Cloaking of the Cylindrical Dielectric Structure with Double Slot Square Loop Cells

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***Abstract*— In this paper, a modified frequency selective surface (FSS) is proposed for cloaking of a dielectric cylinder. To this end, the needed value of surface reactance (X_s) of the FSS structure to eliminate scattering coefficient of the dielectric cylinder, is analytically calculated; the obtained value is 195 Ω. The modified double slot square loop unit cell, is designed to realize the calculated value of z_s. A dielectric cylinder with radius 12.45mm and height 180mm is covered with the array of the designed unit cell. Scattering width and electric field distribution of the dielectric cylinder with and without the designed FSS structure are obtained by CST software. Based on the simulation results, the total (SW) of the dielectric cylinder with the proposed FSS structure is about 0.88, which is about 10 units lower than that of value in uncloaked cylinder. The designed FSS is a suitable structure in dielectric cylinder cloaking applications.**

***Keywords*—Frequency selective surface; cloaking; scattering coefficient; double slot square loop; scattering width.**

I. Introduction

In recent years, electromagnetic cloak has been widely investigated in literature. J. Pendry et al. [1], theoretically introduced a cloak structure that covers an object and make it invisible to a plane wave. This cloak structure which be composed of metamaterial, causes to travel the incident wave around object and subsequently diminish scattering power from object. This conceptual structure was called ideal cloak [1]. By using power fullwave soft waves, fields configuration of reflected and incident electromagnetic waves were obtained and their results confirm Pendry theory. For the first time in 2006 at Duke-university a cloak structure by metamaterial substance was fabricated with some approximations [2]. The measurement results verified the theoretical results which cause to attract researchers attention to cloaking field. In 2005 Alu and Engheta presented a different cloaking method based on impedance matching of object to its peripheral area with eliminating scattering. Using homogenous and isotropic layer around the object was the advantage of this method [3]. A new method, mantle cloak, was introduced in 2009 by Alu et al. [4,5]. In this method frequency selective structure (FSS) was utilized for scattering suppress and impedance matching between object and free space [4,5]. Due to the capability of mantle cloaking to realize with printed technology, without requiring values of bulk permittivity or permeability, mantle cloak can be extensively used in conformal covers with ultralow profile to camouflage objects with different shapes [6]. Reducing antenna blockage and mutual coupling between co-sited antennas are recent applications of mantle cloaking reported in various works [7]. By use of this method, cloaking with various FSS structure for planar, cylindrical and spherical objects was presented [5]. The scattering properties of FSS cloaking is similar with that of metamaterial covers, but it is easier and more practical to realize and may offer an improved bandwidth [6].

In this paper cloaking of a dielectric cylinder with FSS structure is presented. To this end surface impedance is considered loss less. Required surface reactance of a unit cell is calculated in section III. To realize this reactance, a unit cell is proposed and its reactance is simulated with respect to frequency. A dielectric cylinder is covered by a cylindrical FSS structure consisted of the proposed unit cell in section III; subsequently the scattering width and fields configurations are discussed.

II. Theory

In order to analytically obtain FSS parameters which are important in cloaking, a dielectric cylinder with radius, a, and height, h, is considered and shown in fig. 1. In order to cloak this cylinder, it is surrounded by a cylinder FSS structure with radius a_c. Dielectric material with permittivity ε_c and permeability μ_c is placed between FSS structure and the cylinder with the constitutive parameters, ε_d and μ_d. A FSS structure which consists of periodic unit cells, covers curved surface of the dielectric cylinder. The surface impedance (z_s) of the FSS structure which is the ratio of tangential component of electric field to the tangential component of magnetic field ($z_s=E_z/H_\varphi$), plays an important role in cloaking of the cylinder. In order to analytically obtain the value of z_s, Maxwell's equations should be solved in the geometry at hand, shown in fig. 1(a). For sake of simplicity, variation of total structure along z axis is assumed to be zero, so three dimensional (3D) structure can be considered as a two dimensional (2D) problem, shown in fig. 1(b). As shown in this figure, the geometry at hand is divided into three regions. Region 1 and 2 are inside the dielectric cylinder, $\rho<a$, and confined area between radiuses a and a_c, respectively.

Region 3 is exterior sector of FSS structure, $\rho > a_c$.

