Optical invisibility of cylindrical structures and homogeneity effect on scattering cancellation method

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Optical cloaking for cylindrical structures with arbitrary cross-section by using scattering cancellation method is presented. Nano-strips of silver in a dielectric host are used as a cloaking shell around the cylindrical object with arbitrary cross-section shapes. In this approach, the homogeneity effect on cloaking efficiency in the cloaking structure with circle cross-section is studied. The number of silver strips is the criteria of shell homogeneity. By increasing the number of strips for a constant filling factor, their widths become narrower and so the cloaking shell becomes more homogenous. It is shown that the cloaking efficiency is affected by the homogeneity of the cloaking shell and there is an optimum size of embedded particles to achieve required homogeneity in a cloaking structure.

Introduction: A variety of theoretical and numerical methods have been considered to achieve electromagnetic cloaking in different frequency regimes. Some categories of cloaking approaches can be mentioned as transformation optics [1], transmission-line (TL)-based structures [2, 3] and scattering cancellation [4–9]. Scattering cancellation method is based on reducing the scattering wave from an object. In this approach, one should consider shell layer around the object with specific reduction of permittivity. As a brief description, considering cloaking shell with small permittivity with respect to the object permittivity and specific radius causes scattering reduction for the whole structure involves the cloaked object and the cloaking shell. These cloaking layers can be implemented in microwave and terahertz regime in both shapes of bulk and mantle layers [7, 8]. However in infrared and optical ranges, because of permittivity function of the natural metals, using the mantle cloak is impossible and bulk layers of cloaking shell have been presented [9]. To make such a cloaking shell, some metallic particles are embedded in a dielectric host, and so an inhomogeneous medium is formed [4, 5]. In this Letter, inserting silver strips in a dielectric host around the cylindrical structure is utilised for realising the optical cloaking with scattering cancellation method. It will be shown that this approach can be applicable to arbitrary cross-sections such as flower-shaped cylindrical cloaked object. The radar cross-section (RCS) as a common criterion of cloaking are calculated numerically for these cylindrical cloaking structures. Embedding silver strips in the host dielectric creates inhomogeneous medium and one can calculate effective permittivity of this medium by using effective medium theory. On the basis of this theory filling factor of embedded particles is the key parameter of the effective permittivity. The same filling factor can be achieved by a large number of small particles (homogenous medium) or a small number of large particles (inhomogeneous medium). We show that the homogeneity is important feature and if the cloaking shell has more monotonic media, the cloaking results become more efficient. The number of nano-strips of silver in the host medium for the same filling factor is the criteria for this evaluation.

Cylindrical cloaking structure in optical regime: A cylindrical shell, as the cloaking medium with radius r_c and a dielectric cylinder as the cloaked object with radius r_{ob} are considered with circle cross-section (Fig. 1*a*). The structure is exposed by a transverse magnetic (TM) plane wave with electric field of E_z. For electrically small cylinders, based on Mie theory in the quasi-static condition, the following relation provides the minimum scattering from cloaking shell and the cloaked object [5]:

$$\frac{A_c}{A_{ob}} = \frac{1-\varepsilon_{rob}}{\varepsilon_{rc}-1} \tag{1}$$

where ε_{rc} and ε_{rob} are the relative permittivities of cloaking shell and the cloaked object, respectively. A_{ob} and A_c are surface areas of arbitrary cloaked object and cloaking shell, respectively. The scattering cancellation is affected by shell radius, r_c and permittivity, ε_c. An appropriate radius of shell with negative permittivity material decreases the scattering of cylindrical objects.

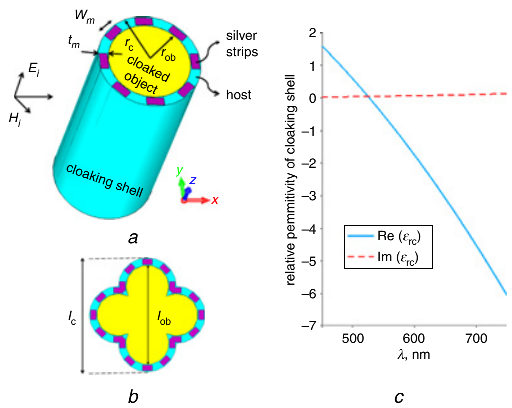

Fig. 1 *Cloaked object and silver strips in host dielectric as cloaking shell with*

a Circle-shaped cross-section
b Flower-shaped cross-section, as an arbitrary shape exposed by a plane wave
c The relative permittivity of the cloaking shell for embedded nano-strips of silver in the host dielectric with $\varepsilon_{rh} = 6.5$

