Review of RF Cloaking Techniques for Antenna Applications

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Abstract **─** This paper reviews the background phenomenon of various cloaking techniques such as transformation optics, transmission line network, microwave network cloak, scattering cancellation techniques in the applications of antenna field particularly in hiding the obstacle from the electromagnetic source and reducing the mutual coupling between two antennas that was placed closed to each other. Cloaking at multiple frequencies in each cloaking techniques are also compared. The comparative study showed that the scattering cancellation technique based on aperiodic Frequency Selective Surfaces (FSS) structure will dominate the electromagnetic cloaking field in near future.

Index Terms **─** Antennas, cloaking techniques, dual band cloaking, interference reduction, Modulated meta-surface.

I. INTRODUCTION

Electromagnetic cloaking technology is a stealth or camouflage technology that renders an object to be invisible to the Electro Magnetic (EM) spectrum. This can be achieved by cancelling or minimizing the scattering properties of an object. Some of the theories that are adopted in this technology are transformation optics [1, 2], transmission line network [3-7], microwave network [8-11] and scattering cancellation [14-22]. Many theoretical and experimental results are being carried out in the radio frequencies of the electromagnetic spectrum. Recently this technology finds its place in antenna applications. One such application is to hide an object that obstructs the antenna's field performance using a cloak structure which was designed on basis of any one of the above said theories. The hindrance of the antenna may be an object which is either external to the antenna or may be an integral elemental parts of antenna itself as the case of ground plane in monopole antennas and the reflector and director elements in Yagi-Uda antenna. In another perspective, the cloak can also play a role in reducing the mutual coupling between two antennas that are placed close to each other.

Review literatures that describe and compare various EM cloaking technology are not uncommon. However, reviews on the application of EM cloaking in the antenna field are seldom discussed. Thus, in the present review paper, an attempt has been made particularly in comparing various techniques of EM cloaking in antenna applications. Section II briefly describes the principles of various cloaking techniques related to antenna applications in the radio frequency range. The application of those cloaking techniques in hiding an obstacle from the antenna and in reducing mutual interference between two antennas are explained in Section III. Finally, Section IV concludes with the comparison of RF cloaking technique in antenna applications.

II. BACKGROUND PRINCIPLE OF CLOAKING TECHNIQUES

A. Transformation optics

Transformation optics concept was implemented earlier to a three-dimensional meta-material structure for cloaking a large object [1]. The properties of material were varied in order to control the propagation of EM wave as given by below set of equations:

$$\boldsymbol{\varepsilon_r' = \mu_r' = \frac{R_2}{R_2 - R_1}\frac{(r' - R_1)^2}{r'}},$$

$$\boldsymbol{\varepsilon_\theta' = \mu_\theta' = \frac{R_2}{R_2 - R_1}},$$

$$\boldsymbol{\varepsilon_\varphi' = \mu_\varphi' = \frac{R_2}{R_2 - R_1}},$$

where R_1 and R_2 are the radius of object and cloak respectively and $R_1 < r < R_2$.

The EM wave was allowed to bend around the cloaked object so as to make the object invisible to the EM source. The transformation based meta-material

Submitted On: June 2,2018
Accepted On: August 11, 2018

cloak had the limitation of cloaking an object only in narrowband.

B. Transmission line networks

The transformation optics was extended to two-dimensional cloak structure made up of transmission line network of inductors and capacitors [3] and of conical metal plate structures for broadband cloaking [4]. However, the two-dimensional cloaking had a limitation of bulky volumetric cloaking structure.

C. Microwave network cloak

Large sized object can also be cloaked with microwave network cloaking technique [8]. The microwave network cloak comprised of metallic patches interconnected with micro-strip lines. It worked on the principle of superluminal propagation. The cloak structure covering the object was responsible for receiving, transferring and re-transmitting the incoming EM wave from the source to the rear side of the object. So the cloak covering an object is designed in such a way that, the time travelled by the EM waves around the object was made to match with that of EM waves travelling in the same space as if the object was not present. The length of the metallic patches determines the cloaking frequency.

D. Scattering Cancellation (SC) techniques

Scattering cancellation technique, predominantly known as mantle cloaking, utilizes the meta-screen of periodic Frequency Selective Surface (FSS) elements [13]. In this technique, cloaking was based on reducing the scatters of incident wave by the object. The underlying principle was that the reactance of object that scattered wave was made equal and opposite with the surface reactance of periodically patterned FSS structures over the cloak. The reactance of the 2D cylindrical object that exhibit the scattering property was calculated from Mie's expansion [14] as:

$$X_s = \frac{2}{\omega a \gamma \varepsilon_0 (\epsilon_r - 1)},$$

where, $\gamma = a/a_c$, ω, a and a_c are angular frequency, radius of object and cloak respectively, ε_0 and ε_r are the dielectric constant of vacuum and material, and the surface reactance for the periodic arrangement of horizontal strip array of FSS structure was calculated from the Floquet's principle [15] as:

$$X_s = \frac{-j\eta_0 c\pi}{\omega(\epsilon_r + 1)D}\left(\frac{1}{\log\csc\left(\frac{\pi g}{2D}\right)}\right),$$

where η_0 is the free space wave impedance, D and g are the width and gap between the strips respectively.

