Planar microwave retroreflector based on transmissive gradient index metasurface

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Keywords: planar retroreflector, transmissive metasurface, radar cross section, backscattering enhancement, wide-angle view

Abstract

In this paper, a novel planar microwave retroreflector based on a transmissive gradient metasurface combined with a curved metal mirror is proposed and demonstrated. The transmissive metasurface can efficiently converge a wide-angle incident wave to a pre-designed curved metal mirror behind it with a proper distance, which acts as an effective reflective surface that can greatly enhance the backscattering of the incident wave with a wide-angle view. According to the full-wave simulations, the proposed metasurface retroreflector can perform an excellent retroreflective effect for incident microwaves of angle view between \(-30^\circ\) and \(30^\circ\) range. A prototype was fabricated and the experimental results verify that the metasurface retroreflector can realize the monostatic radar cross section (RCS) enhancement with a continuous wide incident angle view from \(-30^\circ\) to \(30^\circ\) at 10 GHz within a stable 3 dB RCS level. It is further demonstrated that the excellent wide-angle backscattering performance (absolute RCS enhancement value, operational bandwidth and/or incident angle view) of the proposed microwave metasurface retroreflector is competitive against the traditional trihedral corner reflector with comparable dimensions, thus opening up new possibilities to substitute the traditional bulky radar retroreflector by using a planar compact metasurface structure for microwave engineering. The presented microwave metasurface retroreflector is promising to develop into a low-profile, light weight and planar radar retroreflector which possesses tremendous RCS backscattering enhancement and wide-angle view operation range.

1. Introductions

The retroreflector is a kind of device which can reflect most of the incident waves upon it to their original direction within a wide-angle view. Traditional passive retroreflectors which are commonly used in microwave and optical engineering includes corner reflectors \([1]\), Luneburg lens reflectors \([2, 3]\) and cat’s eye retroreflector \([4, 5]\). These devices are commercially available and play a significant role for a variety of civil and military applications such as target tracking, radar calibration, deception and many others. Conventional microwave retroreflectors can greatly enhance the radar cross section (RCS) within a continuous wide-angle view range but usually occupy a large space and are thus very bulky, which limits their further applications in some compact platforms like aircraft, missiles and so on. For example, trihedral corner reflector, a widely used microwave retroreflective device consists of three perpendicular intersecting metal surfaces, can realize radar backscattering enhancement in the almost whole \(\pm 20^\circ\) angle view range within 3 dB RCS level.

Recently, planar retroreflective devices to realize backscattering enhancement have received much attention in the community \([6–19]\). For an active retroreflector such as Van Atta patch antenna arrays \([10]\), it can also be compact with a planar low-profile structure and can work well for a relative wide-angle incident wave within 3 dB RCS level. However, it also suffers from complex connections between array elements thus increasing the device cost. Reported passive planar backscattering enhancement techniques
are mostly based on the flat and ultra-thin gradient metasurface structure. Metasurface is a two-dimensional version of metamaterials, and provides an excellent and versatile tool to control incident wave arbitrarily [20]. Based on the abrupt phase shift associated with reflective and/or transmission magnitude control within sub-wavelength scale, an engineered metasurface can bring out many novel phenomena such as anomalous refraction and reflection, polarization switching and splitting [21, 22]. Besides, the ultrathin and flat low-profile designed metasurface is promising to develop into some novel compact devices such as achromatic metalens, meta-coupler and holograms [23, 24], etc. Up to now, retroreflective metasurface based on the designed phase gradient profile at a specific oblique incident direction for backscattering enhancement has been demonstrated in microwave band [11, 14–16]. The operation angle view of these backscattering enhancement metasurfaces within a stable retroreflective power level is very narrow, which is intrinsically limited by the specific phase response of the considered retroreflective angle according to generalized Snell’s law [16]. Multi-channel retroreflectors based on the multiple phase gradient metasurfaces are also reported in [12, 15] which can increase the retroreflective angle. However, the backscattering enhancement effect between the discrete retroreflect channel cannot be guaranteed, thus it is not desirable for practical engineering. By cascading a transmissive gradient metasurface and a reflective surface, the wide-angle planar retroreflector can be realized which has been demonstrated in optical [18] and acoustic [19] band. For microwave engineering, it is very important and urgent to develop this new type of planar metasurface retroreflector which is not yet demonstrated. Besides, the accurate backscattering enhancement performance comparison with conventional microwave retroreflector (e.g. corner reflector) can pave the way for the practical applications of the considered planar metasurface retroreflector.

