Multiple Frequency Cancellation Method for Stealth Design of UWB End-Fire Antenna Array

Rong Xinghua, *He Xiaoxiang*, *Yang Yang* *, *Ye Xingwei*, *Wang Wei*

College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics,
Nanjing 211106, P. R. China

Abstract: A multiple frequency cancellation (MFC) method is proposed for stealth design of ultra-wide band (UWB) end-fire antenna array. The proposed method can produce significant radar cross section (RCS) reduction in the whole operating band. The 1×4 and 4×4 Vivaldi antenna arrays of different kinds of cancellation structures are discussed as examples to validate the effectiveness of the MFC method on both linear and planar arrays. On average, 22.6 dB reduction of monostatic radar cross section (MRCS) is obtained in the whole X-band. MRCS under oblique incident waves is also reduced within $\pm60°$. Basically favorable radiation characteristics are maintained.

Key words: stealth design; antenna array; ultra-wide band (UWB); multiple frequency cancellation (MFC)

0   Introduction

Ultra-wide band (UWB) antenna arrays have been typically applied to fire control system of aircraft and high-data rate wireless communications[1]. However, due to their great contribution to the total radar cross section (RCS), carriers are vulnerable to the enemy in the battlefield. Therefore, it is important to control the strong scattering of UWB antenna arrays in-band. For the out-band, the RCS can be reduced by employing frequency selective surface (FSS) radome[2].

Various stealth design methods have been investigated, most of which focus on the study of antenna element. Structures, such as electromagnetic band-gap (EBG)[3], artificial magnetic conductor (AMC)[4], and phase-switched screen (PSS)[5], are widely applied to the antenna stealth design. These materials usually perform spatial and filtering functions. Recently, structural modification seems to be an effective way to realize low profile characteristics[6-8]. By altering the shapes of UWB antennas, the bionics is inte-

grated in antenna stealth design where a clover-disc monopole antenna[6], an insect tentacle antenna[7], and a plant blades YAGI-UDA antenna[8] are presented with low RCS feature, respectively. On the other hand, Refs. [9-12] attempt to lower the RCS from the perspective of overall antenna array rather than single element. However, all the in-band stealth design methods mentioned above are subject to narrow bandwidth or complexity in antenna designs and manufactures.

To avoid these drawbacks, Chen et al.[13] present a universal method to reduce the RCS of antenna array with the help of cancellation theory. By employing ladder arrangement, they lower the structural mode RCS of antenna array in the whole X-band. Since the "ladder" is designed at only one frequency of 10 GHz, significant RCS reductions are confined to separated narrow bands. Although, the maximum 16.3 dB RCS reduction is achieved on the 3×7 Vivaldi antenna array, the minimum value of RCS reduction is only 1.5 dB[13]. Thus, the stealth performance is

unstable when the antenna array is exposed to broadband detecting wave.

In this paper, multiple frequency cancellation (MFC) points are employed to achieve significant RCS reduction over the whole operating band of UWB end-fire antenna array. The proposed MFC method ensures that the antenna array keeps low profile under broadband detecting wave.

1   Stealth Design Method

The schematic of structure with MFC is shown in Fig. 1. d_i denotes a quarter wavelength of cancellation frequency f_i. Antennas 1 and 2 have a distance of d_i in Z-direction, which forms a cancellation structure at frequency f_i. For an incident plane wave from Z-direction, the back scattering waves of the two antennas share the same magnitude but have 180° phase difference at frequency f_i, and as a result, cancel each other out[13]. Consequently, the structure mode RCS reduction will be achieved near the cancellation frequency. But the radiation waves of the two antennas also have 90° phase difference. Fortunately, such problem can be eliminated by phase compensation in source. In the same way, Antennas 2, 3 and 4 form another two cancellation structures at frequency f_2 and f_3. Although each cancellation structure alone operates at separated narrow bands, when f_1, f_2, and f_3 are set close to each other, several narrow bands can be combined together to form a wider one. One step further, in large-scale antenna arrays, such cancellation structure can be employed by all of the adjacent elements. If the Z-coordinate of each element is properly designed, the cancellation frequency points can contribute to significant RCS
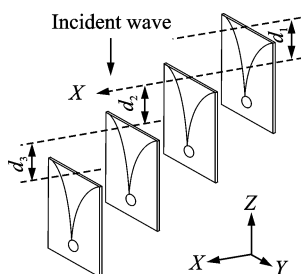
reduction in the whole operating band of UWB antenna array. Therefore, the end-fire antenna array with MFC can keep in low profile under the whole-band detecting waves.

