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Enhancement of backscattering by a conducting cylinder coated with gradient metasurface

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This paper proposes a highly effective method for enhancing the backscattering by a conducting cylinder that is coated with a gradient metasurface. The employed metasurface exhibits a phase gradient continuously varying along the circumferential direction of the cylinder so that in-phase retroreflection can be produced to enhance the backscattering. It is demonstrated that the cylinder coated with the proposed gradient metasurface can generate backscattering very close to that from a conducting plate with the same dimensions as the cylinder's cross-section perpendicular to the incident plane wave. Compared with a bare conducting cylinder, the backscattering is significantly enhanced by the gradient metasurface made of conducting strips printed on a grounded dielectric substrate. Effects of cell numbers along the cylinder axis, incident angle, and polarization of the incoming electromagnetic wave on the backscattering enhancement are examined and discussed. A good agreement between simulated and measured backscattering results validates the observations.

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I. INTRODUCTION

The main body of many radar targets usually consists of cylindrical structures, such as aircraft, missiles, and drones. The electromagnetic scattering by conducting cylinders has therefore been treated as a canonical problem and received extensive attention over the years.¹ With regard to the control of backscattering by conducting cylinders, impedance loading² and coating wrapped around cylinders were extensively reported in the past so as to obtain backscattering reduction for stealth applications. Examples of those coatings are dielectric and absorbing layers,³ periodic strip grating,⁴ and electromagnetic cloak.⁵ However, enhancement of backscattering from conducting cylinders has attracted limited interest, though the wide utilization of radar nowadays stimulates practical applications of backscattering enhancement, especially for airborne targets.⁶

Methods reported for backscattering enhancement mainly include the shaping of target surface, lumped or distributed impedance loading, and the integration of pre-engineered enhancement device to the target.^{6–9} The enhancement devices are reflector, dielectric lens, photonic jet, as well as active enhancer. Traditionally, reflectors use the principle of multiple reflections for backscattering enhancement, such as dihedral or trihedral corner reflectors, top-hat, brotherhedral, biconical, and spherical reflectors.^{6,9–12} The reflectarray,^{13–16} retrodirective passive array,¹⁷ and transformation medium^{18–20} were also used to design corner or flat reflectors. Arrays with the configuration of cross-dipole or Yagi-Uda elements were also studied for backscattering enhancement.^{21–23} Due to the functions of focusing and collimation, dielectric lens can be used as the retroreflector. Examples are Luneburg lens or homogeneous

dielectric sphere with a metallic cap around their focal point,^{24–26} ground-backed hemispherical Luneburg lens,²⁷ and metamaterial lens.²⁸ Furthermore, the photonic jet was recently reported to enhance the backscattering from particles and metallic wires by focusing a beam with high intensity.^{29–31} Reported active enhancement designs involve the change of induced current on target surface or amplification of the received signal, such as monopole or strip dipole loaded with active diodes,^{32,33} self-structuring scatterer loaded with switches,^{34,35} active corner reflector and transponder-type enhancer containing antennas and amplifiers,^{36–38} planar Luneburg lens and retrodirective active array loaded with amplifier.^{39–41} Generally speaking, the active method has the advantage of flexible control of enhancement over the passive method, while it suffers from the substantial increase in system complexity and cost. Because of aerodynamic drag, applications of shaping, traditional corner reflector, dielectric lens, and photonic jet in airborne platforms are limited. The difficulty in identifying suitable loading points for complex targets complicates the impedance loading towards airborne applications. Therefore, the design of passive enhancement devices suitable for being integrated with airborne targets is of practical importance.

Recently, metasurfaces were reported to control the wave transmission^{42,43} and reflection,^{44–46} such as the flat metasurface with parabolic reflection phase profile and the holographic metasurfaces with various phase distributions.^{47–51} In this paper, a conformal gradient metasurface is proposed and employed to enhance the backscattering by a conducting cylinder. In order to effectively redirect the reflection by the conducting cylinder towards back the direction where the incident wave is coming, the phase gradient of the metasurface is continuously varying along the cylinder's circumferential direction, which differs from a planar metasurface^{16,44} where

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the phase gradient is a constant. The varying phase gradient is implemented by an array of conducting strips printed on a grounded dielectric substrate. Through simulations and measurements, it is seen that the conducting cylinder coated with the designed gradient metasurface can exhibit a strong backscattering close to that from a corresponding flat conducting plate. Section II describes the cylindrical geometry considered for backscattering enhancement and the design of the coating metasurface. Numerical examples are shown in Section III. Section IV provides the experiment verification. Section V summarizes the work reported in this paper.

