Ultra-wideband and Polarization-insensitive RCS Reduction of Microstrip Antenna using Polarization Conversion Metasurface

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Abstract **─** A new type of polarization conversion metasurface (PCM) is presented to reduce radar cross section (RCS) of microstrip antenna. The proposed PCM consists of evolved split ring (ESR) resonators. Through designing of the PCM unit cell with five resonances and symmetrical layout, a high polarization conversion ratio and ultra-wideband passive cancellation are achieved. The proposed antenna (with PCM) and a reference antenna are designed, simulated and measured. The measured results show that our proposed antenna can achieve 10 dB in-band and 5 dB out-of-band RCS reduction in an ultra-wide frequency band from 6 GHz to 26.7 GHz. Moreover, the PCM works efficiently for both x- and y-polarized incident waves. The measured results show a good agreement with the simulations. Compared to previous researches, the proposed PCM features a compact profile and wider operating bandwidth of RCS reduction.

Index Terms **─** Microstrip antenna, polarization conversion metasurface (PCM), radar cross section reduction, ultra-wideband.

I. INTRODUCTION

Metasurface is a kind of artificially periodic structure surface which consists of sub-wavelength unit cells. Due to its unusual performance of manipulating electromagnetic (EM) wave, it has been widely applied to radar stealth. To avoid the radar detection, it is important to reduce the radar cross section of stealth platform. As an electromagnetic radiation and received device of radar systems, antenna always makes great contribution to the overall RCS. Several solutions have been proposed in literature, such as target shaping, radar absorbing materials (RAMs), and passive cancellation. By shaping the radiation patch [1], or exploiting radar absorbing materials which transform the radio frequency energy into heat [2] could greatly reduce RCS of antenna. However, these two methods could lead to negative effects, including narrowing the bandwidth and degrading the gain of antenna, in addition, exploiting RAMs would make device bulky.

The basic principle of passive cancellation is to make a 180° phase difference on the reflect wave, so the backscattering energy could be redirected away from the boresight direction. In 2007, Paquay used artificial magnetic conductors (AMC) and perfect electric conductors (PEC) to constitute of a planar chessboard structure, and realized 20 dB RCS reduction from 15.25 GHz to 15.5 GHz [3]. Due to the bandwidth limitation of AMC, this design worked only in a narrow band. Research in [4] replaced the PEC cell with another AMC structure which worked at other resonance frequency, and achieved a 180° (±30°) phase cancellation in 5.52-6.63 GHz, broadening RCS reduction bandwidth to 20%. Two Jerusalem crosses in different size was used in [5], the RCS reduction bandwidth reached to 40.88%. Similarly, reference [6] exploited a chessboard configuration consists of Jerusalem crosses and square patches, meanwhile achieved 65.2% relative bandwidth. Reference [7, 8] proposed a metasurface which composed of two types of electromagnetic band-gap (EBG) lattice, and broaden the relative bandwidth to 80% and 80.2%, respectively. Reference [9] proposed a polarization rotation reflective metasurface which composed of quasi-L-shaped patches, realized 106% relative bandwidth and 2 dB RCS reduction of planer structure. A broadband RCS reduction for microstrip antenna by utilizing polarization conversion metamaterial was realized in [10]. By employing a different design of polarization conversion unit cell, a 3 dB RCS reduction of microstrip antenna from 6 to 18 GHz (100% relative bandwidth) was achieved in [11].

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In this paper, we proposed a new type of polarization conversion metasurface (PCM) to reduce in-band and out-of-band RCS of microstrip antenna. The proposed novel PCM is formed by evolved split ring (ESR) resonator. The RCS reduction bandwidth can be broadened by using the PCM with multiple resonances. Through designing the evolved split ring resonator with five resonances, an ultra-wideband and high efficient polarization conversion is achieved. Then, the radiation patch of the proposed antenna is surrounded by the PCM unit cell in symmetrical layout, thus an ultra-wideband passive cancellation and RCS reduction are realized. The designed PCM is verified through full-wave simulations and experiments. The measured results show that the proposed antenna has a remarkable (5 dB) RCS reduction over 126.5% relative bandwidth from 6 GHz to 26.7 GHz. Compared to other designs, the proposed PCM shows a compact profile and wider operating bandwidth. Moreover, the proposed PCM has excellent RCS reduction performance for both x- and y-polarized incident waves.