To calculated z_s, the 2D structure of fig. 1(b) is illuminated with TM polarized electromagnetic wave [6,8]:

$$E_z^i = E_0 \sum_{n=-\infty}^{\infty} (i)^n J_n(k_0\rho) e^{-in\phi} \quad , \tag{1}$$

$$H_\phi^i = \frac{k_0 E_0}{j\omega\mu} \sum_{n=-\infty}^{\infty} (i)^n J_n'(k_0\rho) e^{-in\phi} \, , \tag{2}$$

where k_0 is wave number in region 1 and E_0 is initial electric field magnitude.

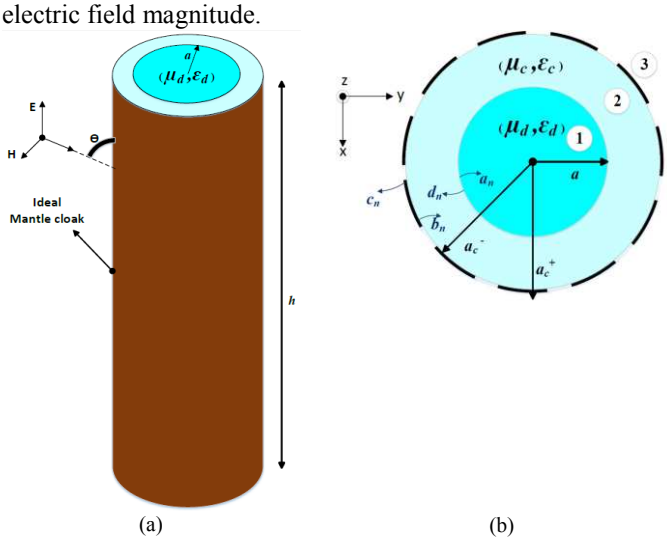

Fig. 1. The cross section of geometry at hand (a) 3D view of the dielectric cylinder with an ideal mantle cloak (b) top-view of (a)

According to incident wave, electric and φ-component of magnetic fields in regions 1, 2 and 3, can be written as:

$region 1 (\rho < a)$:

$$\begin{cases} E_z^{(1)} = E_0 \sum_{n=-\infty}^{\infty} i^n [a_n J_n(k_d\rho)] e^{-in\varphi} \\ H_\varphi^{(1)} = \frac{E_0 k_d}{j\omega\mu} \sum_{n=-\infty}^{\infty} i^n [a_n J_n'(k_d\rho)] e^{-in\varphi}, \end{cases} \tag{3}$$

$region 2 (a < \rho < a_c)$:

$$\begin{cases} E_z^{(2)} = E_0 \sum_{n=-\infty}^{\infty} i^n [b_n J_n(k_c\rho) + d_n Y_n(k_c\rho)] e^{-in\varphi} \\ H_\varphi^{(2)} = \frac{E_0 k_c}{j\omega\mu} \sum_{n=-\infty}^{\infty} i^n [b_n J_n'(k_c\rho) + d_n Y_n'(k_c\rho)] e^{-in\varphi}, \end{cases} \tag{4}$$

$region 3 (\rho > a_c)$:

$$\begin{cases} E_z^{(3)} = E_0 \sum_{n=-\infty}^{\infty} i^n [J_n(k_0\rho) + c_n H_n^{(2)}(k_0\rho)] e^{-in\varphi} \\ H_\varphi^{(3)} = \frac{E_0 k_0}{j\omega\mu} \sum_{n=-\infty}^{\infty} i^n [J_n'(k_0\rho) + c_n H_n^{(2)\prime}(k_0\rho)] e^{-in\varphi} \end{cases} \tag{5}$$

where b_n and d_n are transmission and reflection coefficients of electromagnetic fields in region 2, respectively. k_d, k_c, k_0 are wave number in region 1, 2, 3, respectively. At the interface $\rho=a$ amount of electromagnetic field with coefficient a_n is transmitted into region 1. Furthermore, c_n represents coefficient of reflected field from $\rho=a_c$. In order to obtain unknown coefficients, a_n, b_n, c_n, d_n, boundary conditions on surfaces, $\rho=a$ and $\rho=a_c$ are applied. Continuity tangential electric and magnetic fields on $\rho=a$ can be written as:

$$E_z^{(2)}(\rho = a^+) = E_z^{(1)}(\rho = a^-) \rightarrow$$
$$\sum_{n=-\infty}^{\infty} i^n [b_n J_n(k_c a) + d_n Y_n(k_c a)] e^{-in\varphi} = \sum_{n=-\infty}^{\infty} i^n [a_n J_n(k_d a)] e^{-in\varphi}, \tag{6}$$

$$H_\varphi^{(2)}(\rho = a^+) = H_\varphi^{(1)}(\rho = a^-) \rightarrow$$
$$\frac{E_0 k_c}{j\omega\mu_c} \sum_{n=-\infty}^{\infty} i^n [b_n J_n'(k_c a) + d_n Y_n'(k_c a)] e^{-in\varphi} \tag{7}$$
$$= \frac{E_0 k}{j\omega\mu} \sum_{n=-\infty}^{\infty} i^n [a_n J_n'(k_d a)] e^{-in\varphi},$$