II. BACKSCATTERING ENHANCEMENT PRINCIPLE USING CONFORMAL METASURFACE

The cylindrical geometry considered for backscattering enhancement is depicted in Fig. 1, where the cylinder axis lies in the z -axis and the conducting cylinder is illuminated by a plane electromagnetic wave of E -polarization. Aspect angle φ characterizes the direction of the incoming plane wave, while angle α denotes the central angle and r represents the radius of the cylinder.

It is well known that the specular reflection by a flat conducting plate can contribute a large backscattering when viewed normal to the plate surface, whereas the singly curved surface of a cylinder disperses the reflection direction, which leads to a reduced backscattering. For the sake of the backscattering enhancement through redirecting the scattering by the conducting cylinder, the reflection property of a gradient metasurface governed by the generalized law of reflection⁴² is used. The design of the metasurface begins with the determination of the incident angle at a specific location. It is noted that only half of the cylindrical surface can be directly illuminated by an incident wave. The central angle α corresponding to that semi-cylindrical surface ranges from $(\varphi - 90^\circ)$ to $(\varphi + 90^\circ)$, which is the coverage of the metasurface. Thus, the incident angle of each point on that semi-cylindrical surface can be determined as $|\alpha - \varphi|$. Due to the curvature, it is understood that the incident angle changes for different locations along the cylindrical surface. In order to redirect the reflection by the conducting cylinder

back to the direction where the incident wave is coming from, the desired angle of reflection is equal to the negative angle of the incidence $|\alpha - \varphi|$. Therefore, by inserting the angles of incidence and reflection into the generalized law of reflection, the phase gradient of the cylindrical metasurface devoted to backscattering enhancement is expressed as

$$\frac{d\Phi}{d\alpha} = 2k_0(r+h)\sin(|\alpha - \varphi|), \quad (1)$$

where k_0 is the free-space wavenumber and h is the thickness of the dielectric substrate supporting the metasurface. For a specific φ , the range of the central angle α can be halved as $\varphi \leq \alpha \leq (\varphi + 90^\circ)$, due to the symmetry between $(\varphi - 90^\circ) \leq \alpha \leq \varphi$ and $\varphi \leq \alpha \leq (\varphi + 90^\circ)$.

III. NUMERICAL ANALYSIS

As a numerical example, the phase gradient of the cylindrical metasurface is calculated for $\varphi = 0^\circ$, $h = 0.508$ mm, and a conducting cylinder with radius $r = 68$ mm that is around $2.22 \lambda_0$, where λ_0 is the free-space wavelength at 9.8 GHz. Under the current situation, the calculated range of α is halved as $0^\circ \leq \alpha \leq 90^\circ$. Moreover, the incident angle at each point on that cylindrical surface is exactly same as the corresponding central angle. The calculated phase gradient varying as the central angle α is shown in Fig. 2. Because of the sine function, it is seen that the phase variation gradually becomes steep as the incident angle increases.

In order to map the calculated phase gradient onto the cylinder, an array made up of metallic strips^{16,44} supported by the substrate of thickness $h = 0.508$ mm is used to construct the metasurface. However, different from those reported doubly periodic arrays, one unit cell in this design contains only one strip element and the dimension of the n -th element of the array is determined according to the variation of reflection phase between adjacent cells

$$\Phi_n - \Phi_{n-1} = 2k_0(r+h)\delta \sin(|\alpha_n - \varphi|), \quad (2)$$

where δ is the angular interval between adjacent cells and α_n is the incident angle at the n -th element. The separated elements used in the physical array indicate a discretization of the phase gradient and incident angle. Thus, the angular interval should be properly chosen so as to achieve a fine

FIG. 1. A conducting cylinder illuminated by a plane wave at an aspect angle φ .