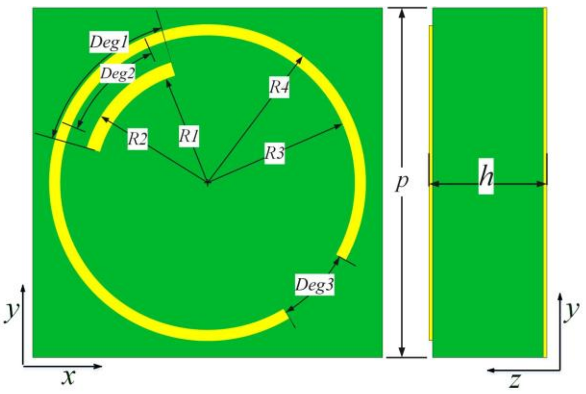
II. DESIGN AND SIMULATION

A. Design of the proposed PCM unit cell

Extensive research interest in manipulation of electromagnetic waves by using polarization conversion technology [9-13] has been applied in the microwave, terahertz, and even optical frequency bands. The proposed PCM is based on polarization conversion, and composed of an evolved split ring resonator. Figure 1 shows the geometry of the PCM unit cell, which is separated by a dielectric substrate F4B ($\varepsilon_r=2.65$, $\tan\delta=0.001$), with its top layer based on evolved split ring, and the bottom layer is metallic ground plane. The structure of ESR has a symmetric axis which along the 45° direction with respect to positive y-axis direction. In particular, the evolved split ring is designed in sunken deformation to increase the length of the entire metallic ring, which can increase the inductance and broaden the bandwidth.

The numerical simulation is carried out to analyze the reflection characteristic of the PCM unit cell with a commercial program, CST2015 (time domain solver). In the simulation, Floquet boundary and genetic algorithm are used to optimize the unit cell to make a better compromise between bandwidth and polarization conversion ratio (PCR). As shown in the Fig. 1, the optimize sizes of PCM unit cell are p=6 mm, R1=2.02 mm, R2=2.27 mm, R3=2.53 mm, R4=2.78 mm, Deg1=55.15°, Deg2=36.60°, Deg3=26.95°, h=3 mm.

To better understand the polarization conversion of electromagnetic waves of PCM, the reflection coefficients of the proposed PCM unit cell for x-polarized waves under normal incidence are depicted in Fig. 2. It is found that the bandwidth of polarization conversion is broaden to an ultrawide range by generating multiple resonances, and more than 80% PCR occurs from 5.8 GHz to 26 GHz. Five resonance frequencies are excited at 6.1 GHz, 8.2 GHz, 14.5 GHz, 22.6 GHz, 25.7 GHz where the PCR are nearly 100%, and which means that nearly all the electric field energy of x-polarized incident waves is converted to the y-polarized direction. Table 1 shows a comparison of PCR between the proposed PCM and other researches. It is noted that the proposed PCM unit cell has an excellent polarization conversion characteristic which can change a linearly polarized incident waves into cross-polarized reflected waves significantly in an ultra-wideband range. In addition, there are 45° angle between the symmetry axis of proposed unit cell and both x-axis and y-axis, so the proposed PCM unit cell can also convert normally incident y-polarized waves into x-polarized reflected waves with the same conversion efficiency.



(a) (b)

Fig. 1. Geometry of the PCM unit cell: (a) top view and (b) side view.