By using two-sided impedance boundary condition at interface of region 2 and 3 ($\rho=a_c$), we have:

$$E_z^{(3)}(\rho = a_c^+) = E_z^{(2)}(\rho = a_c^-) =$$
$$Z_s (H_\varphi^{(3)}(\rho = a_c^+) - H_\varphi^{(2)}(\rho = a_c^-)) \rightarrow$$
$$E_0 \sum_{n=-\infty}^{\infty} i^n [J_n(k_0 a_c) + c_n H_n^{(2)}(k_0 a_c)] e^{-in\varphi} = z_s \frac{E_0 k_0}{j\omega\mu_0} \times$$
$$\sum_{n=-\infty}^{\infty} i^n [J_n'(k_0 a_c) + c_n H_n^{(2)\prime}(k_0 a_c) - b_n J_n'(k_c a_c) - d_n Y_n'(k_c a_c)] e^{-in\varphi}, \tag{8}$$

By multiplying both sided of Eqs. (6), (7) and (8) by $e^{-in\varphi}$, and integrating over φ, both equations are simplified. By solving the obtained equations, transmission coefficients, a_n, b_n and reflection coefficients, c_n, d_n can be achieved. In a perfect cloaking, electromagnetic power reflected in region (3) from object including dielectric cylinder and cloaking structure should be zero. Since, dominant mode (n=0) of TM polarized incident wave has the largest contribution to scattering values, herein reflection coefficient from the outer surface of FSS structure for dominant mode (c_0) only is equated to zero. By use of equations system comes from Eqs. (6), (7) and (8), the required surface impedance ($z_s=R_s+jX_s$ and $R_s=0$) that diminishes c_0, is numerically calculated respect to a_c and illustrated in fig. 2. It is noted that the required value of X_s for diminishing reflected power is depends on structure parameters a_c, a, ε_d.

III. DESIGN AND DISCUSSION

In this section a proper FSS structure to cloak a dielectric cylinder with a=12.45mm and h=18cm and with constitutive parameters ($\varepsilon_d=3\varepsilon_0$ and $\mu_d=\mu_0$), region 1 in fig. 1, is designed at 3.73 GHz. Region 2 is air with constitutive parameters, ($\varepsilon_c=\varepsilon_0$ and $\mu_c=\mu_0$). In order to compare the obtained results with results of reference [6], parameters of the dielectric cylinder are selected similar with that of in reference [6]. The value of needed z_s of FSS structure for cloaking of this cylinder is obtained by fig. 2, and its value is 195Ω.

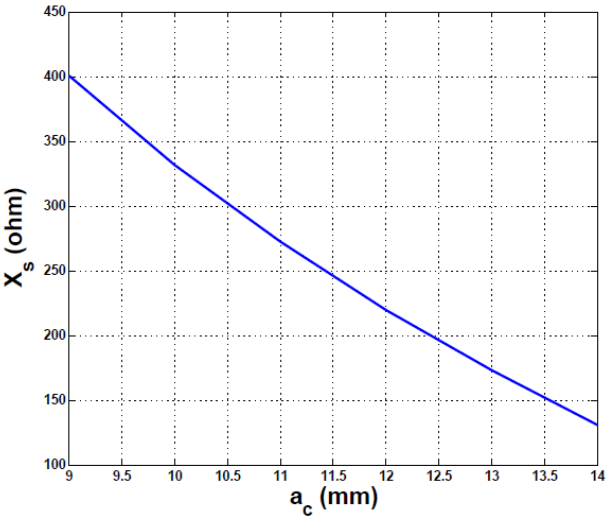

Fig. 2. Surface inductive reactance, which eliminates c_0 according to radius of cloaking structure (frequency 3.73 GHz, $\varepsilon_d=3\varepsilon_0$)

To realize 195 Ω surface reactance (X_s), a modified unit cell is proposed and shown in fig. 3(a). This unit cell consists of two slot square loops connected in the middle of their sides [9]. The proposed unit cell is simulated within CST and achieved optimum values of its parameters for z_s=195 Ω is tabulated in table1.

