A New Implementation of Frequency Selective Surface Cloak for Cylindrical Structures

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Abstract: The main purpose of this paper is to design, implement and measure a new sample of mantle cloak. A new method called mantle cloak is introduced by cloaking an object by a single, conformal meta-surface which can drastically suppress the scattering of the desired object. In this paper, a grid lattice is placed around a dielectric object as the cloaking structure. Previously, this FSS has been utilized for the cloaking of PEC object; but, when patch structure is placed around the dielectric it has inductive equivalent circuit with appropriate designing, it can be used for cloaking of dielectric cylinder. Numerical simulations of near field and far field of the designed structure are derived to prove the effectiveness of our meta-surface cloak. Also, measurement results of S_{11} and S_{21} related to cloaked structure and their comparison with single dielectric proves suitable performance of the designed cloak. The results show more than 20% bandwidth for this structure. This means that this structure is suitable for broadband operations.

Keywords: Mantle Cloak, Frequency Selective Surface (FSS), Surface Reactance.

1 Introduction

In recent years, experts have provided the cloaking advance notice as an interesting application for meta-materials. This issue has been investigated theoretically and proven experimentally in numerous papers. In 2005, a new method was discovered which was based on suppressing the scattering from the object [1]. The main feature of that method was the homogenous and isotropic coating. In 2006, Pendry investigated a coating layer that was able to cover the inner object and made it invisible [2]. Most of the efforts in this field are based on transformation optics [3] and meta-materials [4-10]. These techniques utilize bulk meta-materials with the thickness which is often comparable with the cloaked objects and complicated realization.

In 2009, the mantle cloak was exhibited by Alu in which cloaking was achieved using frequency selective surfaces. The main idea of mantle cloak was similar to plasmonic cloak [11]. In this cloaking technique impedance matching between air and object could eliminate the reflected wave. Following this idea, cloaking for planar, cylindrical, and spherical objects was achieved in 2011 [12]. At the same time, the idea of using graphene cloak was proposed for cloaking the objects in THz band [13]. Recently, this kind of cloak has been implemented for the first time [14]. Also, based on the theory of mantle cloak, acoustic meta-surfaces have been developed [15].

As a successful method, FSS cloak can reduce the dimension of cloaks and has easier implementation than other techniques [12]. In this paper, the second sample of FSS cloak is implemented and measurement for this cloak is proposed. In Section I, a brief explanation of the theory of these cloaks is presented after that in Section II, the steps of design and simulation of our cloak and the measurement results are presented.

2 The Theory of FSS Cloak

As it was mentioned previously, in this article the FSS is used for cloaking an object. Similar to plasmonic cloak [16-17], this technique is based on the scattering cancelation. The main purpose of this method is suppressing the scattering of the object by matching the impedance between object and the free space. Indeed, this method has the advantage of making an object invisible using the ultrathin meta-surface rather than bulk covering.

When the wave impinges on the FSS, the current is induced on its surface. Current flow along the conductor creates inductive effect, as well as, capacitive effect on the gaps between two conductors.

Fig. 1 shows the prototype of FSS cloak. The structure has three regions, the outer FSS, the middle free space between the FSS and the object, and the inner object. The exact analytical solution was presented in [12] for planer, cylindrical, and spherical structures.

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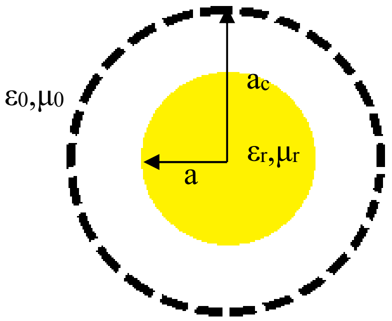


Fig. 1. Geometry of the scattering problem. The inner region is the object with radius, a, and electric properties, ε_r , and, μ_r. The outer shell is cloak with radius a_c and electric properties ε_0 and μ_0.

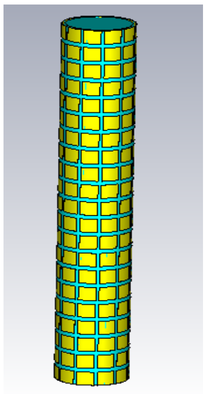


Fig. 2. The implemented structure.