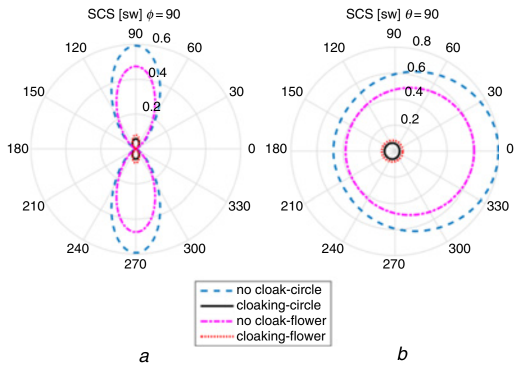

Fig. 2 *Scattering width (sw) for cloaking structure with circle cross-section for*

a $\phi = 90°$
b $\theta = 90°$ at wavelength of $\lambda = 645$ nm that cloaking shell is realised with 16 embedded silver strips in host medium

In this Letter, a dielectric cylinder with a relative permittivity of $\varepsilon_{rob} = 3$ is assumed as the cloaked object. According to (1), the appropriate shell with a relative permittivity of $\varepsilon_{rc} = -3$ can be considered with $r_c \approx 1.22 r_{ob}$. This cloaking method has potential to be extended to other shapes of cylinder cross-sections. For example, a cylinder with flower-shaped cross-section can be considered as the cloaked object (Fig. 1*b*). For this flower-shaped structure, the largest diameter of the cloaked object is $l_{ob} = \lambda/4$ and for $\varepsilon_{rc} = -3$ the largest diameter of cloaking shell is obtained as $l_c \approx 1.22 l_{ob}$. For realising the negative permittivity of cloaking shell, the embedded nano-strips of silver can be used in a dielectric host. The permittivity of silver (ε_m) is calculated by Drude model with $\varepsilon_\infty = 5$, $\omega_p = 13666$ rad/s, and $\Gamma = 2733$ rad/s [10] and the relative permittivity of the host is assumed to be $\varepsilon_{rh} = 6.5$. One can use Maxwell Garnett effective medium theory for driving the effective permittivity parallel to ($\varepsilon_\parallel$) and perpendicular to ($\varepsilon_\perp$) nano-strips [11]

$$\varepsilon_\parallel = f\,\varepsilon_m + (1-f)\varepsilon_h, \quad \varepsilon_\perp = \varepsilon_h \frac{(1+f)\varepsilon_m + (1-f)\varepsilon_h}{(1+f)\varepsilon_h + (1-f)\varepsilon_m} \tag{2}$$

where f is the filling factor of nano-strips in the host dielectric. Since the electric field is just in the z-direction and completely parallel to the nano-strips, we just focus on $\varepsilon_\parallel$. By using (2) for embedded silver strips in a dielectric host with $\varepsilon_{rh} = 6.5$, appropriate permittivity of the cloaking shell in wavelength of $\lambda = 645$ *nm* is obtained. The radius of the cloaked object is $r_{ob} = \lambda/8$ and according to these assumptions the values of w_m (width of silver strips) are calculated.

For example, this parameter is ~34 nm for 8 silver strips or 17 nm for 16 silver strips with thickness of $t_m = 15$ nm in the host medium. Fig. 1*c* shows the relative permittivity of this cloaking shell. For cloaking evaluation, the scattering width of the structure with and without cloaking shell is numerically calculated with full wave simulator [12]. The structure is exposed by a normal incident TM polarised lightwave. In this case, we consider 16 embedded strips of silver in the host medium for realising the cloaking shell. Fig. 2 shows the scattering width for $\phi = 90°$ and $\theta = 90°$. The scattering width for the cloaking structure is smaller than the uncloaked object and the dielectric cylinder with circle and flower-shaped cross-sections is optically invisible.

