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A Novel Passive Jamming Method Against ISAR Based on Resonance Absorption Effect of Metamaterials

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ABSTRACT Based on resonance absorption effect of metamaterials, a novel passive jamming method against Inverse Synthetic Aperture Radar (ISAR) is proposed in this paper. By adopting a cross-shaped metamaterial, the resonance frequency is designed within the ISAR bandwidth. Using the finite integration technique to calculate the electromagnetic reflection characteristics, the scattering point model and distorted radar echo of the target coated with the designed metamaterial are obtained. Then, the ISAR imaging analysis model of the target coated with the cross-shaped metamaterial is established. Finally, jamming effects of the cross-shaped metamaterial on the ISAR imaging are studied and verified. The range profile result indicates that besides the energy attenuation, the single radar target becomes two false radar targets, both of which are not located at the real target position. The ISAR imaging result shows that the target becomes blurred and many low-brightness points are produced. The passive jamming method could have a negative impact on the ISAR image target recognition applied to aircrafts, ships, and missiles.

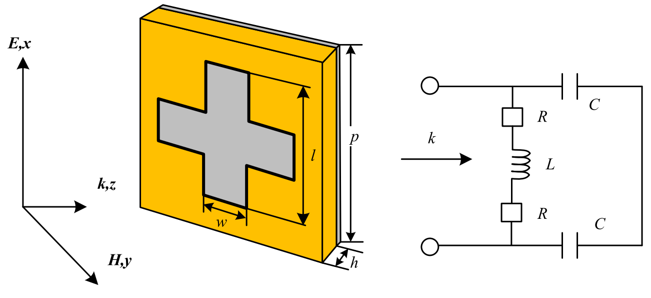
INDEX TERMS Passive jamming, ISAR imaging, cross-shaped metamaterial, range profile.

I. INTRODUCTION

During the last few decades, metamaterials have attracted great attention due to its unusual electromagnetic property that the conventional material does not possess. The exclusive electromagnetic (EM) phenomena such as super lens imaging, perfect absorption, invisibility cloaks, polarization control, and asymmetric transmission effect can be achieved by designing the particular structure parameter of the micro units cell [1]–[7] Because of its ultra-thin, polarization independent and excellent absorption properties, metamaterials configured with a periodic arrangement of compact frequency selective surfaces on the top of a thin dielectric substrate can be matched to the impedance of free space and act as a perfect absorber [8]–[11].

As mentioned above, researchers have mainly focused on the perspective of power attenuation of metamaterial absorber. But, some metamaterials can be used as a passive jamming material. Practically, through units designing, metamaterials can achieve strong resonance absorption effect [12]–[13] to realize intense changes in amplitude and phase characteristics in radar signal bandwidths. Thus, when the radar wave is incident on a target coated with the metamaterials, the radar echo waveform will be distorted greatly. Especially for the Inverse Synthetic Aperture Radar (ISAR) wideband signals, the reflection characteristics of metamaterials will change greatly in the bandwidth due to the strong resonance absorption effect. However, few work has concentrated on the effects of metamaterials on the radar echo waveform, and the jamming effects of metamaterials on the ISAR imaging have not been studied.

For this purpose, a novel passive jamming method against ISAR imaging is proposed in this paper. The remainder of this paper is organized as follows. In Section II, the physical model of the cross-shaped metamaterial absorber is given, and the resonance absorption effect is discussed. In Section III, ISAR imaging analysis model of target coated with the cross-shaped metamaterial is established. In Section IV, based on the multiple point target model, the radar echo of the ISAR imaging target coated with cross-shaped metamaterial is calculated. Moreover, the jamming



(a) (b)

FIGURE 1. **Cross-shaped metamaterial absorber (a) element structure (b) equivalent circuit model.**

effect of cross-shaped metamaterial on the ISAR imaging result is studied. The simulation result shows that the cross-shaped metamaterial has an excellent jamming effect on the ISAR imaging. Finally, the conclusion is reported in Section V.