If the dimension of patterns on the FSS is smaller than the wavelength, the equivalent surface impedance can be considered for the FSS. When an electromagnetic wave impinges on the FSS surface a current is induced on its surface. With appropriate choose of the FSS this current can suppress the scattering from the inner object. It means that by matching the impedances of the free space to the inner dielectric, the cloaking can be achieved and the scattering will be suppressed. Useful formulas for required Z have been brought [13].

In this paper, the main purpose is to implement a new type of meta-surface to cloak a cylindrical dielectric under illumination TE wave. The dielectric covered with FSS under the illumination of TE wave is shown in Fig. 2 Under these conditions, the fields in each layer have been written as the following equations:

$$H_z^i = H_0 \sum_{n=-\infty}^{\infty} (-j)^n D_n^3 J_n(k_d \rho) e^{jn\phi} \qquad \rho < a \tag{1}$$

$$H_z^2 = H_0 \sum_{n=-\infty}^{\infty} (-j)^n [C_n^2 H_n^{(1)}(k_0\rho) + D_n^2 H_n^{(2)}(k_0\rho)] e^{jn\phi} \quad a < \rho < a_c \tag{2}$$

$$H_z^3 = H_0 \sum_{n=-\infty}^{\infty} (-j)^n [J_n(k_0\rho) + A_n H_n^{(2)}(k_0\rho)] e^{jn\phi} \quad \rho > a_c \tag{3}$$

The unknown coefficients are achieved by applying the boundary conditions which were presented in [13]. Scattering width is calculated by Eq. (4).

$$\sigma_{2-D} = \lim_{\rho\to\infty}(2\pi\rho \,|\frac{H_z^s}{H_z^i}|^2) = \frac{2\lambda}{\pi} |\sum_{n=0}^{\infty} \varepsilon_n A_n \cos(n\phi)|^2 \tag{4}$$

where ε_n is 1 and 2 for $n = 0$ and $n \neq 0$, respectively. Also, A_n is the coefficient of scattered field in the third region. By selecting the radius of cloak, a_c, and reactance, X_s, the scattering width may be set equal to zero. As a result, the overall scattering of object is reduced.

Selecting the frequency selective surface is an important issue. Fig. 3 demonstrates the scattering width versus X_s of the covering cloak for different frequencies. As it can be observed in figure, inductive characteristic of the cloak is necessary for reducing the scattering from the dielectric cylinder at the designing frequency. Since this technique is based on impedance, cloaking in all the frequencies is not possible. Although, cloaking bandwidth is acceptable.

Here, the design frequency is 10 GHz. As presented in the figure, at this frequency, X_s reactance should be inductive. So, the dimension of the desired FSS is chosen to have this range of reactance.

In this paper, the patch structure for FSS cloak is selected. The equivalent circuit of this structure is shown in Fig. 4 Moving the wave on the FSS surface creates the surface reactance, which may be capacitive or inductive and it depends on the shape, dimension, and dielectric substrate of the desired FSS.

In [18], the same equations were utilized for both horizontal strips and patch structure; these equations are given in Eqs. (5) and (6):

$$Z_s^{TE,Hstrips} = \frac{-j\eta_0 c\pi}{\omega(\varepsilon_r+1)d} \frac{1}{\ln\csc\left(\frac{\pi g}{2d}\right)} \frac{1}{\left(1-2\frac{\sin^2\theta_s}{\varepsilon_r+1}\right)} \tag{5}$$

$$Z_s^{TM,Hstrips} = \frac{-j\eta_0 c\pi}{\omega(\varepsilon_r+1)d} \frac{1}{\ln\csc\left(\frac{\pi g}{2d}\right)} \tag{6}$$

where g is the gap between the strips and d is the period of the strips. These equations are modified in [19] and an inductive term is added to patches equivalent equation. So the resulting equations are as follows.