The cancellations will also exist at frequencies $N \times f_i$ ($N = 3, 5, 7, \cdots$) or between non-adjacent elements, e. g. Antennas 1 and 3. As the corresponding frequencies are usually out of the operating band, such cancellations are not considered in the design.

2   Analysis and Results

The Vivaldi antenna proposed in Ref. [14] is chosen as the element of the following arrays. As shown in Fig. 2 with $a = 20$ mm, $b = 25.2$ mm, $d = 3.8$ mm, $z_1 = 11.4$ mm, $z_2 = 2.8$ mm, $l_1 = 10.05$ mm, $l_2 = 1.8$ mm, $l_3 = 1$ mm, $t_1 = 0.6$ mm, $t_2 = 0.28$ mm, $r = 2.8$ mm, the substrate thickness is 0.635 mm. The substrate thickness is 0.635 mm. The metal patch and the feeding structure are printed on each side of a FR-4 substrate. In the front view, the tapered slot line consists of two parts. The first part is determined by function $y_1(z) = 0.14e^{0.27z}$ ($0 < z \leqslant z_1$) and the second part is determined by function $y_2(z) = 0.14e^{0.27z_1} e^{0.425(z - z_1)}$ ($z_1 < z \leqslant z_1 + z_2$). In the back view, the fan-shaped feeding structure has a flare angle of 90°. Return loss of the antenna terminated with 50 Ω is given by simulation and experiment in Fig. 3, which are both less than -10 dB through the whole X-band and meets the engineering application requirement. The difference between simulated and measured results comes from the fact that the 50 Ω subminiature-A(SMA) is connected to the substrate by hand, which degrades the impedance match.
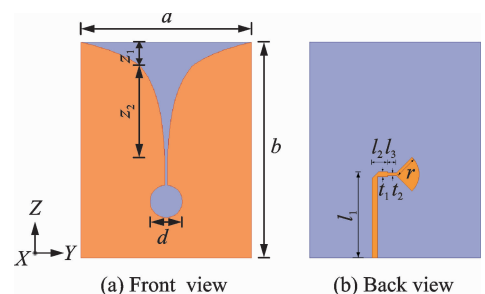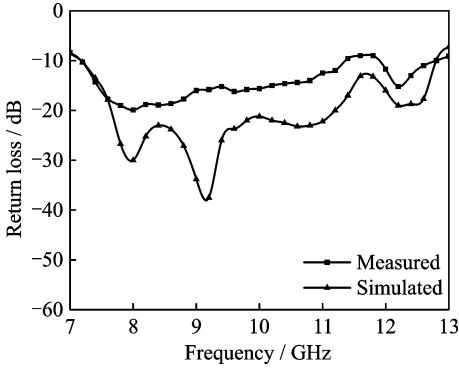

Fig. 1   Schematic of 1×4 antenna array with MFC

(a) Front view   (b) Back view

Fig. 2   Geometry of Vivaldi antenna

Fig. 3   Return loss for the antenna shown in Fig. 2

Fig. 4   MRCS of 1×4 array with equal-height arrangement and MFC arrangement

To understand the effect of MFC method, we consider a 1 × 4 Vivaldi antenna array as shown in Fig. 1. The distance between elements in X-direction is 21 mm which is 0. 7 times the wavelength corresponding to 10 GHz. We set $d_1 = 9.375$ mm, $d_2 = 6.25$ mm, and $d_3 = 18.75$ mm, which corresponds to a quarter wavelength at $f_1 = 8$ GHz, $f_2 = 12$ GHz, and $f_3 = 4$ GHz, respectively. The large frequency space can help distinguish each cancellation point from the other. For a co-polarized incident wave in grazing angle, the monostatic radar cross section (MRCS) according to the frequency is shown in Fig. 4, and the MRCS of the conventional equal-height array is also given as reference. It can be observed from Fig. 4 that the MFC method produces considerable RCS reduction at 11, 14. 6, and 6 GHz which contributes to low scattering performance over a wide frequency band. The three frequency points with the minimum MRCS are 2—3 GHz higher than the design due to the mutual coupling under asymmetric arrangement. This problem can be solved by optimization in practical designs. It can be seen in Fig. 5 that as d_1 decreases from 9. 375 mm to 6. 25 mm while d_2 and d_3 remain unchanged, the cancellation frequency f_1 increases from 11 GHz to 12. 5 GHz accordingly. So, by optimizing d_i, we can shift f_i to the desired frequency.

