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A dogbone metamaterial based electromagnetic cloaking scheme for microwave applications

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Abstract

The practical demonstration ofinvisibility cloaking has attracted the attention of electromagnetic research community over the decade. The invention of metamaterials has boosted the research on electromagnetic cloaking due their exotic material parameters under plane wave incidence. In this paper, we are proposing the experimental realization of cylindrical cloaking scheme using the dogbone metamaterial by efficiently routing the incident electromagnetic fields around the target metal obstacle under consideration. Experimental and simulation studies reveals that the proposed cloaking scheme can effectively suppress the Scattering Cross Section of the metal cylinder and significantly suppresses the back scattered power compared to the bare cylinder.

1. Introduction

Over the past decades there has been a considerable interest in the practical demonstration of different types of invisible electromagnetic cloaks in the microwave and plasmonic regime. The initial theoretical study on electromagnetic cloaking, based on coordinate transformation methods, relies on the creation of electromagnetic voids in free space [1]. Since the phase velocity of the wave passing through this cloak exceeds light velocity,this method is inherently narrow banded. The practical realization of this concept was proposed by Pendry using an array of Split Ring Resonators arranged in cylindrical fashion [2]. Another approach known as the plasmonic cloaking schemeutilizes the negative permittivity offered by the plasmonic shell to suppress back scattered power from the target. Engheta utilized the effective negative permittivity of parallel plate structures for back scattering reduction [3-4]. Plasmonic cloaking has also been used for cloaking a dipole antenna from the surrounding without sacrificing its receiving capabilities [5]. Many studies have been performed on the physical insights and reliability of plasmonic cloaking techniques for regular and irregular objects [6-8]. Another technique is the usage of non-magnetic non-resonant inclusions of ring resonators around the cylindrical target for backscattering reduction [9-10]. In plasmonic cloaking, increasing size of the target increases its visibility due to the excitation of higher order multi-poles. To overcome this disadvantage, Andrea Alu proposed the mantle cloaking technique in which the surface reactance of the cloaking frequency selective surface is properly designed for back scattering reduction [11-12]. Tretyakov utilized parallel metallic cylinders for effectively guiding the electromagnetic waves impinging upon the cloak boundary so that broad band operation can be achieved [13-14]. Experimental realizations of electromagnetic cloaking at optical wavelengths are well known [15-16]. The different topological aspects, classifications and characterization of metamaterial cloaking schemes are discussed in review reports [17-18].

In this paper, we are reporting a cylindrical cloaking scenario using dogbone metamaterials in the microwave frequency range. The dogbone metamaterials and the cut-wire pairs are alternatives of the split ring resonator-wire pair arrays, for obtaining negative refractive index behavior [19-20]. The dogbone metamaterials can be reconfigured to operate in the absorption and left handed modes by controlling the inter array thickness [21]. Here, we are arranging the dogbone plates in a manner similar to the parallel plate cloaking model proposed by Engheta [3-4]. In plasmonic cloaking, the structure effectively acts as a negative permittivity layer which reflects the incoming electromagnetic waves with opposite phase as compared to the dielectric shell. For the artificial dielectric inclusions like the parallel plate medium, the surface currents on the adjacent metal layers will be in phase constituting an effective negative permittivity medium. But, in the dogbone metamaterials both electric and magnetic responses will be present. The in phase current distributions cause the electric dipole response and anti-symmetric distributions or the loop currents creates the magnetic response. The target to be cloaked is a metallic cylinder and it is shown that the cloaking scenario is efficiently used to reduce backscattering from the target under plane wave illumination. The simulation studies of the structure are done using the CST Microwave Studio and the experiments are conducted using PNAE8362B vector network analyzer.