FIG. 2. Calculated phase gradient for a cylinder with radius $r = 68$ mm.

approximation of the phase gradient. With $\delta = 1.25^\circ$, Fig. 3 illustrates the reflection phase distribution along the circumferential direction of the cylinder for a sampled central angle $\alpha_n = \delta n$, $n = 1, 2, \dots, N$, $N = 90^\circ/\delta$. The initial phase is $\Phi_0 = 0^\circ$ at $\alpha = 0^\circ$, although other values can also be selected.

According to the chosen angular interval, the period of each unit cell along the circumferential direction of the cylinder is determined as $p_c = 1.5$ mm. It is noted that the difference between p_c and the chord length corresponding to δ is negligibly small. Thus, the planar counterpart of the unit cell of metallic strip can be simulated using periodic boundaries in Computer Simulation Technology (CST) for an incident angle α_n to obtain the reflection phase in Fig. 3. The strip is printed on a grounded substrate with relative permittivity of 2.2 and dielectric loss tangent of 0.0009. Figure 4 shows the geometry of a unit cell with $p_z = 15$ mm and $w = 0.5$ mm. Its reflection phase is also shown in Fig. 4 as an example when the incident angle is $\alpha_1 = 1.25^\circ$. It is seen that the reflection phase can be arbitrarily modified within the range of $\pm 180^\circ$ by changing the length l of the strip, while other parameters remain unchanged. Finally, the array of strips with different lengths can be used for implementing the phase gradient along the circumferential direction of the cylinder.

Through simulations of the reflection phase from the metallic strip printed on a grounded substrate for each angle of α_n , the length of each strip distributed along the circumferential direction of the cylinder is then determined, in combination with the calculated reflection phase distribution. The cylinder coated with the designed conformal metasurface with six cells along its axis is shown in Fig. 5(a). The plane wave of E -polarization originates from the incident angle of ($\varphi = 0^\circ$, $\theta = 90^\circ$) and propagates along the negative x -axis. Its electric field amplitude is $E_0 = 1$ V/m. Dimensions of strips in the first and second quadrants are symmetric with respect to the x -axis. The strips of one cell of the cylindrical metasurface in the first quadrant are shown in a planar arrangement so that the geometry can be clearly seen in Fig. 5(b).

In order to examine the effect of the number of unit cells along the cylinder axis on the backscattering enhancement, simulated results of the backscattering by a cylinder coated with one cell and three cells are shown in Figs. 6(a) and 6(b), respectively, while Fig. 6(c) shows the backscattering from the structure in Fig. 5(a). Meanwhile, backscattering by the

FIG. 3. Calculated reflection phase distribution with initial phase $\Phi_0 = 0^\circ$ for a cylinder with radius $r = 68$ mm and angular interval $\delta = 1.25^\circ$.

FIG. 4. Simulated reflection phase varying as the metallic strip length l under the oblique incidence of 1.25° at 9.8 GHz.

corresponding conducting cylinder without any coating and by a conducting plate with the same dimensions as the cross-section of the corresponding cylinder are also shown in Fig. 6 for comparison.

The backscattering values as well as calculated enhancement efficiencies at 9.8 GHz are summarized in Table I. The

