A carpet cloak based on gradient metasurfaces

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Abstract. In this paper, we numerically demonstrate a carpet cloak operating in reflection with the incident wavelength of 800 nm. The carpet cloak comprises gradient metasurfaces with a metal-insulator-metal configuration. The gradient metasurfaces reroute the incident light and restore the reflected wavefront by compensating the phase differences between each unit cell of the metasurface. The proposed cloak is ultrathin, simple and easy for practical implementation.

1. Introduction

Metamaterials are artificial composites made up of micro-structures at the subwavelength scale [1]. Due to their amazing ability to manipulate electromagnetic waves, metamaterials exhibit novel promising applications [1], such as invisibility cloaks, negative index of refraction, superlenses, superabsorber, and so on. Among all the applications above, the invisibility cloaks, which can hide objects from the detection of incident electromagnetic waves, have received considerable attention in recent years [2]. The most popular approaches for invisibility cloaks based on metamaterials are transformation optics [3] and scattering cancellation [4]. However, inherent issues, such as anisotropy, inhomogeneity, and complex electromagnetic parameters of metamaterials, make the fabrication of the device rather complicated. On the other hand, based on the quasi-conformal mapping technique [5], the carpet cloak can relax the requirements of anisotropy and material properties. However, they are still bulky in size, and it is a great challenge to realize an ultrathin carpet cloak.

The development of metasurfaces [6] provides a novel method to manipulate the optical waves. They consist of subwavelength-sized elements in an optically thin layer, and can locally tailor the response of light at the nanoscale. Metasurfaces enable a series of unique phenomena and applications, such as the anomalous reflections/refractions [7], planar optical lenses [8], and high-resolution hograms [9]. An ultrathin directional carpet cloak was demonstrated in the microwave region based on metasurfaces [10]. As for the cloaking in the regions of the near-infrared and visible light, an ultrathin invisibility skin cloak was proposed to conceal a 3D arbitrarily shaped object by completely restroating the reflected wavefront at the incident wavelength of 730 nm [11]. However, since the metasurfaces for the skin cloak tightly wrapped over the object, point-to-point design and fabrication were necessary for this nanostructure, rendering the cloaking scheme unrealistic.

In this letter, we numerically demonstrate a reflective carpet cloak under the incident wavelength of 800 nm. The carpet cloak consists of gradient metasurfaces with a metal-insulator-metal (MIM) configuration. A super cell of the metasurfaces comprises 5 units with different sizes of the top gold rods. The gradient metasurfaces will compensate the phase differences between the adjacent unit cells, and the reflected wavefront can be effectively restructured for a specific polarization of the incident
beam. Two mirror symmetrical gradient metasurfaces provide a triangular space, which is suitable to conceal arbitrarily shaped objects underneath. Point-to-point design and fabrication are not needed according to our configuration. The proposed carpet cloak is ultrathin, simple, and more straightforward for practical implementation.

2. Simulation Results and Discussion

The fundamental unit cell of the MIM metasurface is plotted in Figure 1(a). It comprises a gold rod (the thickness is $t_1 = 30$ nm) and an optically thick gold substrate (the thickness is $t_3 = 150$ nm) separated by a SiO$_2$ layer with the thickness of $t_2 = 50$ nm. The length and the width of the gold rod are $L$ and $w$, and the subwavelength lateral dimensions of the unit cell are $L_x = 120$ nm and $L_y = 300$ nm, respectively. When a y-polarized incident beam (the vacuum wavelength is $\lambda = 800$ nm) normally illuminates the MIM metasurface, electric currents will be induced both in the gold rod and substrate. Since the gold rod and substrate are separated by a thin dielectric layer (the thickness of SiO$_2$ is only 50 nm), strong near-field coupling can be effectively excited. The induced antiparallel electric currents on the upper and lower gold layers lead to a magnetic resonance inside the intermediate dielectric layer at a particular frequency. Obviously, the magnetic resonance properties of the unit cell, such as the reflection amplitude and phase delay, can be efficiently tuned by the geometrical parameters of the nanostructures.

![Figure 1](image_url)

Figure 1. (a) The unit cell of MIM metasurface with $t_1 = 30$ nm, $t_2 = 50$ nm, $t_3 = 150$ nm, $L_x = 120$ nm, $L_y = 300$ nm, and $w = 90$ nm. The length $L$ of the upper gold rod varies. (b) The reflection amplitude ($r$) and phase ($\Phi$) versus the length $L$ of the upper gold rod. (c) Top view of the super cell of the gradient metasurface with $P_x = 5L_x = 600$ nm and $P_y = L_y = 300$ nm.