2. Geometry of the cloak

Numerical simulations have been performed on the target as shown in Fig.1 using CST Microwave Studio software. For practical demonstrations, a plastic cylinder covered with Aluminum foil is used as the target. Initially we have taken the metallic cylinder (uncloaked) as the target. The diameter of the cylinder is set to be 5 cm and it is taken as the standard target. The height of the PEC cylinder is set to be 50 cm. The outer diameter of the cloaked target is found to be 82 cm. The dogbone metamaterial is printed on a low cost epoxy substrate of dielectric constant 4.4. Ten dogbone cells are utilized along the z-axis of the cloaked target and two cells are used along the ρ direction. Along the ϕ direction there are eight dogbone structures around the target so that there is a total of 80 dogbone unit cells incorporated around the target cylinder. The dimensions of the dogbone metallization are L_1=18mm, L_2=12mm, W_1=4mm and W_2=2mm.

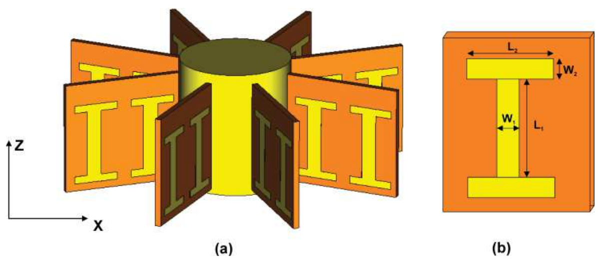

Figure1. *Geometry of the unit cell a) the metallic cylinder target having a dimension of 30mm is surrounded by the dogbone type metamaterials printed on epoxy substrate and (b) dimensions of the dogbone metallization.*

3. Results and Discussions

Numerical simulations have been performed on the target as shown in Fig.1 using CST Microwave Studio software. For practical demonstrations, a plastic cylinder covered with Aluminum foil is used as the target. To retrieve the reflectance of the structure, unit cell simulation has been performed with Perfect electric boundary conditions along Z axis and open boundary conditions along the two other axis of the unit cell. Two types of simulations have been performed, one with the metallic cylinder alone in free space and the second with the cloaked metallic cylinder with the dogbone metamaterial cover. It is to be noted that the plane wave is propagating from the left of the computational domain to the right. For a far field plane wave source exciting the unit cell comprising of the metallic cylinder, the computed electric field distributions and the Poynting vector distributions on the computation domain for the bare cylinder are depicted in Fig. 2. As expected, the uncloaked cylinder produces significant shadow behind the object due to the heavy scattering offered by the metallic parts. This can be verified by the reduction in the Poynting vector magnitude above and below the cylinder. The uniformity of power flow is disturbed by the presence of the target and the target could easily be detected by backscattering measurements.

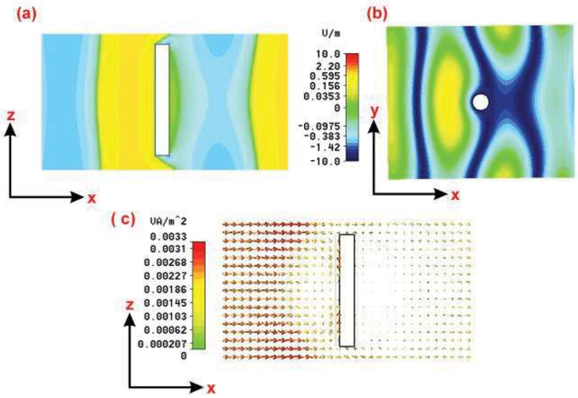

Figure 2. *Numerical simulations for the uncloaked target (a) Magnitude of electric field distributions for the uncloaked scenario from the XZ plane. (b) Magnitude of electric field distributions for the uncloaked scenario from the XY plane. (c) Poynting vector distribution for the uncloaked scenario from the XZ plane.*

Fig.3 depicts the computed field and Poynting vector distributions on the computational domain for the cloaked cylinder. By covering the cylinder with the dogbone metamaterials, the scattering can be considerably decreased and near plane wave fronts are observed. The shadow produced by the uncloaked cylinder is avoided in the cloaked scenario and a downward flow of electromagnetic power is observed. A better uniformity in the electric field distribution is observed as compared to the uncloaked cylinder. This means that the dogbone metallization efficiently routes incoming electromagnetic waves around the cylinder and hence scattering from the target is reduced considerably.