$$Z_{c,s}^{TE,Paches} = \frac{-j\eta_0 c\pi}{\omega(\varepsilon_r+1)d} \frac{1}{\ln\csc\left(\frac{\pi g}{2d}\right)} \tag{7}$$

$$Z_{l,s}^{TE,Paches} = j\eta_0 \left(\frac{2\pi dc}{\omega}\right) \ln\csc\left(\frac{\pi g}{2d}\right) \tag{8}$$

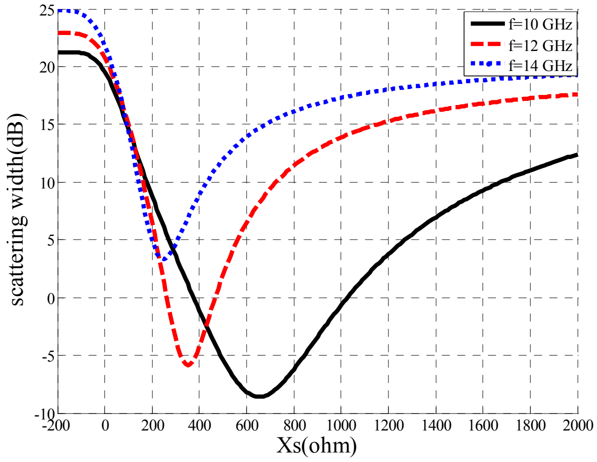


Fig. 3. Scattering width versus surace reactance.

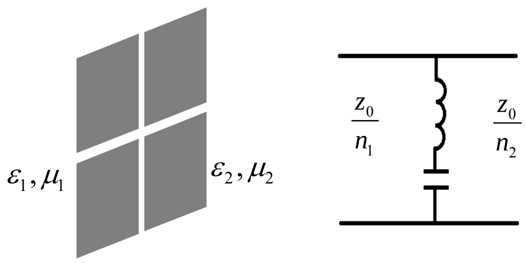


Fig. 4. The left hand image is the patch frequency selective surface and the right hand one is the equivalent RLC circuit for the patch FSS.

where g is the gap between the patches length and d is the period of the strips. With appropriate choice for the patch and gap dimension surface impedance will be inductive. In Fig. 5 surface impedance versus the ratio of a/g is illustrated for different frequency where 'g' is the gap between the paches and 'a' is the patch length. This figure is plotted for d= 97 mm and a/g is changed from 0.08 to 18.

In [19], it was proven that patch structure is suitable for cloaking the conductive object under the illumination of both TE and TM incident waves. Here it is shown it can be used for dielectric objects with appropriate designing, since patch structure may be capacitive or conductive depending on its dimension.

Bending the surface of the FSS adds some coupling capacitors to this structure; so, these values have some errors. Dimensions of the selected FSS are shown in Fig. 6. These dimensions are achieved by minimizing the scattering width at 10 GHz by using CST.

Scattering width of the object with and without cloak is shown in Figs. 7 and 8. In these figures the scattering width for the cloaked object and dielectric cylinder without cloak are depicted with solid line and dash line, respectively. Results in Fig. 7 represent that scattering width is reduced strongly at the designing frequency.

Fig. 8 shows the scattering width in all directions at the frequency of f_0. It is understood from the figure that the scattering width decreases in the all directions.

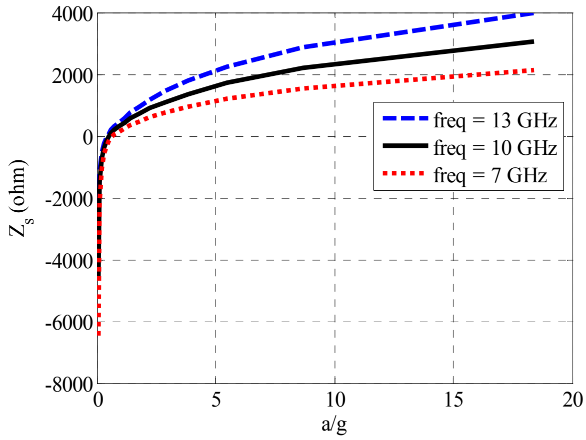


Fig.5. surface impedance versus a/g for different frequencies.