Homogeneity effect on cloaking efficiency: Using embedded nano-strips of silver in dielectric host provides inhomogeneous medium, inevitably. For enhancing the homogeneity in the shell medium, the number of silver strips can be increased by keeping the same filling factor (the ratio of metals volume to the dielectric host volume) for them. Fig. 3 presents numerically the calculated RCS of the uncloaked and cloaked objects with cloaking shells that contains 8–128 embedded nano-strips in the host medium. The filling factor is kept constant for all samples. By increasing the number of embedded nano-strips, the cloaking shell becomes more homogeneous and wavelength of cloaking approaches the design wavelength of $\lambda = 645$ nm. In this approach, size and periodicity of the metallic particles should be in sub-wavelength range. If these parameters are considered too large with respect to the operational wavelength, the desired value of the effective permittivity cannot be achieved in the designed wavelength and the wavelength will shift to the longer values. This shift for cloaking shells with 8–32 strips is very large, but for 32 and 128 strips the cloaking wavelength is similar. Then, it can be concluded that the cloaking shell with 32 strips is appropriately homogeneous. In the case with 32 strips the width of each strip is $w_m \approx \lambda/70$.

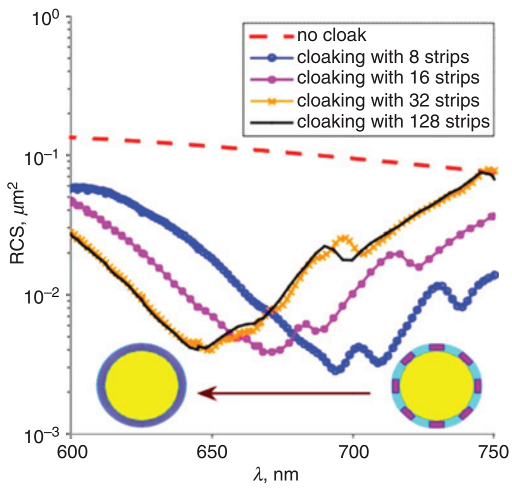

Fig. 3 *RCS of uncloaked and cloaked objects with different cloaking shells containing 8–128 embedded nano-strips*

If one considers nano-strips with higher widths, the cloaking spectrum is shifted to larger wavelength. The scattering width for uncloaked object and cloaking structures with 8, 16, and 32 silver strips in wavelength of $\lambda = 645$ nm are demonstrated in Figs. 4*a* and *b* for $\phi = 90°$ and $\theta = 90°$, respectively. It is clear that homogeneity plays effective role in scattering reduction and cloaking efficiency in desired wavelength.

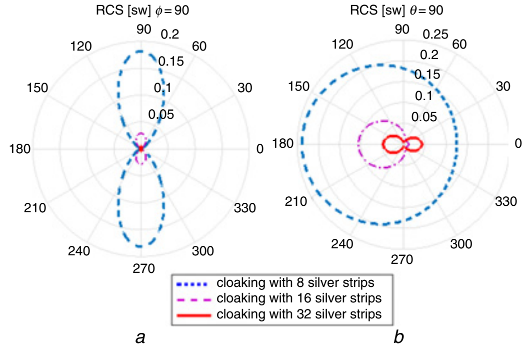

Fig. 4 *Scattering width (sw) for cloaking with 8, 16, and 32 silver strips for*
a $\phi = 90°$
b $\theta = 90°$ in wavelength of $\lambda = 645$ nm

Conclusion: In this Letter, realisation of cloaking shell based on scattering cancellation method for cylindrical structures in optical regime is presented. The cloaking shell around the object contains some embedded nano-strips of silver in a dielectric host around the cloaked object. This cloaking method does not have any limitations on the shape of cylinder cross-section and it works not only for common shapes, but also for arbitrary ones. Cloaking structure is applied for circle, and flower shape as an arbitrary example at the wavelength of $\lambda = 645$ nm. Additionally, the homogeneity effect on cylindrical cloaking in scattering cancellation method is studied. Accuracy of Maxwell Garnett effective medium theory completely depends on the size of particles and periodicity of them in the host medium. For evaluation of the homogeneity effect, RCSs of the cloaking structures with different numbers of silver nano-strips are numerically calculated and compared with the uncloak RCS. These results show that homogeneity has direct effect on the cloaking efficiency and inhomogeneity causes wavelength red shift in the cloaking spectrum.

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One or more of the Figures in this Letter are available in colour online.
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