II. PHYSICAL MODEL OF METAMATERIALS AND RESONANCE ABSORPTION EFFECT

Theoretically, the metamaterial structure composed of arbitrary metal conductive pattern, lossy dielectric substrate and metal floor can be used as perfect absorber by the geometric parameter optimization designing. On one hand, based on the impendence matching design of metamaterials, the reflection of incident waves is almost zero, making all the waves enter the absorber. On the other hand, strong electric resonance on the upper surface of metal conductive pattern which is equal to an electromagnetic oscillator excited by incident waves, forming strong surface induced current, the direction of which is opposite to the surface current of bottom metal pattern. Then, a strong electromagnetic coupling resonance effect is induced, and the coupled electromagnetic energy bounded between intermediate medium layers is lost.

Having the advantages of simple configuration, easy construction and test, cross-shaped surface metal structure is considered as one of the best metamaterial micro-structure pattern models. For ease of design and theoretical analysis, simple cross-shaped flat is selected as the basic unit cell model of absorber. The designed absorber cross-shaped structure unit and its equivalent circuit model are shown in Fig.1. Consisting of a number of unit structures, the cross-shaped metamaterial having strong resonance characteristics can be seen as electric dipole, which can generate the electric dipole radiation oscillations on the incident waves. The ‘sandwich’ structure composed of the cross-shaped metal conductive pattern and the bottom metal film can be seen as a magnetic dipole, which can generate the magnetic dipole radiation oscillations on the incident waves, thereby appearing magnetic resonance characteristics.

In order to implement the regulation of absorber, the equivalent circuit theory model is established to qualitatively analyze the dependence between the electromagnetic resonance characteristics of the cross-shaped metamaterial absorber’s single structure and geometrical parameters. According to the L-C equivalent resonant circuit theory, the cross-shaped structure can be equivalent to inductance L, the expression of inductance approximated as helix is:

$$L \approx \mu_0 l \ln(h/w). \tag{1}$$

The expression of capacitance C composed of cross-shaped structure and bottom metal film can be approximated as the parallel plate capacitance:

$$C \approx \varepsilon_r \varepsilon_0 lw/4h. \tag{2}$$

For the single-layer cross-shaped metamaterial absorber, the ‘sandwich’ structure absorbs the electromagnetic waves mainly based on the magnetic resonance mechanism, the expression of its resonant frequency can be approximated as:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \approx \frac{c_0}{\pi l \sqrt{(\varepsilon_r w/t)}\ln(w/h)}. \tag{3}$$

Thus, the resonant frequency range can be adjusted by adjusting the structure parameters (cross line length l, cross line width w, interlayer medium thickness t). According to the effective medium theory, the electromagnetic absorption rate of the composite structure is

$$A(\omega_0) = 1 - e^{-2Ft\omega_0^2/c_0\gamma}, \tag{4}$$

where F, γ are the electromagnetic resonance factor (or geometry factor) and the attenuation factor, respectively. Their expressions are approximated as follows.

$$F = (-2lw - w^2)/p^2, \tag{5}$$

$$\gamma = ac_0 \ln(h/t_m)/2\sigma t_m wl, \tag{6}$$

where a is numerical factor, having correlation with dielectric layer loss. Therefore, we can adjust the absorption region and strength of the resonance frequency through the adjustment of the cross-shaped geometry parameters.

According to the above theoretical analysis, by optimizing the parameters of the structure, we can obtain a cross-shaped sandwich structure using FIT method for ISAR signal (central frequency is 10GHz, bandwidth is 1GHz). The resonant absorption effect of the designed cross-shaped metamaterial absorber is shown below.

The geometric parameters of the cross-shaped sandwich structure above are: $p = 8.20$mm, $t = 0.16$mm, $l = 7.64$mm, $w = 5.00$mm. The amplitude-frequency characteristic is shown in Fig.2, and the phase-frequency characteristic is shown in Fig.3. As is shown in Fig.2, the design has a strong resonant absorption effect, making the attenuation difference of radar wave can reach near 35dB in the radar frequency band. As is shown in Fig.3, the phases of the reflected coefficients are reverse when the frequency is 10GHz. At this time, the real part of the relative wave impedance is close to 1, while the imaginary part is close to zero.