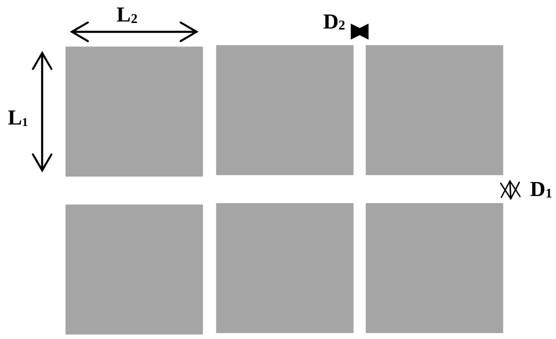


Fig. 6. The frequency selective surface which is used for cloaking here. D2= 14.4 mm, D1= 22 mm, L1=75 mm and L2= 78.8 mm.

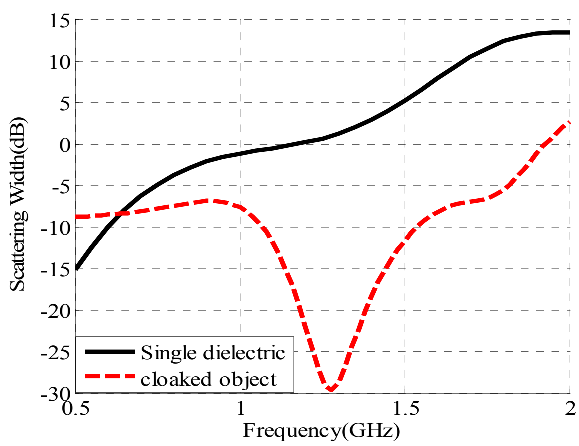


Fig. 7. The scattering width versus frequency; the scattering width for the cloaked and the object without cloak.

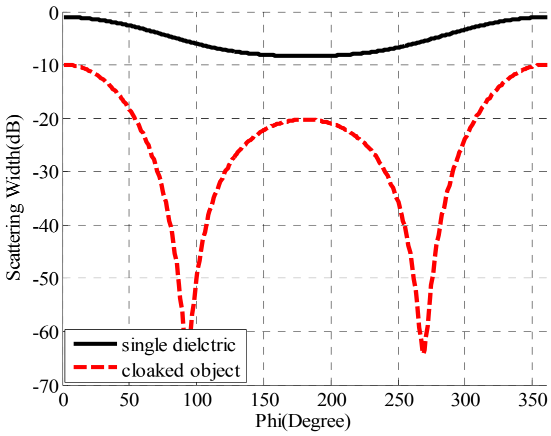


Fig. 8. The scattering width versus the angle of view (phi) for cloaked object and the single dielectric cylinder at the frequency of f_0.

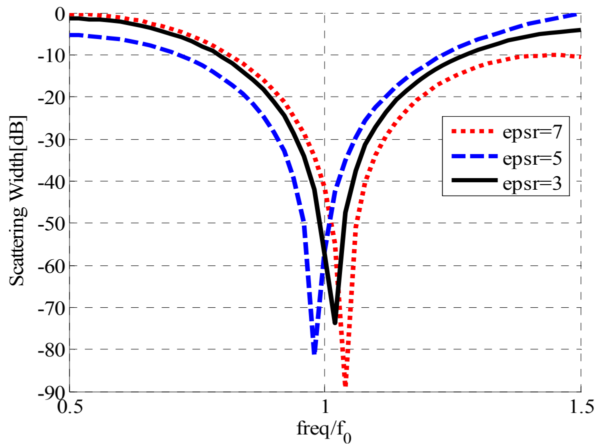


Fig. 9. Scattering width for different values of ε_r.

3 Simulation and Implementation

In this section, the results of simulation and implementation for the cloaked dielectric and single dielectric objects are presented. The Polyamide ($\varepsilon_r = 3$) is selected as the substrate of the FSS. Fig. 9 shows scattering width for different values of ε_r. As it is observed in figure ε_r has a small effect on the scattering width.