Thus, the interaction of object and cloak characteristic parameters had its advantageous in cloaking both passive as well as active objects like sensors etc. [16-19].

Modulated meta-surface based scattering cancellation theory is considered as one of an emerging technology in electromagnetic cloaking field. In case of modulated meta-surface cloaking, geometry of the FSS structure was varied in such a way that the equivalent impedance of cloaking structure was optimized with that of the external hindering object appropriately in order to achieve a desired task. This results in the variation of phase velocity and propagation path of a surface wave. The object satisfying only the quasi static condition (object size << operating wavelength) can be cloaked may be considered as its main drawback.

III. APPLICATION OF CLOAKING TECHNIQUES IN ANTENNAS

A. Hiding an object

1) Transformation optics and transmission line network cloak

The application of hiding a scatterer from an antenna environment using transformation optics was first reported in 2008, by enclosing the scatterer with a dispersive cloak [2].

Two-dimensional cloak structure made up of a combination of a periodical set of conical metal plates and a transition layer that couples the incident EM wave to a transmission line network was introduced to the antenna application in 2012 for reducing the blockage of the antenna. Any external metal cylindrical volumetric object that hindered the horn antenna, was covered by the above said two-dimensional cloak structures [5, 6]. The incident EM wave from horn antenna was made to bend around the metal object by the structured cloak, thereby reducing the visibility of the object from its EM wave path. The directive patterns of the horn antenna depicted the success of corresponding cloaking phenomenon. Dual frequency EM cloak was also made possible through the introduction of multiple LC resonating circuits [7]. However, these two-dimensional cloaking had the limitation of bulky volumetric cloaking structure.

2) Microwave network cloak

The structure made up of metallic patches interconnected with microstrip lines was applied to both circular and other arbitrary shaped objects [8, 9]. The distance between the edge of horn antenna and the center of the object is 64 mm. Figure 1 shows such various configurations of microwave network cover. The geometrical shape of the cloak plays an important role in the cloaking performance by reducing the maximum and the averaged scattered width [12]. Also, the limitation in material flexibility of circular cloak can be avoided using polygon structures.

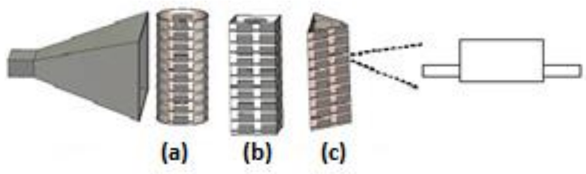


Fig. 1. Various configuration of microwave network cover: (a) circular cloak, (b) square cloak, and (c) triangular cloak.

The variations in the S11 parameter and 3D radiation patterns as shown in Fig. 2 (a) and Fig. 2 (b) brief the significance of cloak geometry.

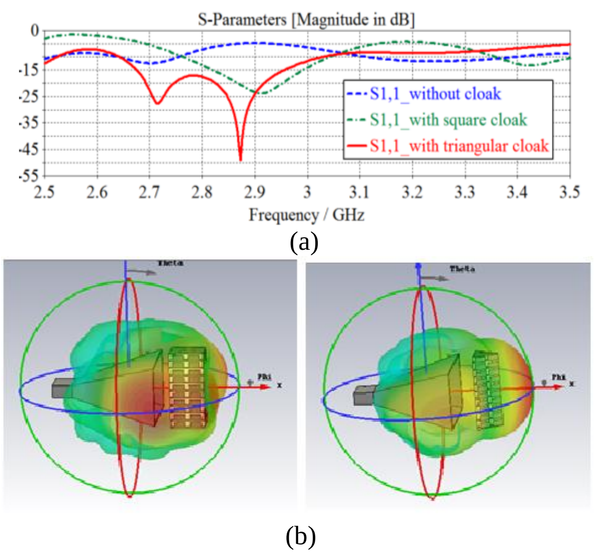


Fig. 2. (a) Simulated S11 parameter (solid red – triangular cloak, dash dotted green – square cloak, dashed blue – without cloak) for different microwave network cloak geometry; (b) 3D radiation patterns for different microwave network cloak geometry.