To verify the analysis above, the reflection characteristics of the unit cell are simulated by COMSOL Multiphysics. The width $w$ of the upper gold rods is fixed as 90 nm. The refractive index of the SiO$_2$ layer is set to be $n = 1.45$, and the permittivity of gold is taken from the experiment results [12]. The reflection amplitude ($r$) and phase ($\Phi$) as functions of the length $L$ of the upper gold rod are illustrated by the black and blue curves in Figure 1(b). The reflection amplitude maintains a relatively high stable value (> 0.8), and does not vary too much according to the length $L$. Due to the Ohmic loss and the resonant absorption of the gap surface plasmons (GSPs), the reflection amplitude cannot reach 1. The reflection phase can be adjusted to a certain value according to the length $L$. Based on the simulation above, five different lengths ($L = 20, 90, 110, 125$, and 250 nm, respectively) of the upper Au rods are carefully selected to form a super cell of the gradient metasurfaces, the top view of which
is plotted in Figure 1(c). The corresponding reflection phases provide a linear increase, as listed in Table 1. The gradient metasurfaces essentially support the anomalous reflection with high efficiency. The linear phase gradient can be written as

$$\Delta \phi = \frac{2\pi}{P_x} = \frac{2\pi}{m \cdot L_x}$$

(1)

where \(m = 5\) is the number of the unit cells in a super cell of gradient metasurfaces.

Table 1. The selected lengths and the corresponding reflection phases of the gradient metasurfaces.

| The number of unit cells | \(L\) (nm) | \(\Phi\) (°) |
|--------------------------|------------|-------------|
| 1                        | 20         | -72.5       |
| 2                        | 90         | -2.1        |
| 3                        | 110        | 70.4        |
| 4                        | 125        | 136.1       |
| 6                        | 250        | 206.2       |

The operation of the carpet cloak is illustrated in Figure 2. The gradient metasurface is laid on the ground plane with a tilt angle of \(\beta\). When the incident beam (the black solid arrows) normally illuminates the dielectric (SiO\(_2\)) and metallic (gold) layers without any metasurfaces (the upper gold rods), the reflected beam (the black dashed arrow) will be deflected towards an angle of \(2\beta\) away from the incident direction. By introducing the gradient metasurfaces above the SiO\(_2\) layer, the reflected beam can be steered back to the direction of the incident beam due to the anomalous reflection discussed above, as plotted by the red solid arrows.

The optical path difference \(\Delta h\) between the adjacent unit cells of metasurfaces is

$$\Delta h = L_x \cdot \sin \beta$$

(2)

And the phase difference \(\Delta \phi\) between the adjacent unit cells is

$$\Delta \phi' = 2k_0 \cdot \Delta h = 2 \cdot \left(\frac{2\pi}{\lambda_0}\right) \cdot L_x \cdot \sin \beta$$

(3)
where \( k_0 \) is the wave number in the free space, and \( L_x \) is the lateral distance between the adjacent unit cells along \( x \) axis. If the phase gradient provided by the metasurfaces can compensate the phase differences between the adjacent unit cells \( (\Delta \varphi = \Delta \varphi^*) \), the reflected wavefront can be effectively restructured as if it were reflected from the ground plane. The objects under the metasurfaces are concealed from the outside detection. Combining the equation (1) and equation (3), the tilt angle \( \beta \) of the carpet cloak is

\[
\sin \beta = \frac{\lambda_0}{2 \cdot P_x}
\]  

(4)

According to the geometrical and optical parameters of the MIM gradient metasurfaces above, the tilt angle \( \beta \) of the carpet cloak can be calculated as 46.5\(^\circ\).

Based on the analysis and the design above, the cloaking characteristics of the gradient metasurfaces are simulated as well. The metasurface is horizontally laid, and the \( y \)-polarized incident beam \( (\lambda = 800 \text{ nm}) \) illuminates the metasurfaces with an incident angle of 46.5\(^\circ\), corresponding to the tilt angle \( \beta = 46.5^\circ \) of the carpet cloak, as plotted in Figure 3(a). Periodic boundary conditions are set to simulate the infinite carpet cloak and the plane wave excitation. As we can see from Figure 3(b), the wavefronts of the reflected \( E_y \) far field from the gradient metasurface are nearly parallel to the incident wavefronts in Figure 3(a), which means the reflected wavefronts are effectively restructured. The white solid arrows in Figure 3(a) and (b) illustrate the directions of the wave vectors of the incident and reflected light. Arbitrarily shaped objects can be hidden under the triangular space formed by two mirror symmetrical gradient metasurfaces. The overall thickness of the metasurface \( (t_{\text{total}} = 230 \text{ nm}) \) is only a quarter of the operating wavelength \( (\lambda = 800 \text{ nm}) \), leading to an ultrathin cloaking device. The quality of the reflected plane wave is deteriorated by the fluctuation of the reflection amplitude \( r \) within a super cell due to the Ohmic loss and the resonant absorption of the gap surface plasmons. To improve the efficiency of the wavefront restructuration, dielectric metasurfaces [13] will be good candidates. Additionally, the polarization dependence of the device can be overcome by implementing a circularly symmetric cross section of unit cells [8].

![Figure 3](image)

**Figure 3.** The simulated cloaking characteristics of the gradient metasurfaces. (a) The incident and (b) the reflected \( E_y \) far field patterns of the gradient metasurfaces.

3. Conclusion
In this paper, we have reported an ultrathin carpet cloak based on the gradient MIM metasurfaces. The gradient metasurfaces compensated the phase differences between the adjacent unit cells, and the reflected wavefronts were nearly reconstructed to be plane waves. Arbitrarily shaped objects could be hidden under the carpet cloak. The proposed carpet cloak is ultrathin, simple and easy for practical implementation.
4. References
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