The influence of this substrate on the scattering of the wave is small due to the ultrathin thickness and low dielectric constant. Therefore, the effect of this substrate can be ignored. The radius of the inner object is 1.5 cm and its height is 18 cm. The radius of the cloak is considered equal to 1.1a. As mentioned previously, it is demonstrated by Fig. 3 that inductive surface is needed for cloaking the dielectric object. The dimension of the FSS which is used in this paper is shown in Fig. 6.

Figs 10(a) and 10(b) show vector power flow distribution of the cloaked object and single dielectric. As can be seen in these figures single object causes more perturbation than cloaked object. Power perturbation makes shadow region.

As it is clear in Fig. 10(d), the cloaked object had no influence on the near field and the cloak suppresses the scattering of the object in near field. This figure represent that the back scattering is drastically suppressed; also, the far field scattering pattern (figures 10(e) and 10(f)) is reduced about 10 dB. This result can be seen in figure 12(a) more clearly. Figures 10(a) and 10(b) indicate that the power dissipation is not affected by the cloaked object.

For verifying these results, this cloak is implemented. Fig. 11 shows the implemented cloak and the testing radar. For verifying the simulation results, the back scattering and transmitted wave from the cloak are measured.

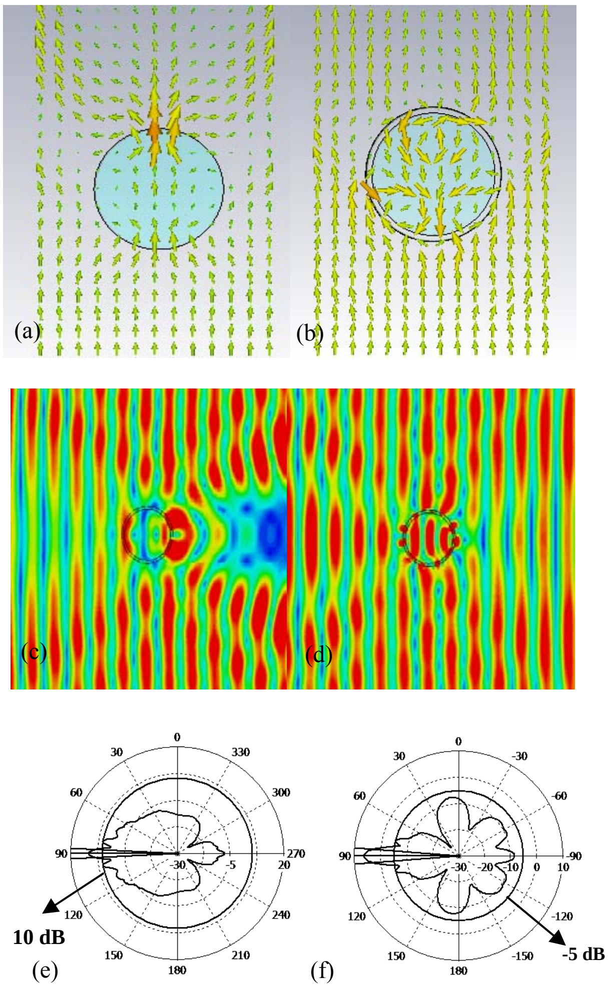


Fig. 10. a) Power flow distribution for dielectric without cloak. b) The same one for the cloaked object. The amplitude of near field electric field for c) without and d) with cloak and the H plane of far field radiation pattern for e) without and f) with cloak.

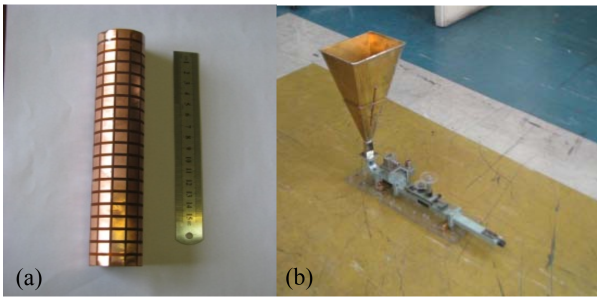


Fig. 11. a) Close view of the cloak. b) The radar which is used for measurement.