It is worth noting that, in most cases, the frequency of detecting wave is unknown, which requires the antenna array to obtain low scattering performance over the whole operating band. Therefore, the average root mean square
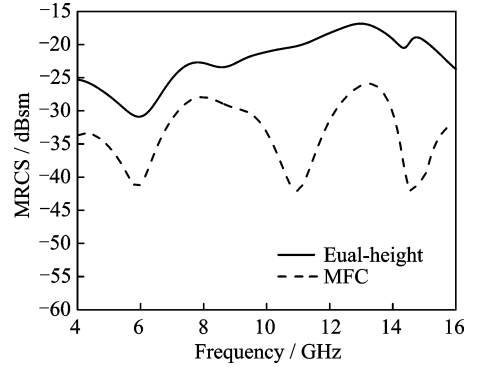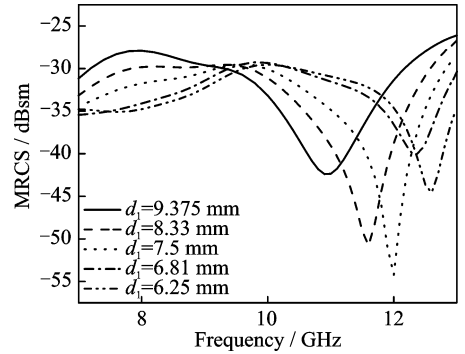

Fig. 5   MRCS of 1×4 array with MFC for the case of different decrease from 9. 375 mm to 6. 25 mm in X-band

(RMS) value of RCS reduction can better reflect the overall effect of the stealth design method.

In order to achieve significant RCS reduction within X-band and compare the MFC method with the ladder arrangement method proposed in Ref. [13], the 1 × 4 Vivaldi antenna arrays of three different structures are studied, as shown in Fig. 6. Structure 0 represents the conventional equal-height arrangement and acts as reference. In Structure 1, we set $d = 8.33$ mm, which involves only one cancellation frequency of 9 GHz. In Structure 2, we set $d_1 = 9.375$ mm and $d_2 = 6.25$ mm, Antennas 2 and 3 d_1 lower than Antenna 1 and d_2 higher than Antenna 4; i. e. Structure 2 represents the MFC employment of 8 and 12 GHz. The MRCS of above three structures is shown in Fig. 7. Results show that, on average, Structure 2 has almost 4 dB additional RCS reduction compared with that

of structure 1 in the whole X-band. According to the radar function: $R^4_{max} = P_t G^2 \delta \lambda^4 / ((4\pi)^2 S/N)$, the detection distance will decrease by 55% in Structure 1 and 64% in Structure 2, respectively.

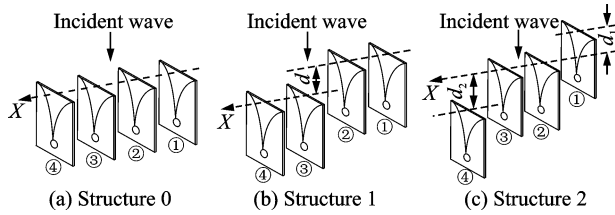(a) Structure 0   (b) Structure 1   (c) Structure 2

Fig. 6   Geometry of 1×4 Vivaldi antenna array with equal-height arrangement, ladder arrangement and MFC
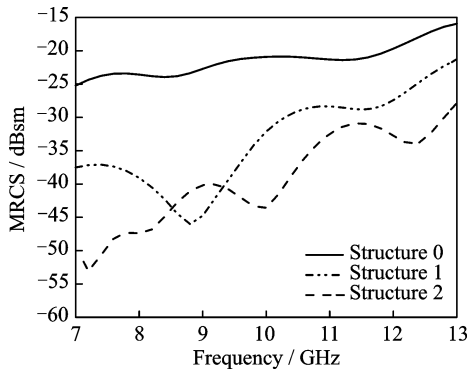