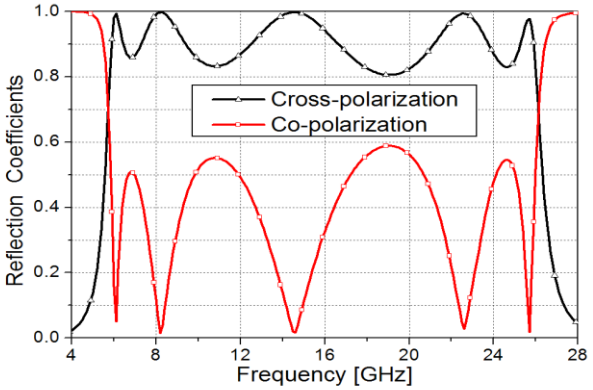


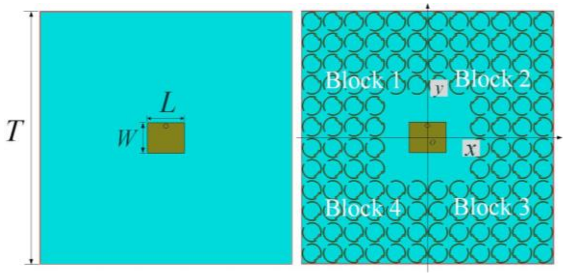
Fig. 2. The reflection coefficients of proposed PCM unit cell for x-polarized waves under normal incidence.

Table 1: Comparison of the PCR and bandwidth

	PCR	Frequency Range [GHz]	Bandwidth
[9]	96.4%	10.74-17.72	49%
[11]	80%	6-18	100%
[12]	90%	12.4-27.96	77.1%
[13]	70%	6-24.2	120.5%
This paper	80%	5.8-26	126.5%

B. Design of the microstrip antenna

The configurations of the reference antenna and proposed antenna are presented in Fig. 3, respectively. The dielectric substrate of antennas is also F4B material, with a dielectric constant ε_r=2.65 and a loss tangent $\tan\delta$=0.001. The reference antenna works at frequency band from 8.75 GHz to 10.1 GHz, and the resonant frequency is designed at 9.3 GHz. The dimensions of antennas are L=10.5 mm, W=8.7 mm, T=72 mm. The thickness of the antennas is 3 mm, so the PCM in the proposed antenna is designed to be coplanar with the antenna, and made up of 4 ESR-blocks. The adjacent ESR-blocks are mirror symmetry with respect to both the x-axis and y-axis. To satisfy period boundary condition used in simulation, every ESR-block is composed of 6×6 unit cells. 16 unit cells in the center of the whole PCM are removed to place the antenna. Furthermore, the structure of overall proposed antenna is mirror symmetry with respect to both the x-axis and y-axis.



(a) (b)

Fig. 3. The configuration of antennas: (a) reference antenna (without PCM), and (b) proposed antenna (with PCM).

Figure 4 shows the reflected electric field of the top layer of proposed antenna at 9.3 GHz for x-polarized waves under normal incidence. Because the adjacent ESR-blocks are mirror symmetry with respect to both the x-axis and y-axis, the y-component of electric field reflected from the adjacent ESR-blocks are mirrored. It is seen that the y-components of the reflected field are reversal (180° phase difference), therefore, a passive cancellation can be obtained. The 3-D scattered patterns of two antennas at 9.3 GHz for x-polarized waves are shown in Fig. 5. Under normal incidence, the proposed antenna converts normally incident x-polarized waves into y-polarized reflected waves, and the passive phase cancellation occurs between the y-polarized reflected waves of adjacent ESR-blocks of proposed antenna, so the backscattering is dramatically reduced along the principal planes (XZ, YZ). Compared with the bistatic RCS of reference antenna, the scattered energy of proposed antenna is redirected away from the boresight direction, and the monostatic RCS is significantly reduced while four sidelobes produce.

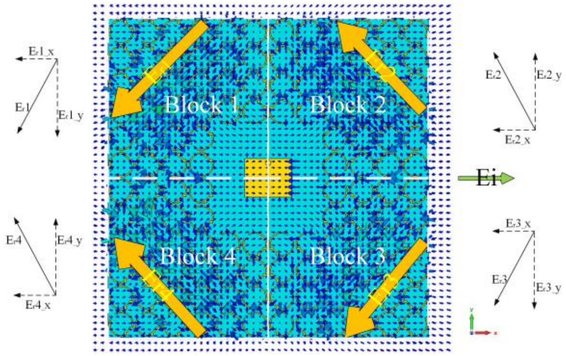
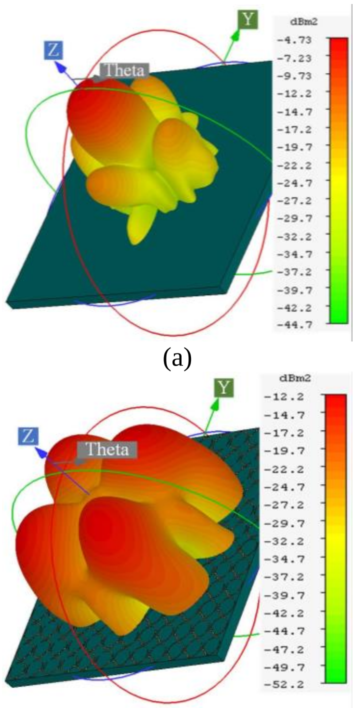


Fig. 4. Reflected electric field of the top layer of proposed antenna at 9.3 GHz for x-polarized waves under normal incidence.