FIG. 5. (a) The conducting cylinder coated by a conformal metasurface with six cells along its axis. (b) Planar geometry of the strips of one cell in the first quadrant, from left to right, the length of each strip is $l_1 = 9.93$, $l_2 = 9.925$, $l_3 = 9.92$, $l_4 = 9.92$, $l_5 = 9.91$, $l_6 = 9.91$, $l_7 = 9.9$, $l_8 = 9.88$, $l_9 = 9.86$, $l_{10} = 9.86$, $l_{11} = 9.82$, $l_{12} = 9.8$, $l_{13} = 9.77$, $l_{14} = 9.76$, $l_{15} = 9.72$, $l_{16} = 9.67$, $l_{17} = 9.61$, $l_{18} = 9.47$, $l_{19} = 9.36$, $l_{20} = 8.99$, $l_{21} = 7.85$, $l_{22} = 1$, $l_{23} = 11.2$, $l_{24} = 10.6$, $l_{25} = 10.36$, $l_{26} = 10.21$, $l_{27} = 10.15$, $l_{28} = 10.08$, $l_{29} = 10.02$, $l_{30} = 9.97$, $l_{31} = 9.94$, $l_{32} = 9.91$, $l_{33} = 9.86$, $l_{34} = 9.81$, $l_{35} = 9.76$, $l_{36} = 9.68$, $l_{37} = 9.5$, $l_{38} = 8.57$, $l_{39} = 11.85$, $l_{40} = 10.4$, $l_{41} = 10.18$, $l_{42} = 10.03$, $l_{43} = 10.02$, $l_{44} = 9.98$, $l_{45} = 9.94$, $l_{46} = 9.88$, $l_{47} = 9.85$, $l_{48} = 9.79$, $l_{49} = 9.74$, $l_{50} = 9.4$, $l_{51} = 14.75$, $l_{52} = 10.3$, $l_{53} = 10.03$, $l_{54} = 10.01$, $l_{55} = 10$, $l_{56} = 9.96$, $l_{57} = 9.92$, $l_{58} = 9.92$, $l_{59} = 9.89$, $l_{60} = 9.81$, $l_{61} = 9.55$, $l_{62} = 10.45$, $l_{63} = 10.06$, $l_{64} = 10.02$, $l_{65} = 9.95$, $l_{66} = 9.87$, $l_{67} = 9.82$, $l_{68} = 9.86$, $l_{69} = 9.77$, $l_{70} = 9.81$, $l_{71} = 9.21$, and $l_{72} = 9.35$; unit is mm.

FIG. 6. Backscattering by the cylinder coated with (a) one cell, (b) three cells, and (c) six cells along its axis. Cylinder in each plot has a same radius $r = 68$ mm. Height of each cylinder h_c is (a) 15 mm, (b) 45 mm, and (c) 90 mm. Accordingly, dimensions of each conducting plate are $2r \times h_c$ and the main plane of the plate is normal to the incoming wave.

enhancement efficiency, which is defined by the ratio of the backscattering by the gradient metasurface-coated cylinder to the backscattering by the conducting plate with its main plane perpendicular to the incoming wave, serves as a measure of the efficiency with which the gradient metasurface redirects the reflection back to the direction of incoming wave. It is seen that the backscattering by the gradient metasurface-coated cylinder gradually approaches to that by the conducting plate as multiple periods are duplicated along the cylinder axis. For the cylinder coated with six cells, its backscattering is only 0.15 dB less than the conducting plate with the same dimensions as the cross-section of the cylinder, which results in an enhancement efficiency of 96.6%. Compared with the cylinder without coating, the backscattering is significantly enhanced by 12.7 dB. Although the cylinder coated with only one cell along its axis shows an obvious enhancement of the backscattering, it is concluded that multiple cells are needed to exhibit a high efficiency due to the periodic nature of the used metasurface. It may be mentioned that similar enhancement can also occur for cylinders with other radii by properly designing the required gradient metasurface.

IV. DISCUSSION AND EXPERIMENTAL VERIFICATION

In order to gain further insight into the backscattering enhancement of conducting cylinders through the use of a

conformal gradient metasurface and estimate its practicability, bistatic and angular responses are discussed on the basis of the cylinder coated with three cells along its axis since it also generates a relatively high efficiency.

A. Bistatic scattering

For the sake of better understanding the operating principle, bistatic scattering patterns of the cylinder coated with three cells along its axis at 9.8 GHz are examined in Fig. 7 and compared with the same cylinder without any coating. The incident angle of plane wave excitation remains the same as ($\varphi = 0^\circ$, $\theta = 90^\circ$) in Fig. 5(a). Figure 7(a) shows the scattered field distribution in the xy-plane. As a result of the gradient metasurface of symmetric configuration with respect to the x-axis, it is seen that the scattered field of the cylinder are symmetrically suppressed. The resultant scattering lobe pointing at the positive x-axis makes the coated cylinder resemble a flat conducting plate normal to the incident wave. The field distribution in the xz-plane has little alteration except the lobe around the backscattering direction, as seen in Fig. 7(b). These observations of bistatic scattering indicate that the dispersed reflection by the conducting cylinder is effectively redirected back to the incident direction by the gradient metasurface coating, which leads to a significant backscattering enhancement.

