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Journal:	<i>Canadian Journal of Physics</i>
Manuscript ID	cjp-2016-0876.R1
Manuscript Type:	Article
Date Submitted by the Author:	04-Mar-2017
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Keyword:	Cloaking, Metamaterials, Invisibility, dogbone metamaterials, bistatic scattering
Please Select from this Special Issues list if applicable:	N/A

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An Experimental Realization of Cylindrical Cloaking using Dogbone Metamaterials

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Abstract: The quest for invisibility has made a deep ardour among research community over the decade. The invention of metamaterials has boosted the research on electromagnetic cloaking due to its unusual electromagnetic parameters under plane wave incidence. In this study, we propose a novel cloaking scheme using the dogbone metamaterials, for effectively routing the incident electromagnetic fields around a target metal cylinder under consideration. Notable reduction in the scattered power is observed from the target in comparison to an uncloaked target. Experiments and simulations validate an effective reduction in the Scattering Cross Section of the target and effective guiding of the incident plane wave around the target.

Introduction: The ability to be invisible from surroundings has been the favourite topic of many science fictions over the last century. Over the past few years, there has been a considerable interest in the practical demonstration of different types of invisible electromagnetic cloaks. The initial studies on electromagnetic cloaking are based on the coordinate transformation methods [1-2]. It relies on the creation of electromagnetic voids in the coordinate system. This method is inherently narrow-band because of the fact that the phase velocity of the electromagnetic wave passing through the cloak exceeds light velocity. The practical realisation of this concept was initially proposed by Pendry et al. [3] using an array of Split Ring Resonators. In order to guide electromagnetic waves around the target, a careful design of material parameters is required. An alternate approach is the plasmonic cloaking technique in which the negative permittivity offered by the plasmonic shell effectively suppresses the scattered power from the target. Engheta et al. utilised the effective

negative permittivity of parallel plate structures for scattering reduction [4-5]. The plasmonic cloaking technique has been successfully implemented for cloaking a dipole antenna from the surrounding without deteriorating its receiving capabilities [6]. Another technique of to use non-magnetic non-resonant inclusions of ring resonators for achieving scattering reduction [7-8]. The main disadvantage of plasmonic cloaking is that increasing the size of the target increases its visibility due to the presence of higher order multipoles. In order to overcome the above disadvantage, Alu et al. proposed the mantle cloaking technique which is easier to realize and have low losses [9-12]. The theory of mantle cloaking is to tune the surface reactance offered by the metasurface, to suppress scattering from the target. Mantle cloaking is an efficient technique for cloaking of antennas in the microwave regime [13-18]. The same group has achieved cloaking for orthogonal TE and TM polarisations using non-resonant grids [19]. Meanwhile, Tretyakov et al. utilised the concept of waveguiding using parallel metallic cylinders for effectively guiding the electromagnetic waves impinging upon the cloak boundary to achieve broadband cloaking [20-21]. Transmission-line networks could also be used to cloak metallic cylinders [22]. Experimental realisations of electromagnetic cloaking at optical wavelengths are well known [23-24]. The different topological aspects and classifications of metamaterial cloaking are already available in review reports [25-26].

In this paper, we report a cylindrical cloaking scheme 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 behaviour [27-28]. The dogbone structure can be reconfigured to operate in the absorption and left handed modes by controlling the electric and magnetic polarizabilities induced on the structure for normal incidence [29]. In this study, we have arranged the dogbone plates in a manner similar to the parallel plate cloaking model proposed by Engheta [4-5]. In Engheta's model, 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 resonances will be present. The in-phase current distributions cause the electric dipole response, and the anti-symmetric distributions or the loop currents create the magnetic response. The target to be cloaked is a metallic cylinder and it is shown that the cloaking scheme is efficiently used to reduce the scattering 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 R&S ZVB 20 vector network analyser.