In this paper, a microwave planar retroreflector based on transmissive gradient metasurface combined with a curved metal mirror is designed, fabricated and tested. The ultrathin transmissive metasurface with gradient meta-atoms can efficiently focus wide-angle incident wave to a pre-designed curved trajectory. By placing a metal mirror on this focused curved plane, the cascaded structure can greatly enhance the wide-angle backscattering of incident wave. Simulation and experimental results demonstrate that the proposed planar microwave retroreflector can enhance the backscattering within 3 dB RCS level at 10 GHz for the incident angles from $-30^\circ$ to $30^\circ$. Compared with traditional trihedral corner reflector with comparable dimensions, the wide-angle backscattering performance of a metasurface retroreflector can be superior in view of wide-angle range, and is thus promising for practical engineering applications based on the presented planar microwave retroreflector.

2. Theory and principles

The schematic diagrams of the proposed microwave metasurface retroreflector are illustrated in figure 1. The transmissive gradient metasurface is designed for wide-angle incident wave focusing with high efficiency. Based on the special phase response of metasurface structure with wide-angle view, the transmissive focused spot locations with normal and different oblique incident wave of $\theta_i$ can be moved continuously along a curved plane. By placing a curved metal mirror which coincides with this focused plane exactly, the wide-angle focused spots can then be reflected back to their original directions efficiently. Thus, the whole structure behaves as an effective planar retroreflector with wide-angle operation range. The ultra-thin metasurface structure (the thickness is only 0.08$\lambda$, $\lambda$ is the operation wavelength) can be easily assembled with the curved metal mirror, thus the proposed microwave metasurface retroreflector can be conformal, lightweight and ultra-compact. Besides, the thickness of the proposed planar microwave retroreflector is determined by the maximum length between metasurface and metal mirror as indicated by $F$ which can be tuned freely according to specific design.

3. Simulation and experimental results

Based on the proposed wide-angle backscattering enhancement mechanism for the planar microwave retroreflector, the transmissive gradient metasurface and its unit cell performance are studied numerically first. Based on the special response of gradient structure with a wide angle view, the focused spots locations which is related with the considered incident angle range can be established and obtained, thus the metal mirror is then designed accordingly. By cascading the designed metasurface structure and metal mirror, the simulated and experimental results of the proposed microwave retroreflector are presented, respectively.
Figure 1. Schematic diagrams of the proposed planar microwave retroreflector based on a transmissive metasurface. The metasurface lens converges the wide-angle incident wave to a pre-designed curved metal mirror on a proper distance behind it as indicated by $F$, which serves as an effective reflective surface to enhance wide-angle backscattering. The incident angle is marked by $\theta_i$. The thickness of the whole device is $F$.

Figure 2. (a) The diagrams of the designed transmissive metasurface lens arrays for wide-angle incident wave focusing. The double layer gradient arrays are used for high-efficiency transmission and large phase shift. (b) The unit cell of the metasurface lens and its structural parameters. (c) and (d) are the simulated transmission magnitude and phase shift along frequency with various radius of $r$, respectively. The polarization of microwave is along $x$ with normal incident.

3.1. Transmissive metasurface and its unit cell performance

Considering our proposed microwave retroreflector is different from some recent demonstrations which are based on reflective phase gradient metasurface [11, 14–16], the design of transmissive gradient metasurface is crucial to the wide-angle backscattering enhancement performance of the proposed microwave retroreflector here. The transmission efficiency of gradient meta-atoms should be very high simultaneously with a relatively huge phase shift for the elements. Here, double layer transmissive metasurface arrays with gradient perforated double symmetric split ring elements on the metal plate are designed and the simulated transmission performance is given in figure 2. The metalens is arranged with $15 \times 15$ elements (the size is $17.25 \times 17.25$ cm$^2$) on the plane as shown in figure 2(a). The gradient meta-atoms as indicated by dotted square block are constructed by varying its split ring radius on the different locations. The structural
Figure 3. (a) and (b) are the simulated transmission magnitude and phase shift along frequency for the oblique incident wave of 10°, 20° and 30°, respectively. The radius of unit cell is \( r = 1.0 \) mm and the others are the same as figure 2.