Through designing, we can make the resonant absorption frequency as close to 10GHz as possible. The intense changes

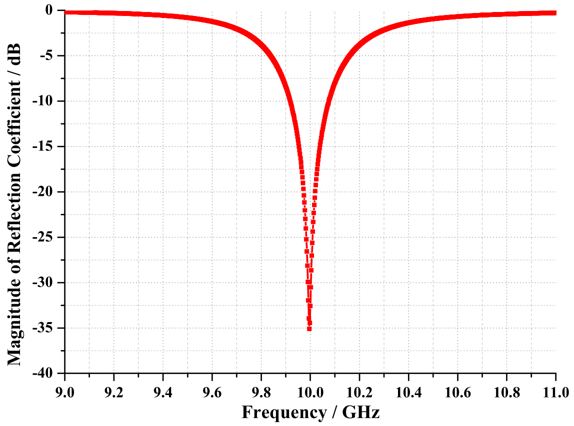


FIGURE 2. The amplitude-frequency characteristics of cross-shaped metamaterial.

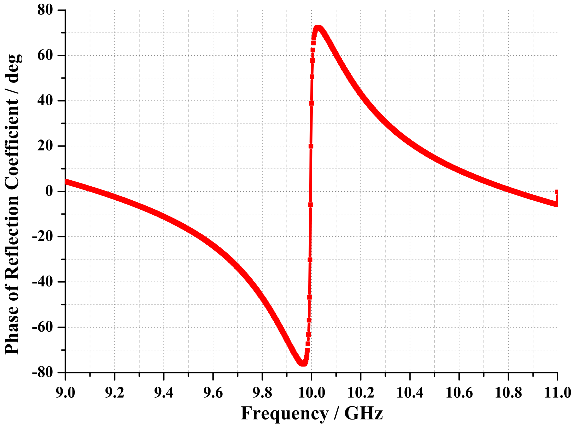


FIGURE 3. The phase-frequency characteristics of cross-shaped metamaterial.

in amplitude and phase characteristics in the ISAR bandwidth make the ISAR echo change further. Thus, based on the resonance absorption effect, a novel jamming method using cross-shaped metamaterial is proposed.

III. ISAR IMAGING JAMMING THEROY

When the radar transmitted wave is incident on the target coated with a cross-shaped metamaterial, the electromagnetic resonance characteristics make the radar echo distort and the energy loss [14]. In Section II, the reflection properties of the ISAR target coated with cross-shaped metamaterial absorber are calculated. The result shows that the amplitude-frequency characteristic and the phase-frequency characteristic are both changed, which is the underlying reason of the radar echo distortion. The echo distortion jams the one dimensional range profile. As it is known that the clarity of the ISAR image depends on the resolution of the image on the range dimension and azimuth dimension. Thus, the change of cross-shaped metamaterial on range profile makes it possible for the ISAR jamming realization.

Coating the ISAR target with the designed cross-shaped metamaterial, the range dimension clarity of the ISAR image can be destroyed because of the resonant absorption effect.

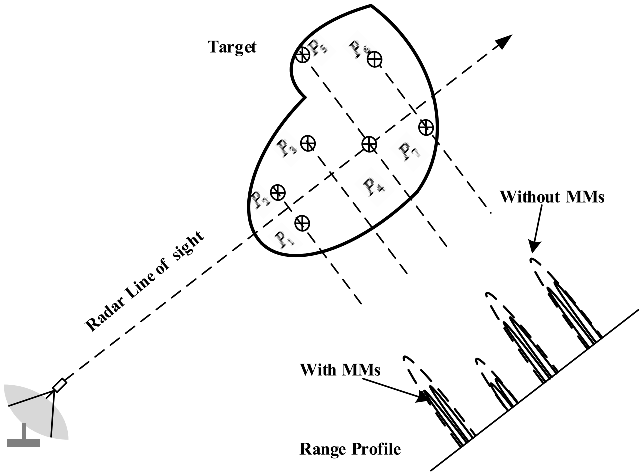


FIGURE 4. One dimensional range profile of target coated with cross-shaped metamaterial.