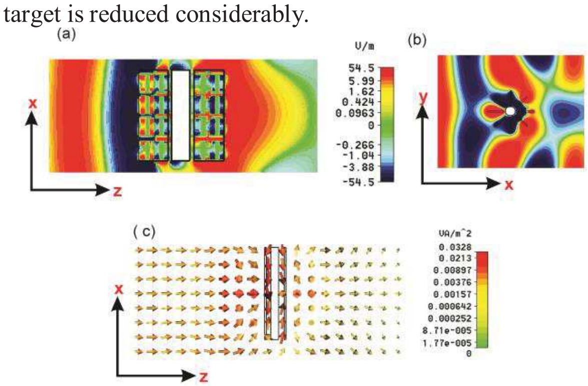

Figure 3.*Numerical simulations for the cloaked target a) Magnitude of electric field distribution for the cloaked case from the XZ plane. (b) Magnitude of electric field distribution for the cloaked case from the XY plane. And (c) Poynting vector distributions for the cloaked case from the XZ plane*

The measured and simulated reflectance of the structure normalized with the uncloaked reference cylinder is shown in Fig.4. The structure shows a very low scattered power of the order of -20 dB as compared to the uncloaked scenario. The resonance is found to be at 2.52 GHz. Monostaticscattering measurement is done with the receiving and transmitting horn antennas located at $\phi=90^0$ along the azimuth plane. The small mismatches in experiment and simulation are accounted due to the fabrication tolerances.

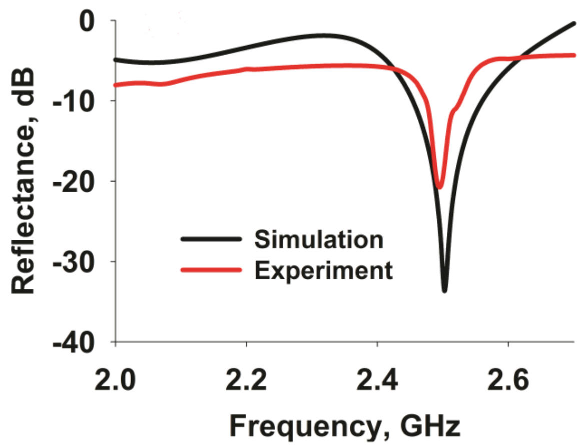

Figure 4.*Measured and simulated reflectance from the structure (from mono static scattering measurement)*

Bistatic scattering measurements have been performed on the structure with the receiving horn antenna located at various angles along the azimuth plane. The results of the bistatic scattering measurement at the resonant frequency is summarized in Fig. 5. The solid black line shows the scattered power from the uncloaked target and it is taken as the reference target. Fig. 3(b) shows the scattered power at the resonant frequency. It is seen that along the boresight ($\phi=90^0$), the scattered power is of the order of -20 dB at the resonant frequency. The scattered power is considerably reduced for all other receiving angles and hence the cloaked target becomes undetectable from the scattering measurements. For all the azimuth angles, scattered power lower than -10 dB is observed at the resonant frequency.

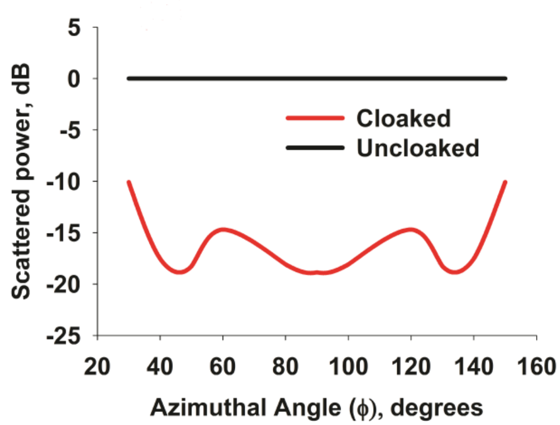

Figure 5. *Measured bistatic scattered power with and without the cloak at 2.52 GHz;*

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