parameters of element are shown by inner groove width \( w_1 \), outer groove width \( w_2 \), gap size \( g \), period \( p \), split angle \( \alpha \) and radius \( r \) in figure 2(b). These parameters are optimized for high transmission magnitude at around 10 GHz to ensure good backscattering enhancement of retroreflector. To design a wide-angle metalens here, the varied radius of element with large phase shift is set from 0.6 mm to 1.6 mm with other parameters of \( w_1 = w_2 = 1 \) mm, \( g = 1.5 \) mm, \( \alpha = 150^\circ \) and \( p = 11.5 \) mm. Simulated results of figures 2(c) and (d) demonstrate that the transmission magnitude can be over 80% in the whole varied range of \( r \) both with large phase shift about 300°. According to the generalized Snell’s law [20, 25], the parabolic phase profile of \( \varphi(x, y) \) on the \( x-y \) plane of figure 2(a) dependent on different location for the metalens can be obtained, i.e.:

\[
\varphi(x, y) = \varphi_0 + \frac{2\pi}{\lambda}(F - \sqrt{x^2 + y^2 + F^2}) + 2\pi n
\]

where \( \varphi_0 \) is the phase on the center of metasurface, \( \lambda \) is wavelength, \( F \) is the focal length which is given around 80 mm, \( n \) is arbitrary integer.

In order to design a wide-angle focused lens which can obey the expression (1) even with large oblique incidence, the transmission performance of the gradient unit cells should keep well with that of the normal incidence. That is to say, the transmission magnitude should still be high and the phase shift on different location in figure 2(a) is almost the same as that of the normal incident case as predicted by expression (1). The transmission performance with varied oblique incident angles of unit cell for \( r = 1.0 \) mm are studied and the simulated results are presented in figure 3. It can be noted that both transmission magnitude and phase shift of wide-angle incident agree well with that of the normal incident one of figure 2 around the frequency range of interest. Thus, the metalens can focus wide-angle incident waves well with the same \( F \) continuously from \(-30^\circ\) to \(30^\circ\) view as predicted by expression (1).

3.2. Design of curved metal mirror

It can be noted that the designed metalens here can focus an incident wave with a large angle view with high efficiency according to the above analysis. Besides, the focused spot locations move continuously along the pre-designed trajectory surface within the considered wide-angle range. The simulated focused spot locations with different incident angles marked by blue points are plotted in figure 4(a). By placing a curved metal mirror on the proposed distance behind the metalens, the whole structure can effectively retroreflect the wide-angle incident wave to its original directions. The designed metal mirror is also illustrated in figure 4(b). The circular radius and open arc radian are marked by \( F \) and \( \beta \), respectively.

3.3. Full-wave simulations of meta-retroreflector and analysis

The microwave metasurface retroreflector based on the above metasurface structure and metal mirror is cascaded and the retroreflective performance is simulated using CST microwave studio suite and the electric field distributions with different incident angle of 0°, 10°, 20° and 30° are given in figure 5, respectively. It can be seen that good retroreflective performance both for normal and wide oblique incident wave are achieved. The focused spot locations with various incident angles can be clearly identified along the curved metal mirror which verify the above analysis of wide-angle metalens focus performance.

3.4. Fabricated sample of retroreflector and measurement results

As a demonstration of the conceptual design for the proposed microwave retroreflector in figure 1, the metasurface structure and the curved metal mirror are fabricated, connected and assembled by the foam for
Figure 4. (a) The simulated focused spot locations with various incident angles of 0°, 10°, 20° and 30° as shown by blue points, respectively. The metal mirror plane is also schematically drawn by red line which coincides with the focused spot locations. (b) The diagrams of the designed metal mirror based on the focused spot locations mapping. The circular radius and open arc radian is marked by $F$ and $\beta$, respectively.

Figure 5. The simulated electric field distribution of the microwave metasurface retroreflector with incident angle of 0°, 10°, 20° and 30° on x–z plane, respectively.

experimental studies. The fabricated planar metasurface retroreflector is illustrated in figure 6(b). The side length of the whole structure is 17.25 cm and the distance between metasurface and metal mirror is optimized and set as about 80 mm. The metasurface structure with double-layer gradient index copper plate sandwiched by a filled dielectric (Rogers 5880 substrate with $\varepsilon_r = 2.2$, loss tan $\delta = 0.008$, thickness is 2.5 mm) is fabricated by printed circuit board (PCB) technology. The open arc radian of the fabricated metal mirror is $\beta = 65^\circ$. The whole structure of the demonstrated retroreflector is very compact, low profile and light weight, thus is promising for various microwave engineering. The measured monostatic RCS response with incident angle view is given in figure 6(d). It can be noted that the excellent wide-angle backscattering performance for a relative stable 3 dB RCS level between $-30^\circ$ and $30^\circ$ is achieved. For the monostatic RCS measurement, two horn antennas are connected with our Rohde & Schwarz Microwave Network Analyzer (version ZVA40). For the angle scanning, the transmitting and receiving antenna move together with an angle step of 0.2° from $-90^\circ$ to $90^\circ$. The frequency is at 10 GHz and the polarization of incident wave is TM.