The jamming effect on the one dimensional range profile of radar echo is verified firstly in subsection A. Based on this, a novel passive jamming method against ISAR is proposed using the cross-shaped metamaterial. The jamming mechanism on ISAR imaging is studied and the model of ISAR echo after being jammed is given in subsection B.

A. ONE DIMENSIONAL RANGE PROFILE OF ISAR TARGET COATED WITH CROSS-SHAPED METAMATERIAL

In order to obtain a high range resolution, ISAR always has a wide bandwidth. Because of the wide bandwidth, the ISAR target can be considered as a multiple point target, and its echo will also contain some target information. The echo signal or the echo power of the target presents a one dimensional range profile [14]–[16].

Fig.4 is a schematic diagram of the one dimensional range profile based on the point scattering model. Due to the electromagnetic resonant absorption effect of cross-shaped metamaterial, the reflection property of the target including the amplitude-frequency characteristic and the phase-frequency characteristic are intensely changed, leading to the range profile distortion. As shown in Fig.4, each scattering point on the ISAR target is coated with a large number of unit cells of cross-shaped metamaterial. When the ISAR wave is incident on the target, the reflection property of every point on the target is changed, presenting the range profile distortion.

In order to obtain the distorted range profile, the reflection property should be recalculated by establishing the ISAR target electromagnetic reflection model. By using the model to calculate the reflection properties at different frequencies, different azimuths and different pitch angles, the ISAR target reflection property can be obtained.

The reflection characteristics of the i-th scattering point P_i can be represented by $\sigma_{P_i}(f, \theta, \phi)$, where f represents frequency, θ represents pitch angle, ϕ represents azimuth. The reflection characteristics of the radar target coated with designed metamaterial is calculated by FIT [17], and the results show that the radar echo amplitude-frequency characteristic and the phase-frequency characteristic are both changed, leading to the radar echo distortion. Because of the echo distortion, the false target and the energy attenuation (reduction of RCS) appear in one dimensional range profile, making it possible for the realization of ISAR jamming.

The amplitude-frequency characteristic and the phase-frequency characteristic of the target are both related to the design parameters of cross-shaped metamaterial. Thus, the amplitude-frequency characteristic can be represented as $Reflection(f, w, l, p, h)$, and the phase-frequency characteristic can be represented as $\phi(f, w, l, p, h)$. Then, the reflection properties of the i-th scattering point P_i can be obtained as follows:

$$\sigma_{P_i}(f, \theta, \phi) = Reflection(f, w, l, p, h) \cdot e^{j\phi(f, w, l, p, h)}. \quad (7)$$

Inverse Discrete Fourier Transform (IDFT) is used to obtain the electromagnetic characteristics of the scattering point in time domain:

$$\sigma_{P_i}(t, \theta, \phi) = IDFT\{\sigma_{P_i}(f, \theta, \phi)\}. \quad (8)$$

In this paper, a linear frequency modulated radar wave is adopted as the transmitted signal $S(t)$, and it is defined below:

$$S\,(t) = rect(\frac{t}{T_p}) \cdot e^{j2\pi(f_0 t + \frac{kt^2}{2})}, \quad (9)$$

where T_p is pulse width, f_0 is initial frequency, k is frequency modulation slope.