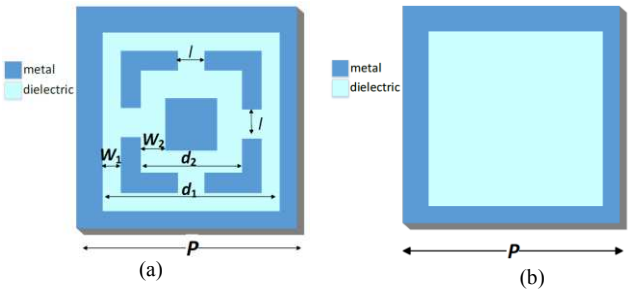

Fig. 3. (a) Two slot square loop with added slots. (b) Unit cell of reference [6].

Tab. 1. Optimum dimensions for the proposed unit cell for z_s=195 Ω at f_0=3.73 GHz, $\varepsilon_d=3\varepsilon_0$.

d_1(mm)	d_2(mm)	w_1(mm)	w_2(mm)	l(mm)	p(mm)
16.5	9.19	0.98	1.45	5	17.5

Simulated results of surface reactance of the designed unit cell and unit cell of reference [6] are shown in fig. 4 as a function of normalized frequency (f/f_0).

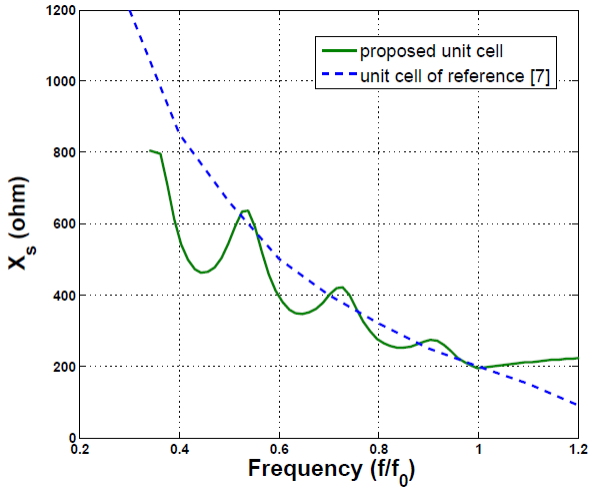

Fig. 4. Surface inductive reactance of the designed unit cell and unit cell of the reference [6] illuminated by TM polarized plane wave at normal incident (f_0=3.73 GHz, $\varepsilon_d=3\varepsilon_0$)

Figure 4, shows that surface reactance values of the proposed unit cell is closer to 195Ω at center frequency in comparison with surface reactance of reference [6] unit cell. Furthermore, reactance variation of the proposed unit cell respect to frequency at frequencies higher than center frequency, $f/f_0\geq1$, is very lower than that of in unit cell of reference [6]. According to these facts, the designed unit cell can be more desirable in cloaking rather than the unit cell of reference [6]. Since the maximum dimension of the proposed unit cell is about one fifth of center frequency wavelength, curvature in the surface of the unit cell dose not very drastically the value of surface reactance. So curved designed unit cell can be utilized cloaking of cylinder. The circumference of the dielectric cylinder is covered by four curved unit cells and these unit cells are 9 times replicated along cylinder axis (z axis) for covering the total height of cylinder as shown in fig. 5. The designed structure is illuminated by TM polarized wave within CST software. Simulated total scattering width (SW) of the dielectric cylinder with and without FSS structure are shown in fig. 6. This figure shows that the FSS structure with the proposed unit cell reduces SW of the bare dielectric cylinder to 0.88. In order to compare, the simulated SW of that cylinder cloaked with the FSS structure of reference [6], is also shown in fig. 6. It can be seen that SW value of the cloaked dielectric cylinder with the proposed FSS structure in this paper is about 27% lower than that of in reference [6]. These obtained results confirm design procedure validity and this fact that the designed unit cell is a more proper unit cell for cloaking applications.

Magnitude of E-field distribution on φ-plane with and without the designed FSS structure are shown in fig. 7. As shown in this figure, in the presence of FSS structure, scattering from the dielectric cylinder is suppressed, meanwhile, without FSS structure, scattering from the dielectric cylinder causes to disturb E-field distribution.