Fig. 7   MRCS of 1×4 Vivaldi antenna array

To further investigate the effect of MFC method on planar arrays, 4×4 Vivaldi antenna arrays of 5 different cases are discussed as follows. The distances between elements in X-direction and in Y-direction are both 21 mm. Overhead view of the array is shown in Fig. 8. Z-coordinates of elements in arrays of each case are given in Table 1, among which, d_i denotes a quarter wavelength of cancellation frequency f_i. As we can see from Fig. 8 and Table 1, Case 0 represents the conventional planar arrays and acts as reference. Cases 1 and 2 comprise the cancellation structure at 10 GHz in two different ways. The MFC method is employed in Cases 3 and 4, where adjacent elements in X-direction comprise cancellation structure at f_2 and in Y-direction at f_3. In Case 3, f_2 and f_3 are assigned to 8 GHz and 12 GHz. In Case 4, f_2 and f_3 are assigned to 9 GHz and 11 GHz.
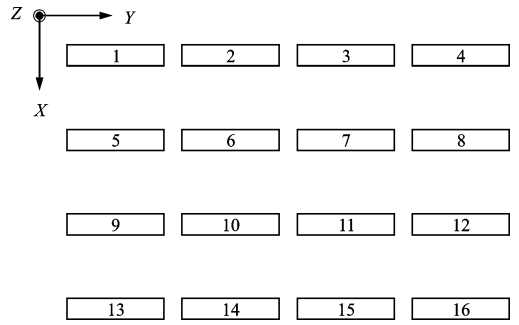

Fig. 8   Overhead view of 4×4 arrays

Table 1 Z-coordinate of elements in 4×4 antenna arrays

Antenna	Case 0	Case 1	Case 2	Case 3/4
#1	0	d_1	d_1	$3d_2 + 3d_3$
#2	0	d_1	d_1	$3d_2 + 2d_3$
#3	0	d_1	0	$3d_2 + d_3$
#4	0	d_1	0	$3d_2$
#5	0	d_1	d_1	$2d_2 + 3d_3$
#6	0	d_1	d_1	$2d_2 + 2d_3$
#7	0	d_1	0	$2d_2 + d_3$
#8	0	d_1	0	$2d_2$
#9	0	0	d_1	$d_2 + 3d_3$
#10	0	0	d_1	$d_2 + 2d_3$
#11	0	0	0	$d_2 + d_3$
#12	0	0	0	d_2
#13	0	0	d_1	$3d_3$
#14	0	0	d_1	$2d_3$
#15	0	0	0	d_3
#16	0	0	0	0
Cancellation frequency/GHz	None	10	10	8，12/ 9，11

The MRCS of above 5 cases are shown in Fig. 9. The average RCS reductions in Cases 1—4 are given in Table 2. By comparison, Cases 3,4 perform more than 5 dB additional RCS reduction than Cases 1, 2. As the MFC method increases the cancellation frequency points, Cases 3 and 4 have MRCS below -25 dB through the whole operating band. It is noted that, more antenna elements usually involve more cancellation structures, so the MFC method can be even more effective for the stealth design of middle- or large-scale antenna arrays.

Table 2   Average RCS reduction in Cases 1—4   dB

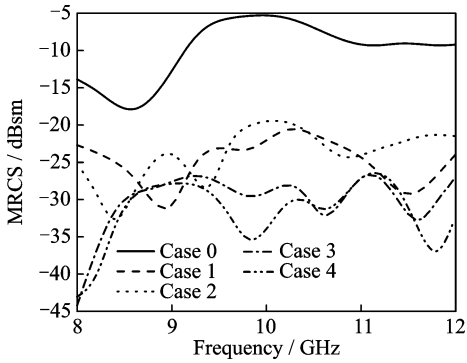| Case	1	2	3	4
RCS reduction	15.5	14.4	20.7	22.6