Numerical simulations: Numerical simulations have been performed on the target as shown in Fig.1 using CST Microwave Studio. For practical demonstrations, a hollow metallic cylinder is used as the target. Due to the periodicity of the structure along the axis of the cylinder, unit cell simulation has been performed for obtaining the reflectance of the structure for normal incidence. Perfect Electric (PEC) boundary conditions are applied to the Z axis and Open boundary conditions are used along the two other axis of the unit cell. The computed electric field and the Poynting vector distributions on the computation domain for a far field plane wave source exciting the entire structure are depicted in Fig. 2. Simulations with and without the dogbone metamaterial cloak on the metallic cylinder are performed. The magnitude of electric field distributions seen from the XZ and XY planes of the computational domain are depicted in fig. 2(a) and (b) respectively. One should note that the plane wave is propagating from the left-hand side of the computational domain to the right side along the X-axis. The polarization of the incident plane wave is directed along the Z-axis. As expected, the uncloaked cylinder produces a significant shadow behind the object due to the acute scattering from the metallic parts. The magnitude of the electric field inside the metallic cylinder is zero. The high scattering offered by the metallic cylinder can be also verified using the Poynting vector distribution shown in fig. 2 (c). The out of phase reflection from the metal cylinder reduces the magnitude of the Poynting vector on the left side of the computational domain near the cylinder. The shadow region is identified from the reduction in the Poynting vector

magnitude on the right side of the domain near the cylinder. It means that the uniformity of power flow is disturbed by the presence of the target and the target could easily be detected by

Fig.1. Unit cell simulation setup for the free space cylindrical cloaking scheme (a) the metallic cylinder target is surrounded by the dogbone type metamaterials printed on an epoxy substrate and (b) dimensions of the dogbone metallization.

scattering measurements. The target could be made invisible by covering it with dogbone metallic structures. The speciality of dogbone metallic inclusions is that both electric and magnetic polarizabilities can be induced on the structure and hence the guiding electromagnetic waves around the target is easily achieved. Hence scattering is considerably decreased and near plane wave fronts are observed for the cloaked target at the resonant frequency. The electric field and Poynting vector distributions in the computational domain for the cloaked cylinder are illustrated in fig. 2 (d)-(f). One could observe that the shadow produced by the uncloaked cylinder is absent in the cloaked case and is clear from the electric field distributions shown in fig. 2 (d) and (e). A steady flow of electromagnetic power along the propagation normal and a better uniformity in the Poynting vector distribution are observed in comparison with the uncloaked cylinder. Thus it is apparent that the dogbone metallization efficiently routes incoming electromagnetic waves around the cylinder and hence scattering from the target is considerably reduced.

Fig.2. Numerical simulations in the computational domain for the cloaked and uncloaked targets (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, (d) Magnitude of electric field distribution for the cloaked case from the XZ plane, (e) Magnitude of electric field distribution for the cloaked case from the XY plane, (f) Poynting vector distributions for the cloaked case from the XZ plane.

Experimental realization: The experimental verification of the cloaking technique uses a free space scattering measurement setup in an anechoic chamber. Two ultra wideband horn antennas, one configured in the transmission mode and the other in the receiving mode, positioned on a turn-table assembly with the target at the origin of the table are used. Bistatic scattering measurements are performed on the target by varying the position of the receiving

horn antenna along the circumference of the turn-table setup [30]. The distance between the target and the horn is fixed at 225 cm. A hollow metallic cylinder with a diameter of 5 cm and height 50 cm is used as the standard target. The physical description of the cloaking structure is described as follows. There are ten dogbone unit cells repeated along the Z-axis, two cells along the ρ direction and eight cells along the ϕ direction around the metallic cylinder. In total, there are 160 dogbone cells distributed around the target cylinder. The outer diameter of the cloaked target is found to be 82 cm. The dimensions of the dogbone metallization are $L_1=18\text{mm}$, $L_2=12\text{mm}$, $W_1=4\text{mm}$ and $W_2=2\text{mm}$. The dogbone metallization is printed on a low-cost epoxy substrate of dielectric constant 4.4.

Monostatic measurement is done with the receiving and transmitting horn antennas placed at $\phi=90^\circ$ along the azimuth plane. The measured and simulated reflectance of the structure normalised with the uncloaked reference cylinder for normal incidence is shown in Fig.3 (a). The structure shows a reduction in scattered power of the order of -20 dB as compared to the uncloaked scenario corresponding to the resonance centered at 2.52 GHz.