B. Angular response of backscattering

With the frequency fixed as 9.8 GHz, Figs. 8(a) and 8(b) present the backscattering for different incident angles in the xy- and xz-planes, respectively. The variation range of incident angles is in the vicinity of the operating angle of incidence ($\varphi = 0^\circ$, $\theta = 90^\circ$). It is seen from Fig. 8(a) that the enhancement occurs from $\varphi = 0^\circ$ to 5° in the plane perpendicular to the cylinder axis. When φ further increases, the

TABLE I. Comparison of simulated backscattering and efficiency results for different cell numbers along the cylinder axis at 9.8 GHz.

	One cell	Three cells	Six cells
Plate (dBsm)	-9.78	-2.41	3.13
Cylinder (dBsm)	-26.61	-15.59	-9.73
Metasurface (dBsm)	-11.06	-2.8	2.98
Efficiency (%)	74.4	91.3	96.6

FIG. 7. Bistatic scattering patterns of the cylinder coated with three cells along its axis in (a) xy- and (b) xz-planes at 9.8 GHz.

coverage and phase gradient of the metasurface coating deteriorate the enhancement. For incident angles in the xz-plane, the enhancement is obtained at least from $\theta = 60^\circ$ to 90° . Thus, the backscattering by the conducting cylinder at 9.8 GHz can be enhanced within the angular ranges of up to $\pm 5^\circ$ in the xy-plane and at least $\pm 30^\circ$ in the xz-plane, due to its configuration symmetry.

C. Rotated E-field vector

In practical environments, the plane wave arriving at the gradient metasurface-coated cylinder may have an electric field vector not exactly parallel to the cylinder axis. Therefore, a certain angle β less than 90° may be formed between the rotated electric field vector and the cylinder axis, as shown in Fig. 5. The effect of different β on the backscattering is studied with the incident angle fixed as ($\varphi = 0^\circ$, $\theta = 90^\circ$); thus, the results shown in Fig. 6(b) are with $\beta = 0^\circ$. The backscattering components σ_θ and σ_φ when $\beta = 30^\circ$ and 60° are shown in Fig. 9.

According to the vector decomposition of the incident electric field, θ -component of the incident electric field vector in such a case is reduced from initially $E_0 = 1$ V/m to $E_\theta = E_0 \cos \beta$ V/m and φ -component is increased from zero to $E_\varphi = E_0 \sin \beta$ V/m. Thus, it is seen from Figs. 9(a) and 9(c) that the backscattering σ_θ by the plate, cylinder, and coated cylinder gradually decreases as β increases, while the backscattering σ_φ in Figs. 9(b) and 9(d) gradually increases. The simulated backscattering data at 9.8 GHz are summarized in Table II. It is concluded that the backscattering $\sigma_{\theta,\varphi}(\beta')$ after a rotation of the electric field vector to angle β' is related with $\sigma_{\theta,\varphi}(\beta)$ at angle β by

$$\sigma_{\theta,\varphi}(\beta') \text{ (dBsm)} = \sigma_{\theta,\varphi}(\beta) \text{ (dBsm)} + \Delta\sigma_{\theta,\varphi} \text{ (dB)}, \quad (3)$$

FIG. 8. Backscattering by the cylinder coated with three cells along its axis for incident angles in (a) xy- and (b) xz-planes at 9.8 GHz.

$$\begin{cases} \Delta\sigma_\theta = 20 \lg \left| \frac{E'_\theta}{E_\theta} \right| = 20 \lg \left| \frac{\cos \beta'}{\cos \beta} \right| \\ \Delta\sigma_\varphi = 20 \lg \left| \frac{E'_\varphi}{E_\varphi} \right| = 20 \lg \left| \frac{\sin \beta'}{\sin \beta} \right|, \end{cases} \quad (4)$$

where $0^\circ \leq (\beta' \text{ and } \beta) < 90^\circ$ for σ_θ , $0^\circ < (\beta' \text{ and } \beta) \leq 90^\circ$ for σ_φ .