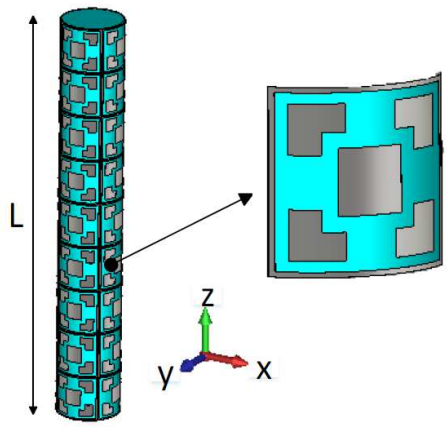

Fig. 5. Dielectric cylinder covered by the designed FSS structure excited by a TM-polarized plane wave at normal incidence

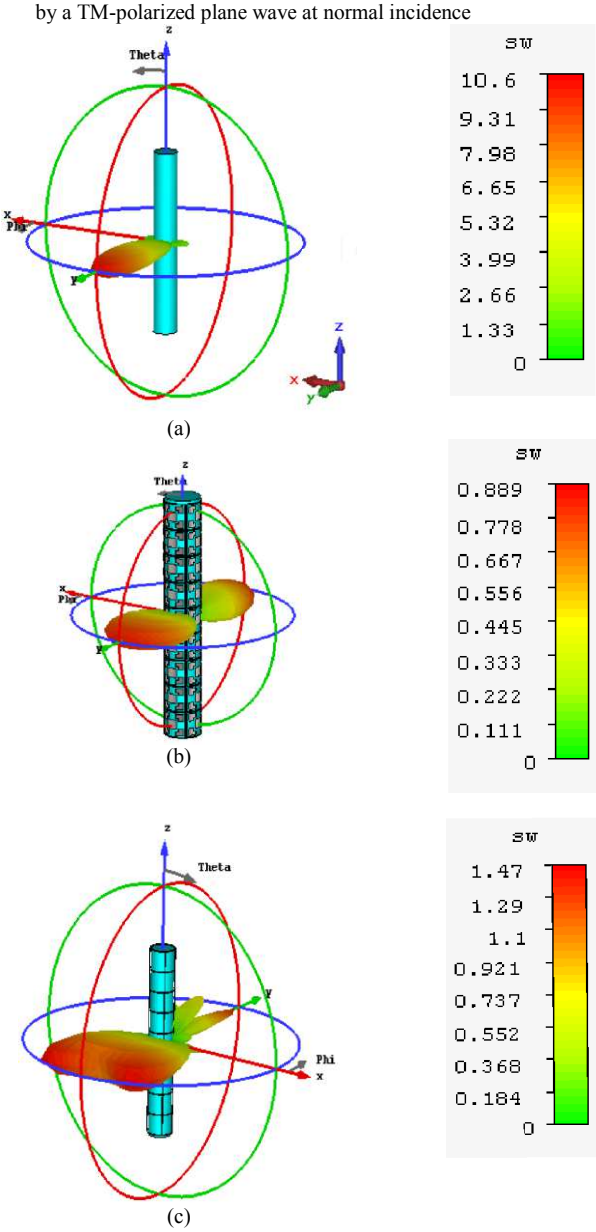

Fig. 6. Total scattering width (SW) of the dielectric cylinder (a) Uncloaked (b) Cloaked with the designed FSS structure (c) Cloaked with FSS structure of reference [6] (The result comes from our simulation.)

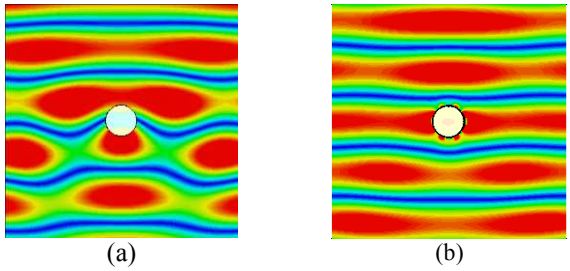

Fig. 7. Electric field distributions in φ-plane of (a) Uncloaked cylinder (b) cylinder cloaked with the designed FSS structure

IV. CONCLUSION

In this paper, a proper FSS unit cell is proposed for cloaking dielectric cylinder. Surface reactance that is required to minimize reflection coefficient from total objects including dielectric cylinder and FSS structure, is analytically derived. Based on the obtained value of surface reactance, X_s=195, a suitable unit cell is designed with 195Ω surface reactance at design frequency. By using the proposed unit cell, a cylindrical FSS structure is designed for cloaking of bare dielectric cylinder. Simulated results show that the designed FSS cylinder reduces scattering width (SW) value of dielectric cylinder to 0.88. This value is about 27% lower than that of similar dielectric cylinder reported in the literature. Furthermore, this design is able to reduce the total scattering about 92%.

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