Fig.3. Measured reflectance and scattering parameters of the fabricated cloak (a) Reflectance of the cloak at $\phi=90^\circ$, (b) bistatic scattered power with and without the cloak at 2.52 GHz, (c)

bistatic scattered power with and without cloaking layer at 2.3 GHz, (d) bistatic scattered power with and without cloak at 2.7 GHz

The small mismatches in experiment and simulation are accounted due to the fabrication tolerances. Bistatic scattering measurements have been performed on the structure with the receiving horn antenna placed at various angles along the azimuth plane. The results of the bistatic scattering measurements for three different frequencies are summarised in Fig. 3 (b) to (d). The solid black line shows the scattered power from the uncloaked target and is taken as the reference target. Fig. 3(b) shows the scattered power at the resonant frequency. It is seen that along the boresight ($\phi=90^\circ$), the scattered power is reduced to -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 reduction better than -10 dB is observed at the resonant frequency. Fig. 3 (c) and (d) shows the bistatic scattered power at two non-resonant frequencies 2.3 GHz and 2.7 GHz respectively. For most of the receiving angles, the scattered power is comparable as that of the uncloaked cylinder at 2.3 GHz. For 2.7 GHz, high scattering is observed and it can be easily detected from scattering measurements.

In order to have a better understanding of the scattering characteristics of the structure, simulated scattering patterns are taken in the CST computational domain and are depicted in fig. 4. Fig. 4(a) shows the Scattering Cross Section (SCS) of the cloaked and uncloaked metallic cylinder. It is seen that for a broad frequency range, the scattering gain (the ratio of SCS's for the cloaked and uncloaked scenario) is less than one, and at the resonant frequency (2.52 GHz), the curve shows a gradual dip. Minimum scattering is observed at this frequency from the target. Fig. 4(b) and (c) shows the 3D scattering patterns (Radar Cross Section) of the uncloaked and cloaked scenarios respectively. Note that the incident plane wave is travelling from the $-Z$ direction to the $+Z$ direction. It is clear that the uncloaked reference target scatters the incident plane wave equally along the azimuth plane and hence it is detectable. In the case of the cloaked cylinder, the scattered power is reduced considerably along the broadside direction. The maximum RCS of the cloaked target is of the order of -12.1

dBsm and the minimum value is -27.1 dBsm. It is to be noted that the traditional dogbone metamaterials are half wavelength resonators. It exhibits both electric and magnetic resonances. The magnetic resonance is contributed due to the virtual loop current distribution between the stacked dogbone metallization. The resonant frequency can be varied by varying the stacking thickness (distance between the consecutive stacked layers). For denser dogbone array along the ϕ -direction, the resonant frequency will be higher and the incident electromagnetic signal will be absorbed and the magnitude of transmission coefficient will be reduced to zero. In other words, when the separation between stacked layers is in terms of the lowest parameter of the dogbone metallization, absorption dominates and hence the target can be detected by bistatic measurements. In the current design, absorption is minimum and the dogbone inclusions route the entire incident power at the resonant frequency.

(a)

(b)

(c)

Fig.4. Scattering characteristics of the structures a) Scattering Cross Sections (SCS) of the cloaked and uncloaked PEC cylinder b) Scattering pattern of the PEC cylinder without cloak and (e) Scattering pattern of the PEC cylinder with the cloak.

The cloaking effectiveness could also be proved by using the antenna radiation pattern measurements proposed by Tretyakov [30]. The analysis is done by measuring the radiation patterns of a standard ultrawideband horn antenna by placing the cloaked and uncloaked targets in front of the antenna and comparing the results. Three cases have been considered here, one with the reference ultra wideband horn antenna alone, second with the uncloaked cylinder in front of the horn antenna and the third with the cloaked cylinder in front of the horn antenna. The measured radiation patterns are summarised in Fig. 5. The two principal planes are considered here for the study. The case with the cloaked cylinder in front of the horn antenna shows radiation patterns

Fig. 5. Measured radiation patterns of the horn antenna under the free space condition, cloaked cylinder incorporated condition and uncloaked scenarios (a) E-plane patterns and (b) H-plane patterns.

similar to the free-standing horn antenna. This means that radiated power from the horn antenna is not blocked or scattered by the cloaked cylinder thereby achieving a steady flow of power through the cloaked structure for both the planes. But for the uncloaked case, radiation

from the horn antenna is blocked by the metallic cylinder causing scattering and hence a reduction in radiated power along the upper hemisphere of the antenna is observed.

Conclusions: The experimental realization of a microwave cylindrical cloaking scheme using dogbone metamaterial layers is proposed. The dogbone layer efficiently routes the incoming electromagnetic wave around the target and an almost steady flow of electromagnetic power is observed within the computational domain. The cloaking scheme is experimentally validated and proved that a very low scattering is observed around the target at the resonant frequency. The cloaking effectiveness is also confirmed using the antenna radiation pattern measurement techniques in an anechoic chamber.

Acknowledgments

The authors would like to acknowledge University Grants Commission (UGC) and Department of Science and Technology (DST), Government of India for financial support.

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