Considering the change of reflection properties, the radar echo expression of the ISAR target coated with cross-shaped metamaterial can be expressed as below:

$$\mathrm{s}_r(t) = \sum_{i=1}^{L} \sigma_{P_i}(t, \theta, \phi) \cdot rect(\frac{t-2r_i}{T_p}) \cdot e^{j2\pi(f_0(t-\frac{2r_i}{C})+\frac{k}{2}(t-\frac{2r_i}{C})^2)}. \quad (10)$$

The pulse compression output of radar echo $s_r(t)$ is one dimensional range profile of ISAR target coated with cross-shaped metamaterial. The intense change of reflection property is the underlying reason of the range profile distortion, making it possible to jam

B. ISAR IMAGING MODEL OF TARGET COATED WITH CROSS-SHAPED METAMATERIAL

ISAR imaging theory is based on the electromagnetic characteristics of target. Through mapping the target to a 2D planar graph, we can get the motion state of the target in order to realize the classification, recognition and tracking of target [18]. However, when the target is coated with the cross-shaped metamaterial, the electromagnetic characteristics will be changed. The ISAR echo of the target is distorted, then, the imaging results will be quite different from the situation without cross-shaped metamaterial coating.

In order to study the jamming effect of cross-shaped metamaterial, the ISAR imaging model of the target coated with cross-shaped metamaterial is established. Because radar imaging often uses reflection point model to represent the targets, all the points on the imaging target should be coated with the cross-shaped metamaterial designed in Section II. Based on the model, the imaging mechanism is given and studied in the following.

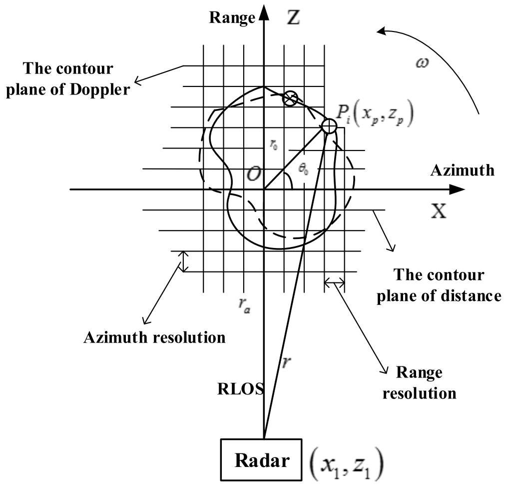


FIGURE 5. The imaging mechanism of rotating targets coated with cross-shaped metamaterial.

The imaging mechanism of rotating targets coated with cross-shaped metamaterial is shown in Fig.5.

Projecting the three dimensional target to the two dimensional plane in the radar illuminating area, rotating around y axis with a uniform angular velocity ω. Coordinate XOZ is the projection plane, O is the center point of imaging target. As Fig.5 shows, the target is composed of multiple scattering points in the two dimensional plane, and every scattering point is coated with the designed cross-shaped metamaterial. Taking the point $P_i(x_p, y_p)$ on the imaging target as an example, this point is coated with cross-shaped metamaterial, so are other points on the target. The reflection properties of the point $P_i(x_p, y_p)$ can be represented by $\sigma_{P_i}(f, \theta, \phi)$, where f represents frequency, θ represents pitch angle, and ϕ represents azimuth. Actually, due to the occlusion effect, not all points can be seen from the radar line of sight. Through coordinate system transformation, the coordinate of the radar in the coordinate system of the target is (u_r, v_r, w_r). Thus, the points in the range of the angle between $[-\pi/2 + \arctan v_r/u_r, \pi/2 + \arctan v_r/u_r]$ can be seen from the radar line of sight.

In this paper, the cone target is adopted as the imaging target and the reflection properties of imaging target can be calculated in the way shown in Fig.6.