Fig. 9　MRCS of 4×4 array in 5 cases

The MRCS in *XOZ*-plane in Cases 0, 3 and 4 are also investigated to study their scattering performance under oblique incident waves. It can be seen from Fig. 10 that, the back scattering of the antenna array in Cases 3, 4 is significantly reduced within ± 60°. Similar low profile characteristic can be observed through the whole X-band.
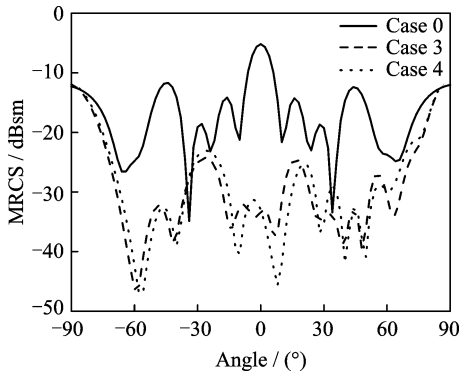

Fig. 10　MRCS of 4×4 array in Cases 0, 3 and 4 for the incident wave ranging from − 90° to + 90° in *XOZ*-plane (*f* = 10 GHz)

It is noteworthy that, as the total energy is not reduced by the MFC method, the reduction in RCS in a certain angle region will lead to the increase in RCS in other angle regions. We compare the bistatis radar cross section (BRCS) of Case 4 with that of Case 0. The co-polarized incident wave comes from *Z*-direction at 10 GHz.

As shown in Fig. 11, the main lobe of scattering in Case 4 is significantly reduced due to the cancellation while the back lobe arise. Fortunately, the strong scattering in back lobe is not in the threatening angle region, and it can be diminished by employing radar absorbing materials.

The simulated radiation pattern of Case 0 and

Case 4 is given in Fig. 12. The phase differences of radiation wave between elements in Case 4 have been compensated in source. Results show that, the main lobe of radiation pattern has 2 dB enhancement but the side lobe has approximately 10 dB deterioration in E-plane. In addition, the back lobe is greatly reduced. In order to maintain the radiation performance, we set 90° phase difference between adjacent elements to compensate the phase difference caused by asymmetric arrangement. However, the compensation also leads to cancellation of radiation waves in back lobe direction for their 180° phase difference. In general, the antenna array keeps a favorable radiation pattern when employed with the MFC method.
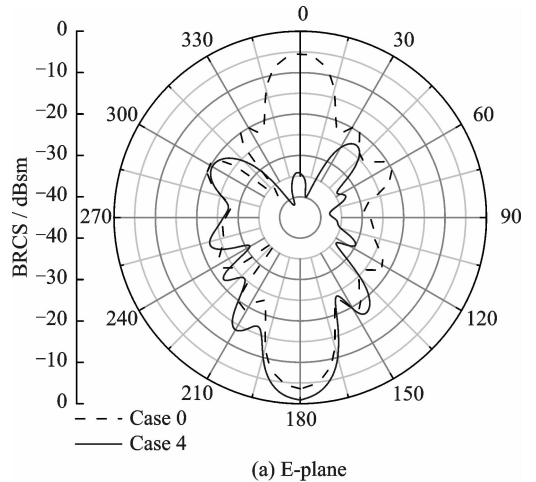
(a) E-plane
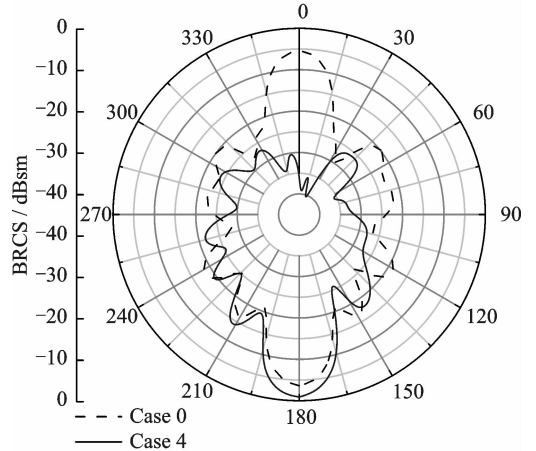
(b) H-plane