4. Discussions

As a specific comparison with the traditional widely-used microwave retroreflector, a trihedral corner reflector is fabricated and also tested as illustrated in figures 6(a) and (c), respectively. The conventional widely-used trihedral corner reflector is usually very bulky and here the side length of triangle is 1.25 m. The effective operation angle view of stable backscattering RCS enhancement 3 dB level is about $\pm 20^\circ$. Thus, our demonstrated metasurface microwave retroreflector is superior to the trihedral corner reflector in view of the wide incident angle. The enhanced RCS value can be improved further by increasing area of the designed planar metasurface structure. The measured conditions for the presented trihedral corner reflector and metasurface retroreflector are the same.

The transmissive metalens directly determines the RCS backscattering enhancement level for the proposed microwave retroreflector since the incident wave passes through the metasurface twice mainly. Compared with other retroreflective devices based on single layer reflective metasurface [15, 16], the peak RCS enhancement value of the proposed metasurface retroreflector based on a transmissive one may be lower. However, the operation angle view ($\pm 30^\circ$) is significantly improved. The monostatic RCS response of the proposed microwave metasurface retroreflector and metal plate is compared with the same area and the measured results are given in figure 7. Compared with a metal plate, the peak RCS of the proposed planar metasurface retroreflector in the middle decreases largely. This is mainly caused by the power loss with non-perfect transmission of some gradient unit cells through metasurface structure for the incident wave twice. Besides, the losing power of the incident wave is scattered to other unpredicted directions as caused by the edge effect of the limited size metasurface structure and the multiple reflective processes of the focused spot bounces between the metasurface and metal mirror. The average 80% transmission amplitude of unit cells in figure 2 can guarantee about above 40% incident power retroreflect back to the source, which mainly contributes to the peak RCS value level reduction compared to the metal plate with almost perfect reflection. However, the operational angle range for retroreflective is largely extended. The angle range of 3 dB RCS value for metal plate is only 5°. Without the metasurface, the curved metal mirror cannot retroreflect the incident wave at all, as shown by the green line. The frequency here is 9.8 GHz which demonstrates a better retroreflective performance compared with 10 GHz in figure 6. Thus, our proposed
microwave metasurface retroreflector also possesses a noticeable operational bandwidth. For the designed metasurface retroreflector, the 3 dB operational bandwidth is lower than the demonstrated trihedral corner reflector which is over 3 GHz of figure 6(a) at 10 GHz. In the future applications, the peak RCS can be further improved by increasing the transmissive magnitude of metasurface and/or increase the metasurface area simultaneous for an extended incident angle range. The operational bandwidth of proposed metasurface retroreflector can also be improved by using some novel metasurface structures.

5. Conclusions

In summary, a novel microwave planar retroreflector based on transmissive metasurface and a curved metal mirror is proposed, designed and demonstrated. Based on the proposed wide-angle backscattering enhancement mechanism, the simulated and experimental results show that the proposed metasurface retroreflector can efficiently retroreflect incident wave with a large angle view from $−30°$ to $30°$ continuously at around 10 GHz. Besides, the monostatic RCS measurement results demonstrate the backscattering enhancement value of the metasurface retroreflector can be kept stable within 3 dB level for the whole considered incident angle view. The backscattering enhancement performance of the proposed microwave retroreflector is competitive to the traditional trihedral corner reflector with comparable dimensions. Compared with other microwave retroreflective metasurface device [8, 9, 11, 14–16], the proposed microwave metasurface retroreflector possesses advantages such as wide-angle operation range and excellent RCS backscattering enhancement values within the whole continuous considered angle view. The presented microwave metasurface retroreflector is promising to develop into a planar, low-profile, light-weight and low cost retroreflective device for microwave engineering.

Conflict of interest

The authors have declared no conflict of interest.

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