Let the number of reflection points be L in the total imaging target. Due to the rotation of target, each scattering point will move in the radial direction. The radial displacement of the i-th point in the m-th radar echo is $R_i(t_m)$, then the corresponding echo expression is:

$$S_r\,(t, t_m) = \sum_{i=1}^{L} \sigma_{P_i}(t_m, \theta, \phi) rect(\frac{t - 2R_i(t_m)/C}{T_p}) \cdot \\ \times e^{j2\pi(f_0(t-\frac{2R_i(t_m)}{C})+\frac{k}{2}(t-\frac{2R_i(t_m)}{C})^2)} \quad (11)$$

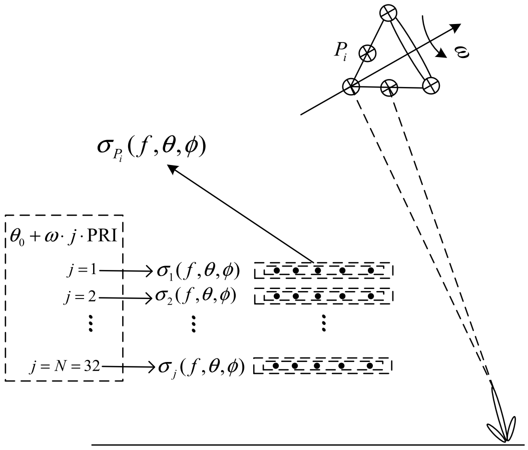


FIGURE 6. The reflection properties of imaging target.

Suppose that each scattering point coated with the cross-shaped metamaterial has the same reflection property, then

$$\sigma(t_m,\theta,\phi)=\sigma_{P_i}(t_m,\theta,\phi)=\sigma_{P_{i+1}}(t_m,\theta,\phi) \tag{12}$$

$\sigma(t_m,\theta,\phi)$ can be regarded as the reflection characteristics of the target in the ISAR signal band, substituted into (11):

$$S_r\ (t,t_m)=\sigma(t_m,\theta,\phi)\cdot\sum_{i=1}^{L} rect(\frac{t-2R_i(t_m)}{T_p})\cdot e^{j2\pi(f_0(t-\frac{2R_i(t_m)}{C})+\frac{k}{2}(t-\frac{2R_i(t_m)}{C})^2)} \tag{13}$$

If the pulse accumulation time is $M\cdot t_m$, after the pulse accumulation time, the total echo used to image is:

$$S_{total}\ (t,t_m)=\sum_{m=1}^{M}\sigma(t_m,\theta,\phi)\cdot\sum_{i=1}^{L} rect(\frac{t-2R_i(t_m)}{T_p})\cdot \times e^{j2\pi(f_c(t-\frac{2R_i(t_m)}{c})+\frac{k}{2}(\frac{t-2R_i(t_m)}{c})^2)} \tag{14}$$

The ISAR imaging result can be obtained by making pulse compression in range dimension and Fourier Transform in azimuth dimension separately. By designing the parameters of cross-shaped metamaterial, we can make the resonant absorption frequency as close to ISAR center frequency as possible in order to obtain the satisfactory jamming effect on the ISAR imaging result.

IV. SIMULATION RESULTS AND DISCUSSIONS

In order to study the jamming effect of cross-shaped metamaterial on the ISAR imaging result, we take X-band radar as an example and adopt LFM wave as the transmitting wave, the radar parameters adopted in the following simulations are specified in Table I.

Firstly, the comparison of one point target range profile coated with and without cross-shaped metamaterial is presented. The jamming effect of cross-shaped metamaterial on the one point target's range profile can be verified. Then, we discuss the jamming effect on the cone points target with ideal distribution, all the points on which are coated with designed cross-shaped metamaterial.

TABLE 1. Simulation Parameters.

Parameter	Symbol	Value
Carrier frequency	f_0	$10GHz$
Radar bandwidth	B	$1GHz$
Pulse width	T_p	$16\mu s$
Pulse repetition period	PRI	$1ms$
Modulation Slope	k	5e12
Target Rotation Speed	ω	$2\pi rad/s$
Pulse Accumulation Number	N	32