Dual band cloaking was also achieved in those interconnected metallic patch cloaks by varying the widths of micro-strip lines as shown in Fig. 3 [10].

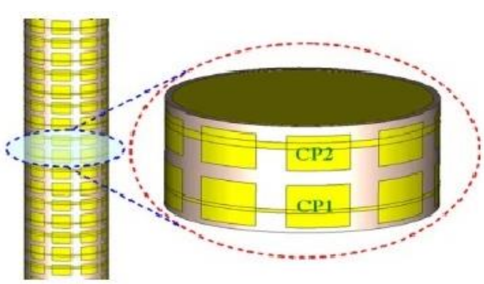


Fig. 3. Microwave network cover for dual band cloak [10].

3) Scattering cancellation techniques

The optimized patterned meta-surface cloak covering the metallic object was placed before the horn or any other antenna. Reduction in scattering cross section ultimately minimized the visibility of a conducting or dielectric object. This was verified through the scattering parameters (S_{11}) and the directive gain pattern of the antenna. Dual band cloaking was also made possible in mantle cloaking by having two layered covers each with the different electrical cross sections of periodic FSS structures but maintaining a constant bi-layer aspect ratio. The structure for dual band mantle cover with two layers is depicted in Fig. 4 [20].

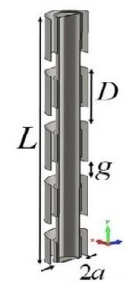


Fig. 4. Structure for dual band mantle cloaking [20].

Aperiodicity in the geometrical structures (modulated meta-surface) was employed for hiding an object from an antenna. Careful design of aperiodicity structure in the cloak results in two different impedances and was able to hide an object from two different frequencies resulting in a dual band cloaking [21].

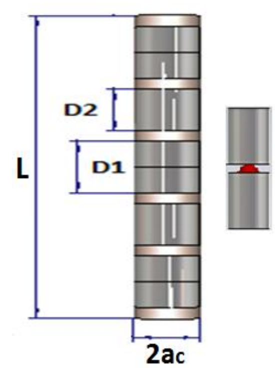


Fig. 5. Structure for modulated meta-surface cloaking.

Figures 5 and 6 shows the structure and simulated results of modulated meta-surface in cloaking at dual band frequencies. Unlike periodic FSS structure where two layered covers were needed to achieve dual band cloaking, aperiodic or modulated meta-surface required only single layer cover to act as dual band cloaking. In simple, a FSS structures incorporated in a single layer covering an object can reduce the scattering at two different frequencies by introducing the aperiodicity in their geometries.

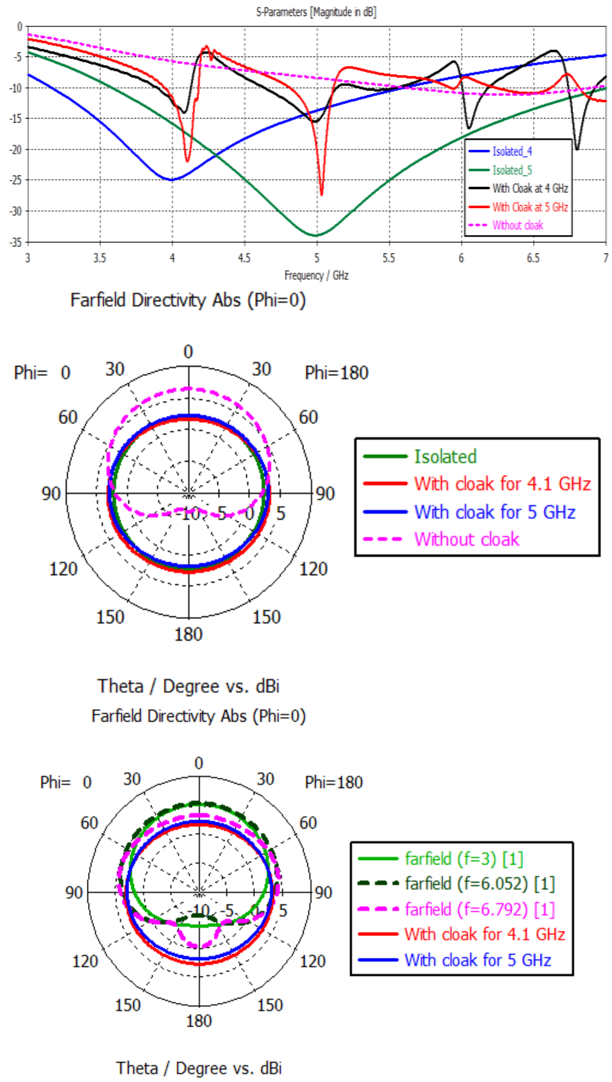


Fig. 6. Simulated results for modulated meta-surface cloaking.