Fig. 11　BRCS of 10 GHz in Cases 0, 4

3　Conclusions

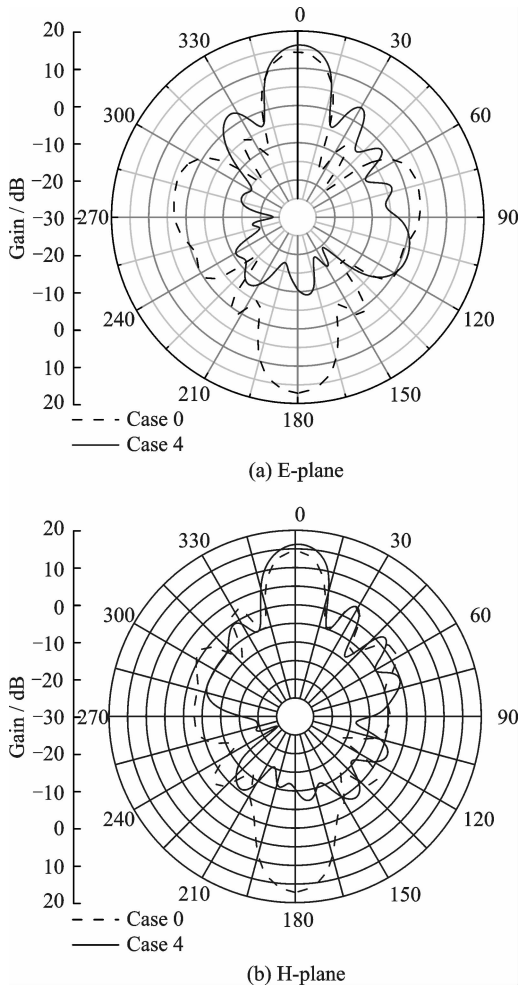A stealth design method based on MFC for UWB end-fire antenna array is proposed. Vivaldi

Fig. 12   Radiation pattern of 10 GHz in Cases 0，4

antenna arrays of different scales are discussed as examples to validate the effectiveness of the proposed method. Results show that the MFC method produces average 17. 6 dB RCS reduction on $1×4$ array and 22. 6 dB RCS reduction on $4 × 4$ array, and favorable radiation characteristics are maintained. By optimizing the Z-coordinate of each element properly，significant RCS reduction covering the whole operating band can be achieved. Therefore，the proposed method can be a good candidate for the stealth design of UWB end-fire antenna array.

Acknowledgement

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Mr. **Rong Xinghua** received the B. S. degree in Information Engineering and the M. S. degree in Electromagnetic Field and Microwave Technology from Nanjing University of Aeronautics and Astronautics(NUAA), Nanjing, China, in 2014 and 2017, respectively. His research interests include antennas, stealth design and phased array, etc.

Dr. **He Xiaoxiang** received the B. S. degree in Electronics Engineering from Yangzhou University, Yangzhou, China, in 1998. In 2003, he received the Ph. D. degree in electromagnetic field and microwave technology from Nanjing University of Aeronautics and Astronautics(NUAA), Nanjing, China. From 2003 to 2005, he was a Postdoctoral Research Fellow in the School of Electronic and Optical Engineering, Nanjing University of Science and Technology (NUST), Nanjing, China. From 2005 to present, he has been with the College of Electronic and Information Engineering, NUAA, where he is currently an associate professor and research supervisor. His research has mainly focused on computational electromagnetism and antenna theory and technology.

Prof. **Yang Yang** received the Ph. D. degree in Electromagnetic Fields and Microwave Theory from Nanjing University of Science and Technology (NUST), Nanjing, China, in 2006. From January 2006 to October 2007, she was a Postdoctoral Research Fellow in Information and Communication Engineering from Nanjing University of Science and Technology (NUST), Nanjing, China. During the period from June 2006 to June 2007, she went to City University of Hong Kong to do a year's cooperative research. From 2007 to present, she joined in the College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics (NUAA). Her research has focused on computational electromagnetics and antenna theory.

Mr. **Ye Xingwei** received the B. S. and M. S. degrees in Information Engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2014 and 2017, respectively. He is currently pursuing the Ph. D. degree at Nanjing University of Aeronautics and Astronautics(NUAA).

Mr. **Wang Wei** received the B. S. degree in Information Engineering and the M. S. degree in Electromagnetic Field and Microwave Technology from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2014 and 2017, respectively. Her research interests include antennas and phased array, etc.

(Production Editor: Xu Chengting)