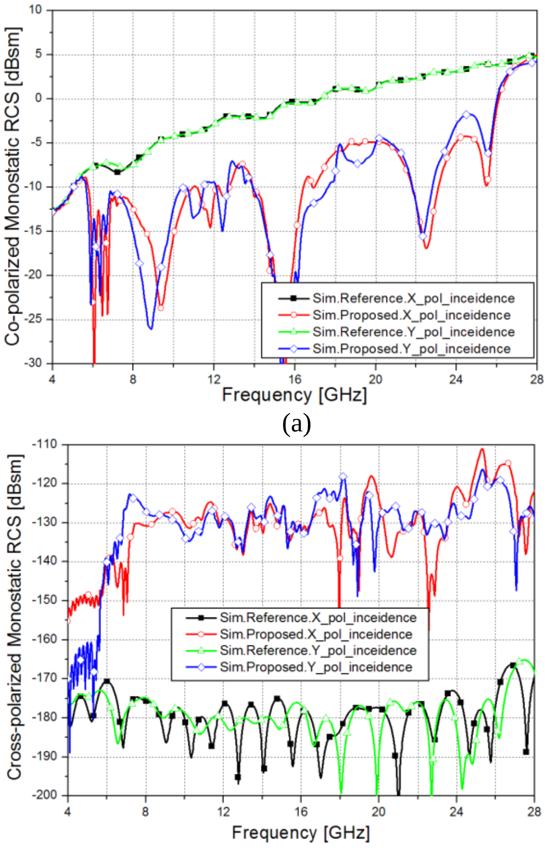
(a)

(b)

Fig. 5. 3-D scattering patterns of antennas at 9.3 GHz for x-polarized waves under normal incidence: (a) without PCM and (b) with PCM.

C. RCS reduction of the proposed antenna

Figure 6 (a) shows the co-polarized results of simulated monostatic RCS of antennas for x-polarized and y-polarized incident waves under normal incidence. The proposed antenna achieves more than 5 dB RCS reduction from 5.8 GHz to 26 GHz. Especially, the RCS reduction value reaches up to 10 dB on the working band of antenna. In addition, it is noted that the RCS reduction curves are almost coincide for x-polarized and y-polarized incident waves. Due to the proposed antenna are symmetric with respect to both the x-axis and y-axis, RCS reduction is insensitive to the polarization of incident waves. The cross-polarized results of monostatic RCS are presented in Fig. 6 (b). Due to 180° phase difference of cross-polarized reflection between the adjacent ESR-blocks of the proposed PCM, and a passive cancellation is realized in the proposed antenna, leading to an ignorable cross-polarization RCS (<-110 dB). Considering the trade-off of radiation performance and RCS reduction, the proposed metasurface is an excellent design for RCS reduction of low profile antenna.



(a)

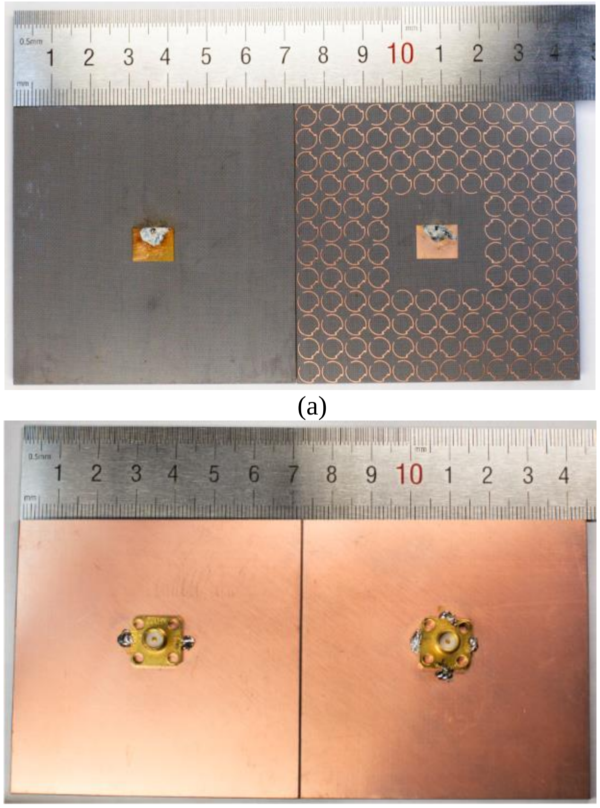
(b)