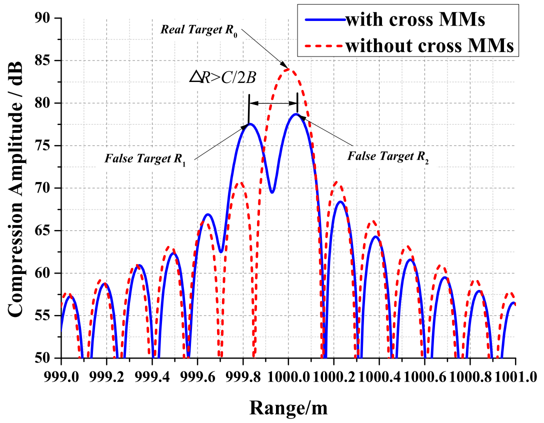


FIGURE 7. Comparison of one dimensional range profile results between the targets with and without cross-shaped metamaterial.

A. THE JAMMING EFFECT OF CROSS-SHAPED METAMATERIAL ON THE ONE DIMENSIONAL RANGE PROFILE

The model of one point target located in 1km coated with cross-shaped metamaterial is established, and the one dimensional range profile is simulated. The simulation result is shown in Fig.7.

The results show that the one dimensional range profile of one point target coated with cross-shaped metamaterial is changed. Besides the half of the energy attenuation, signal radar target becomes two radar false targets, and the two targets are several centimeters apart. Because of the echo distortion, the range profile can be jammed successfully by coating the target with cross-shaped metamaterial. Thus, it is possible for the realization of ISAR jamming.

B. THE JAMMING EFFECT OF CROSS-SHAPED METAMATERIAL ON THE ISAR IMAGING RESULT

Radar imaging often uses reflection point model to represent the targets. Based on the research above, a novel jamming method against ISAR jamming method based on resonance absorption effect of cross-shaped metamaterial is proposed and simulated in this sub-section.

A cone target is taken as an example, its maximum radius is 0.4m and its length is 1m. The three dimensions of polar coordinates are polar radius, angle and height, respectively. There are seven points on the target, the coordinates in the target coordinate system are $P_1(0, 0, 0)$, $P_2(0.2, \pi/10, 0.5)$, $P_3(0.2, 9\pi/10, 0.5)$, $P_4(0.2\ , 3\pi/2, 0.5)$, $P_5(0.4, \pi/10, 1)$,

