Ideal Magnetic Dipole: Scattering and Mantle Cloaking Effects

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Abstract—Artificial magnetic response is one of the recent research topics that is receiving significant attention. Nevertheless, because of the difficulties in exciting not only the magnetic moment but also multipoles of different order, and the presence of losses, the efficiency of its generation is strongly compromised. On the other hand, the presence of a cloaking phenomena can be described in terms of anapole mode, which consists in the compensation of the scattering due to the moment of the electric dipole with the toroidal one. Because of this effect, the remaining part of the field will exhibit a strong(er) magnetic dipole moment response. In the present study, the response of a cloaking device based on a real-life geometry is therefore analysed with particular focus on the anapole mode excitation and ideal magnetic dipole behavior.

Index Terms—Anapole mode, cloaking, magnetic dipole, scattering

I. Introduction

Investigations on how to realize artificial magnetic dipoles (MD) is receiving considerable interest due to the various estimated application scenarios in different fields it allows, such as mangetoinductiove lenses [1] or magnetic nanoantennas [2].

Although an artificial magnetic response could be achieved in resonant structures, for example with the use of metamaterials [3], it is still a challenging aspect at optical frequencies because of the losses in metallic materials and the presence of parasitic electric response.

The scattering from a particle excited by an incident field, can be expanded into a sum of different multipoles contributions, both of electric and magnetic types. Each multipole contributes to the scattered field with an intensity proportional to the associated scattering coefficient.

The firsts two families of multipoles are the electric and magnetic dipoles. A third family of this expansion is composed by the toroidal multipoles which are generated by a poloidal current flowing along a torus meridians. In this way, a toroidal dipole (TD) moment manifests along the torus axis [4]. Interestingly, the TD presents a radiation pattern similar to the one of an electric dipole. This property could lead to the emergence of particular phenomena such as the arising of an anapole mode, in which the scattering due to electric dipole moment is compensated by the toroidal one, resulting in a non-radiation condition [5].

On the other hand, a minimum in the scattered field is associated with cloaking phenomena. In recent years this aspect has been deeply studied also thanks to the theoretical and technological advancements in the field of metamaterials. In a cloaked device, a scatterer object is concealed with a specifically designed metamaterials coating. Due the boundary conditions introduced by the presence of the metamaterial coating, an incident field is guided along the object surface and it is recomposed beyond it [6]. In this way the field is not distorted by the presence of the object itself. Consequently, at the cloaking frequency, the scattered field is strongly attenuated, and the total field (i.e., the sum between thee incident and scattered one) resembles the incident one.

Analysing the scattered field of a cloaked object in terms of multipole decompositions, the minimum of the scattering cross-section can be connected with the fulfilment of the anapole mode condition, defined as the compensation of the electric and toroidal dipole components of the scattering [7].

Moreover, the realization of an anapole mode leads to the strong reduction of the electric types multipoles, so that at the cloaking frequency a predominantly magnetic dipole moment response is obtained. Hence the described phenomenology gives rise to the realization of an ideal magnetic dipole [8].

In this framework, in the present study, the scattering of a cloaked cylinder is analysed in terms of multiple expansion with particular attention on the fulfilment of the anapole mode condition and on the achievement of an ideal magnetic dipole response. In particular, here a geometry is considered, where a metallic cylinder is covered by a sinusoidal shaped metallic layer supported by a constant height dielectric layer. The structure is similar to that introduced in [9], but of a different pattern [10].

II. Theoretical formulation

The scattering efficiency Q_{sca} can be expressed as a sum of electric a_E and magnetic a_M contributions such that:

$$Q_{sca} = \frac{\pi}{k^2} \sum_{l=1}^{\infty} \sum_{m=-l}^{l} (2l+1)(|a_E(l,m)|^2 + |a_M(l,m)|^2) \quad (1)$$

where l denotes the spherical harmonic order of the expansion.

In an ideal magnetic scatterer, the contribution from the electric multipoles a_E tends to zero, and the scattering efficiency is therefore dominated by the magnetic component.

In order to drastically reduce the contribution of the electric multipoles, a possibility is to realise the so called anapole mode which consists in the compensation of the electric dipole moment by the toroidal dipole moment.

Since this two modes have similar fields configurations, the anapole mode condition is fullfilled when [5]:

$$\mathrm{P} = ik\mathrm{T} \quad (2)$$

where P represent the electric dipole moments, while T is the toroidal dipole moment, at a given frequency where the propagation constant in the considered medium is k, and i denotes the imaginary unit.