Fig. 6. Monostatic RCS of antennas for x-polarized and y-polarized incident waves under normal incidence: (a) co-polarized monostatic RCS, and (b) cross-polarized monostatic RCS.

III. MEASUREMENT AND DISCUSSION

In order to verify the novel PCM of RCS reduction, the reference and proposed antennas are fabricated and measured. The fabricated antennas are fed by 50 Ohm SMA coaxial connector whose top view and bottom view are presented in Fig. 7. The overall size of the fabricated antennas is 72 mm × 72 mm, and 128 PCM unit cells are symmetric arrangement in the proposed antenna. Moreover, the periodicity of PCM unit cell is only 0.2λ to the resonant frequency of reference antenna.

All the full wave EM simulations of antennas are conducted in CST (frequency domain solver and PML boundary) and the impedance characteristics of antennas are measured by Agilent E5071C vector network analyzer. Figure 8 shows the measured and simulated results of reflection coefficients. Although the resonant frequency is slightly offset on the measured results, the impedance bandwidth ($|S_{11}| < -10$ dB) of reference and proposed antennas is in good agreement. Figure 9 indicates the E-plane and H-plane radiation patterns of reference and proposed antennas at the resonant frequency (9.3 GHz). Compared with the reference antenna, the radiation characteristics of proposed antenna are effectively preserved for both E-plane and H-plane.



(a)

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Fig. 7. Prototype of the fabricated reference and proposed antenna: (a) top view and (b) bottom view.

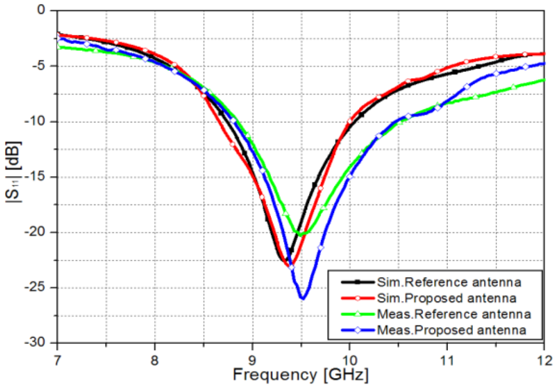
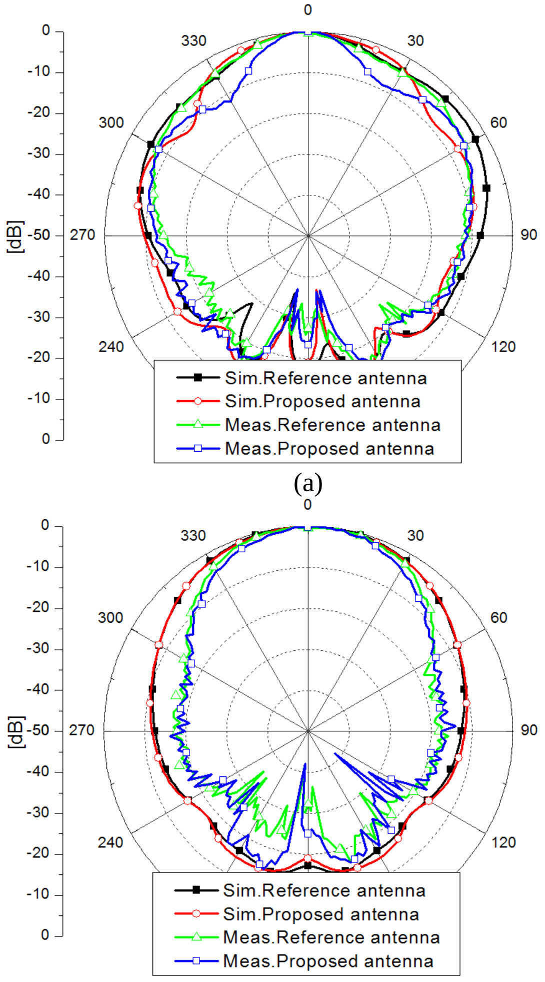


Fig. 8. Comparisons between the simulation and the measured S-parameters of antennas.