B. Mutual coupling reduction

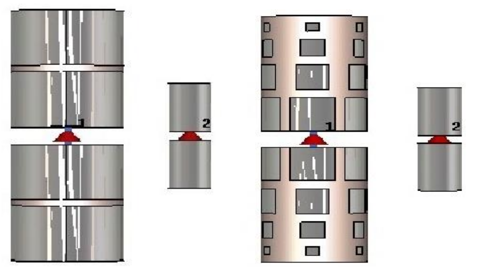
In the practical scenario of existence of two antennas operating at different frequencies that were located close to each other naturally had mutual coupling between them. The implementation of cloaking techniques to reduce the mutual coupling between two antennas was also tried.

1) Transformation optics and microwave network cloak

Very few works have been reported in hiding an antenna from another antenna using transformation optics and microwave network cloak [2, 11]. But still the transmission line network cloak needs exploration in mutual coupling reduction. Since these techniques can only bend the EM wave around the object without the involvement of object properties, cloaking an antenna at different frequency is only possible rather than cloaking at its own resonance frequency.

2) Scattering cancellation technique

The periodic meta-surface cloak (scattering cancellation technique) covering the antennas as designed in the literatures can reduces the coupling. This was due to the interaction between the electromagnetic fields scattered from the object and cloak cover. The presence of mantle covers on one or both the antennas depends on the operating frequencies of the two antennas [17, 18].



(a) (b)

Fig. 7. Scenario of two dipole antennas placed close to each other with one mantle cover: (a) conventional meta-surface, and (b) modulated patch meta-surface.

The scenario of two dipole antennas placed close to each other with the mantle cover on one dipole antenna is as shown in Fig. 7 (a). Later, modulated meta-surface was also applied for reducing the coupling between antennas. Figure 7 (b) shows the structure for the modulated meta-surface in patch configurations. By this aperiodicity, an improvement of 15% in bandwidth was achieved as shown in Fig. 8 [22].

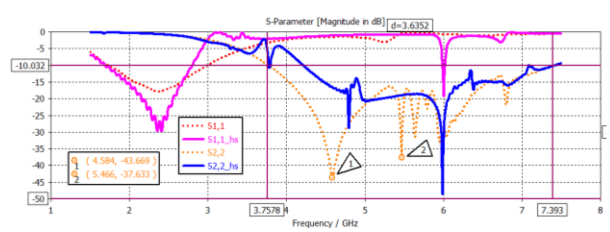


Fig. 8. S Parameter result for modulated patch and horizontal meta-surface cloak in antenna application [22].

IV. DISCUSSION

As an overview, the cloak designed from all the above techniques will be suitable for hiding an obstacle from an antenna. The object and hence its cloak size itself, will be large in transformation optics and transmission line network cloak technique and needs further exploration in mutual coupling reduction application of antennas operating at same frequency. This can be overcome in scattering cancellation technique but it is applicable only for sub wavelength sized object. Although the microwave network cloak technique experiences the same problem as in transformation optics technique in mutual coupling application, it is possible to hide even the larger sized object with the super thin sized cloak. Finally, dual band cloaking had been performed even in a single cloak layer with the help of microwave network cloak and aperiodic scattering cancellation techniques.

V. CONCLUSION

This paper summarizes the various cloaking techniques and its applications in antennas. It is noted that the cloaking phenomenon does an excellent job in antenna applications by restoring the electromagnetic and radiation properties of an antenna which was interfered by any conducting or dielectric object and by reducing the interference between two neighboring antennas. Table 1 summarizes the various parameters for different cloaking techniques.

Table 1: Comparison of different cloaking techniques

Parameters	**Transformation Optics**	**Transmission Line Network**	**Microwave Network**	**Scattering Cancellation**	
				Periodic	**Aperiodic**
Size of the object that can be cloaked	Large	Large	Large	Small (Quasi-static)	Small (Quasi-static)
Cloak structure size	Large	Large	Small	Small	Small
Coupling reduction	Possible for antennas of different frequency	Yet to be verified	Possible for antennas of different frequency	Possible	Possible
Dual band cloaking	Yet to be verified	Multiple layers of cloak structure	Single layer of cloak structure	Multiple layers of cloak structure	Single layer of cloak structure

As discussed in this paper, each cloaking method has its own pros and cons in antenna applications. So the choice of cloaking techniques adopted is based primarily on the requirements. However, from Table 1, it was observed that the scattering cancellation based on aperiodic FSS structure will dominate the electromagnetic cloaking field in near future.

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