III. Description of the model and results

In the following a metasurface structure which could be employed to realise a cloaking effect under certain conditions, is examined in terms of scattering field with both the purpose of establish a cloaking effect and an anapole mode excitation.

The geometry of the patterned metasurface was introduced previously in [10], moreover its efficiency as a cloaking device was also examined. For the sake of completeness, the CAD model of the considered structure is reported in Fig. 1.

In Fig. 2(a), the behavior of the Radar Cross Section (RCS) versus frequency is reported when the structure is illuminated by a linearly polarised planewave with electric field parallel to the cylinder axis.

In the considered frequency range a multipolar expansion of the field inside the dielectric layer has been performed. The different normalized power densities associated to the different components are reported in Fig. 2(b).

As it can be noticed, the frequency corresponding to the minimum of the RCS is quite similar to that where

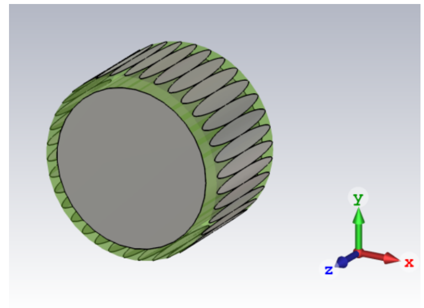
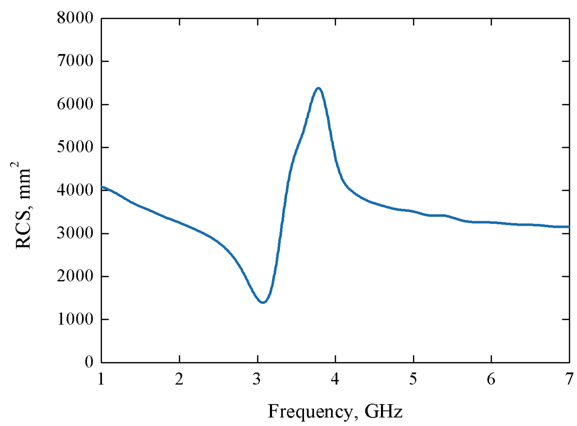
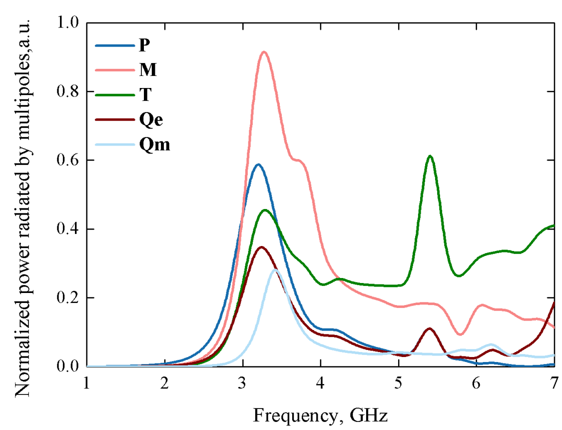


Fig. 1. CAD model of the metallic cloaked cylinder (grey: metal, green: dielectric)



(a)



(b)

Fig. 2. Radar cross section of the cloaked metallic cylinder (a) and normalised scattered power correspondent to different multipoles (b).

the power density associated to the electric dipole and toroidal moment intersects, i.e., their far-field radiations cancel out each other.

Interestingly, at the same frequency there is a pronounced peak of the magnetic dipole moment response. Therefore, thanks to the compensation of the electric and toroidal dipole moments, it is possible to achieve an ideal magnetic dipole configuration in which the magnetic dipole moment is predominant.

IV. Conclusions

In this paper the scattering of a cloaked metallic cylinder was analysed in terms of multiple expansion. The cloaking was realised with a modulated metasurface which has been previously proved to effectively reduce the scattered field for a specific frequency band and cylinder diameter. The scattered field was then analysed in terms of multipole expansion. It has been show that at the cloaking frequency, and therefore in correspondence with a minimum of the scattering, the anapole mode condition is fulfilled and therefore the radiation due to the electric dipole moment is compensated by the toriodal one. Moreover, the strong presence of the magnetic dipole moment was observed and therefore the possibility to realise an ideal magnetic dipole was discussed.

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