(a)

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Fig. 9. Comparison between the simulated and measured radiation patterns of antennas at 9.3 GHz: (a) E-plane and (b) H-plane.

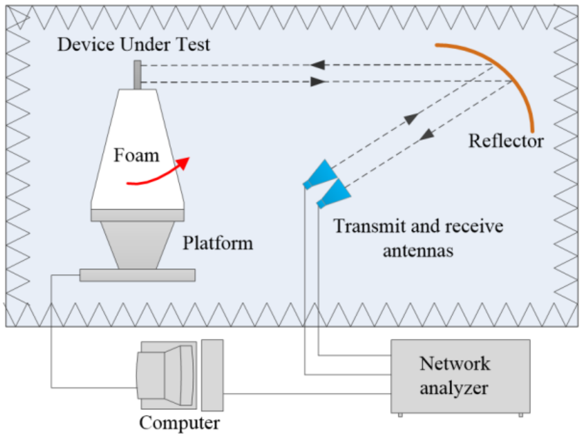

Fig. 10. Schematic setup of the RCS measurement in an anechoic chamber.

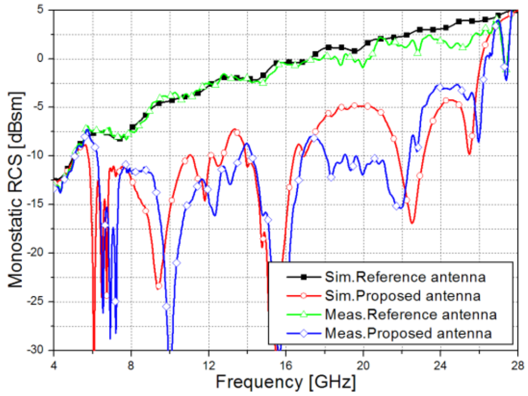

Fig. 11. Comparison of the simulated and measured monostatic RCS of antennas for x-polarized incident waves under normal incidence.

In order to confirm the wideband RCS reduction characteristic, the monostatic RCS of reference and proposed antennas are measured in the anechoic chamber of Science and Technology on Electromagnetic Scattering Laboratory in Beijing. Figure 10 shows the schematic setup of RCS measurement. The comparison of simulated and measured results for x-polarized incident waves under normal incidence are shown in Fig. 11. It is clear that the proposed antenna gives a remarkable in-band and out-band RCS reduction from 6 GHz to 26.7 GHz, and the maximum in-band reduction value reaches 20 dB on the resonant frequency of antenna. Experiment results show good agreement with the corresponding simulation. The slight deviation can be attributed to the measurement and fabrication tolerance. Similar to the previous analysis of PCM, an ultra-wideband polarization conversion and passive cancellation are demonstrated in the measurement.

VI. CONCLUSION

In this paper, a novel metasurface of RCS reduction for low profile antenna is presented. By designing the unit cell of proposed PCM with multiple resonances and symmetrical layout, high polarization conversion ratio and ultra-wideband passive cancellation are achieved. Meanwhile, by loading the proposed PCM, the proposed antenna has a remarkable (5 dB) RCS reduction in ultra-wideband range which the relative bandwidth reach to 126.5%, and the antenna radiation characteristics are also preserved. Meanwhile, because of the symmetry design of both the proposed PCM and antenna, the excellent RCS reduction is insensitive to the polarization of incident waves. The radiation and scattering properties of the proposed antenna is verified by simulations and experiments. The experimental results are in good agreement with the simulated results. Compared to the other kinds of metamaterials, the proposed metasurface is also extremely thin and compact sizes, which makes it convenient for integration with other devices, and can be widely applied to other planar stealth platforms, such as vehicles, ships and aircrafts.

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