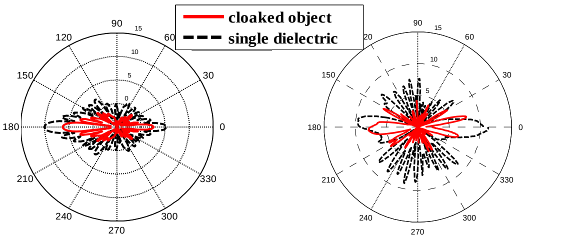
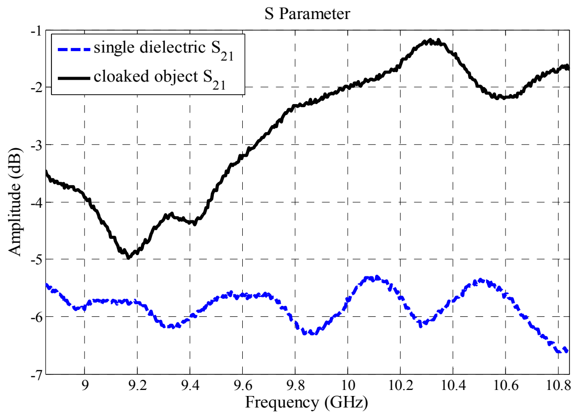
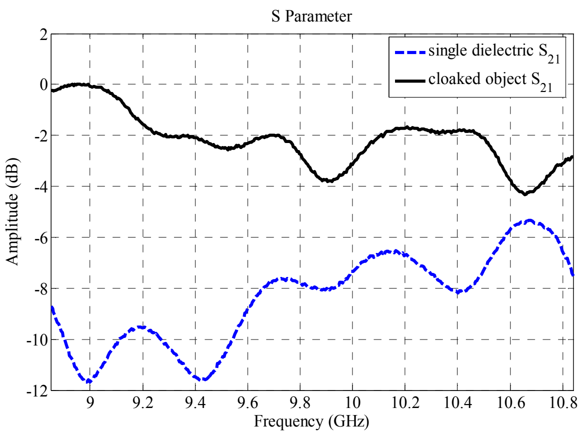


Fig. 12. a) Simulated and b) Measured E plane of scattering pattern for the cloaked object



(a)



(b)

Fig. 13. The measured results: a) S21 for the TE incident wave. b) S21 for the TM incident wave.

The simulated and measured E planes of scattering pattern are plotted in Fig. 12. The cloaked pattern is plotted by red line and cloaked the radiation pattern for single dielectric object is drawn with black dash line. The measured and simulated conclusions have accurate similarity in Fig. 12. It can be seen in Fig. 12(b), the back scattering is reduced to zero; so, no wave returns to the source. Also, the scattering is decreased up to at least 3 dB in the front lob and the reduction of side lobs is at least 7 dB. This means that adding the frequency selective surface suppress the scattering in all directions.

The measurement results for TE and TM incident wave are shown in Fig. 13. It can be observed in Fig. 13, S_{21} is improved in the peresence of the cloak in comparison with the object without cloak. S_{21} for TE incident wave at 10.3 GHz has its maximum value which is -1.2 dB and, for TM incident wave at 9 GHz, it is 0 dB. Also, at other frequencies for both polarization, S_{21} is enhanced by adding cloak. The S_{21} is increased by about 5 dB and 12 dB for TE and TM incident waves, respectively. As verified by the results, both S_{11} and S_{21} are enhanced greatly at 10 GHz for TE incident wave. It means that, at this frequency, cloaking is achieved completely. Also, the results in Fig. 13 represent the more than 20% bandwidth for our designed cloak.

4 Conclusion

In this article, a new method is presented for cloaking an object. This technique is based on suppressing the scattering from the object by matching the impedance between of inner object and outer space. Many figures and curves are plotted to verify this objective. The results of the simulation and implementation of the mantle cloak are also presented. The results represent that this covering greatly reduces the scattering of the object. Using the frequency selective surface, the back scattering is removed completely. Also, the scattering is reduced in all the directions. Maybe, the bandwidth of the cloak will be increased by using other kinds of FSS such as fractal structures, since these structures have more degrees of freedom for designing.

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