Since the designed metasurface is singly polarized, E_φ component of the incident electric field vector is hardly responded by the metasurface. Thus, the backscattering results σ_φ by the bare cylinder and the cylinder coated with a gradient metasurface are similar and they are much smaller than that by the equivalent conducting plate. Although σ_θ decreases as an increased β , the backscattering result σ_θ by the gradient metasurface-coated cylinder is still comparable with that by the conducting plate. Moreover, the enhancement of σ_θ relative to the cylinder without coating and the enhancement efficiency are maintained around 12.7 dB and 91.3%, respectively.

D. Experimental verification

In order to verify the simulations, a conducting cylinder coated with three cells along its axis is fabricated and measured. The used material for the conducting cylinder is aluminum. A photo of this prototype is provided in Fig. 10. Through the use of two horn antennas connected to a vector network analyzer, the quasi-monostatic radar cross section measurement in an anechoic chamber is conducted to retrieve the backscattering. The test prototype and calibration plate are in the far-field of the antennas. Comparison of the simulated and measured backscattering results is shown in Fig. 11, where the backscattering results of the cylinder without coating and an aluminum plate of the same size as

FIG. 9. Backscattering by the cylinder coated with three cells along its axis for rotated electric field vector. (a) σ_θ and (b) σ_ϕ for $\beta = 30^\circ$. (c) σ_θ and (d) σ_ϕ for $\beta = 60^\circ$.

TABLE II. Comparison of simulated backscattering and efficiency results for different rotation angles of E-field vector at 9.8 GHz.

Angle β	σ_θ (dBsm)			σ_ϕ (dBsm)		
	0°	30°	60°	0°	30°	60°
Plate	-2.41	-3.62	-8.39	/	-9.05	-4.02
Cylinder	-15.59	-17.05	-21.83	/	-21.48	-16.9
Metasurface	-2.8	-4.02	-8.79	/	-21.39	-16.62
Efficiency	91.3%			/		

its cross section are also compared. A frequency shift is observed between the simulated and measured backscattering results by the cylinder. Similarly, the backscattering peak of the gradient metasurface-coated cylinder is shifted from simulated 9.8 GHz to measured 9.59 GHz. The

frequency shift is attributed to the dimension tolerances in the fabrication process. However, it is noted that these curves are generally comparable between simulations and measurements. At 9.59 GHz, the backscattering by the equivalent plate, cylinder, and cylinder coated with a gradient metasurface are -2.62 dBsm, -15.28 dBsm, and -3.11 dBsm, respectively. Compared with the cylinder without any coating, the backscattering is then enhanced by 12.17 dB through the gradient metasurface coating. Furthermore, an enhancement efficiency of 89.3% is achieved relative to the plate. Moreover, when the electric field vector of the incident wave is rotated by manually tilting the transmitting horn antenna, the backscattering is measured and also presented in Fig. 9 for $\beta = 30^\circ$ and 60° . Although the tolerances concerning rotation angle β and collimation exist during the experiment, similar behavior of the backscattering is observed through the measurements.

FIG. 10. Photo of the prototype with cylinder height $h_c = 45$ mm and three cells attached along the cylinder axis.

FIG. 11. Simulated and measured backscattering by the prototype under the incident angle of ($\phi = 0^\circ$, $\theta = 90^\circ$). Dimensions of the aluminum plate are $2r \times h_c = 136$ mm $\times$ 45 mm.

V. CONCLUSION

A cylindrical metasurface with its phase gradient varying along the circumferential direction has been presented to enhance the backscattering by conducting cylinders. The backscattering by the conducting cylinder coated with a gradient metasurface can closely approach to that by a conducting plate with the same dimensions as the cylinder's cross-section perpendicular to incident plane wave. In comparison with the cylinder without coating, efficient enhancement of backscattering has been achieved by the proposed gradient metasurface. The low profile characteristic of the gradient metasurface can facilitate its conformal applications to airborne targets.

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