uncloaked object inside and waveguide with the cloaked object inside. (b) Measured transmission phase for the empty waveguide and the waveguide with the cloaked object inside.

The realized "composite material", described above, is mechanically very strong and is a good conductor, as it consists of an interconnected mesh of metal rods and cylinders. Yet, it is "invisible" for vertically polarized microwave radiation even if the waves are incident to the structure from an arbitrary direction in the transverse plane.

Other cloaking techniques

Other cloaking techniques also exist which do not fit into any of the categories discussed so far in this paper. One such technique was proposed by Kildal and his co-authors already more than ten years ago[11]. That technique is based on covering an object, composed of, for example, metal, with a so-called hard surface having an elongated shape in the direction of wave propagation. It has been shown that this technique can be effectively used for reducing the forward scattering from such objects, thus resulting in reduction of the total scattering cross section[11]. The clear drawback of this technique is that the cloaking effect strongly depends on the angle of arrival of the impinging electromagnetic wave. This is a logical consequence of the fact that the "cloaking" device is not symmetrical, but has an elongated shape. Nevertheless, this technique can be used for cloaking in such applications where the angle of the incidence is known, for example in reducing the scattering from antenna support struts[11].

Another very exotic cloaking technique, put forward by Milton, Nicorovici and their co-authors, is based on the use of a so-called "superlens"[17] to cloak scattering objects placed close to such a device12, 75, 76. This cloaking phenomenon relies on the anomalous localized resonances that can be excited at the surface of a superlens. One special property of this cloaking technique is that cloaking can be achieved for objects placed outside the "cloaking device"[75]. As the cloaking method relies on the anomalous resonance phenomenon, it is expected to be very sensitive to losses and manufacturing errors.

Conclusions

Cloaking and invisibility have, in recent years, become facts instead of fiction, after the discovery and realization of various types of metamaterials and plasmonic materials. Many different techniques exist to obtain cloaking from electromagnetic or acoustic waves, and all these techniques have certain benefits and drawbacks as compared to each other. In this paper, we have discussed the principles of the two main cloaking techniques, namely, the coordinate transformation technique and the scattering cancellation technique. In addition, we have reviewed some recent results related to an alternative cloaking technique, which employs networks of transmission lines. References to other cloaking techniques are also given. Currently, the research related to cloaking aims to extend the achievable bandwidths where invisibility of arbitrary or specific objects can be achieved, as well as to extend the realization of such devices into the optical frequency range. Some fundamental restrictions on cloaking, especially with passive devices, exist, but nevertheless, examples of devices exhibiting effective cloaking, although not perfect, have been realized recently.

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