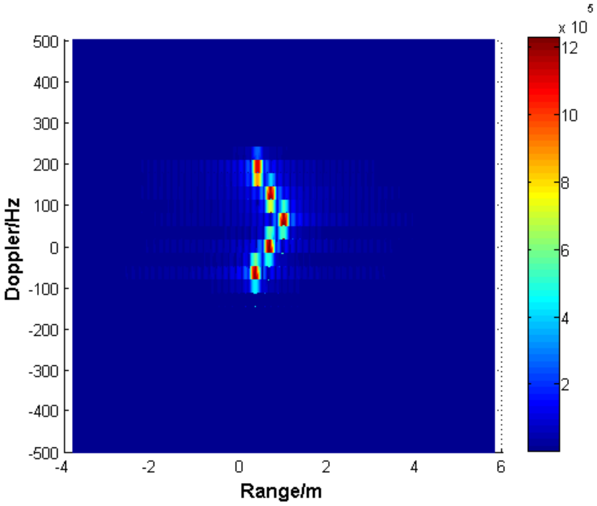


FIGURE 8. **Imaging result of the target without cross-shaped metamaterial.**

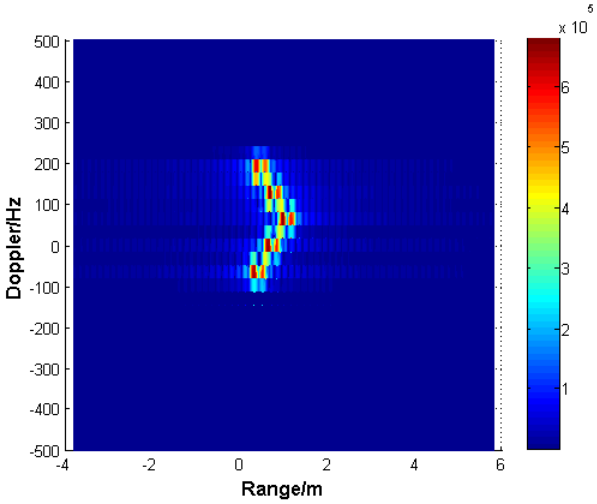


FIGURE 9. **Imaging result of the target with cross-shaped metamaterial.**

$P_6(0.4, 9\pi/10, 1)$, $P_7(0.4, 3\pi/2, 1)$, respectively. The rotation speed of the target ω is 2π rad/s, the target coordinate is $(10^3, 0, 10^3)$ and the radar coordinate is $(10^3, 10^3, 0)$. The number of pulse N equals 32, then, N∗PRI is the pulse accumulation time.

According to the ISAR imaging mechanism, the imaging result of the cone target without cross-shaped metamaterial is simulated, the simulation result is shown as follows.

Considering the light of radar occlusion, radar can only see five point scatters, which are $P_1(0, 0, 0)$, $P_2(0.2, \pi/10, 0.5)$, $P_3(0.2, 9\pi/10, 0.5)$, $P_5(0.4, \pi/10, 1)$, $P_6(0.4, 9\pi/10, 1)$, respectively. In Fig.8, it is found that P_1 is the vertex of the cone; P_5, P_6 have the same distance from the radar, the same Doppler frequency value but are in the opposite direction; P_2, P_3 are the same as P_5, P_6; P_4, P_7 cannot be imaged due to the light of radar occlusion.

In order to study the jamming effect on the ISAR imaging result, the cross-shaped metamaterial is used to cover every point scatters on the cone target model established above. There are seven points on the target, all the points are coated with the designed cross-shaped metamaterial in Section II. Based on the imaging mechanism, the distorted ISAR echo is obtained. Using the R-D imaging algorithm, the imaging result of the cone target with cross-shaped metamaterial is simulated, which is shown as follows.

As is shown in Fig.9, cross-shaped metamaterial has an excellent jamming effect on the ISAR imaging result. Each of the five points turns into more than one point, making the target become blurred. Besides, the half of the energy attenuation leads to the low brightness of the target in the image. The existence of cross-shaped metamaterial could have a negative impact on the image target recognition. Thus, realizing the classification, recognition and tracking of target correctly and accurately will be very difficult.

V. CONCLUSION

Based on resonant absorption effect of metamaterials, a novel passive jamming method against ISAR is proposed in this paper. First, a cross-shaped metamaterial is selected as the passive jamming structure. By optimizing parameters of the unit, the resonance absorption effect in the ISAR signal bandwidth is designed. The reflection properties of the radar target coated with designed metamaterial is calculated by FIT. The results show that the radar echo amplitude-frequency characteristic and the phase-frequency characteristic are both changed, further leading to the radar echo distortion. Thus, the effect of the ISAR echo distortion on the one dimensional range profile is studied further. The range profile result indicates that besides the energy attenuation, single radar target becomes two false radar targets, both of which are not located at the real target position. Then, ISAR imaging analysis model of target coated with the cross-shaped metamaterial is established. The appearance of false target and the energy attenuation make it possible for the realization of ISAR image jamming. Finally, by taking a cone target coated with cross-shaped metamaterial as an example, jamming effects of the cross-shaped metamaterial on the ISAR imaging are studied and verified. The ISAR imaging result shows that the target become blurred and many low-brightness points are produced. It reveals that cross-shaped metamaterial has an excellent jamming effect on the ISAR imaging. This passive jamming method could have a negative impact on the target recognition applied to aircrafts, ships, and missiles. In practical applications, by designing the units, we can make the resonant absorption frequency of the target coated with cross-shaped metamaterial as close to the ISAR center frequency as possible in order to obtain the satisfactory jamming effect. Furthermore, adjustable (EM characteristic) metamaterials would be taken into account to realize jamming effect of different ISAR band.

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