Countering Single-Polarization Radar Based on Polarization Conversion Metamaterial

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ABSTRACT Based on polarization conversion metamaterial, a novel method to counter single-polarization radar is proposed and discussed in this paper. Due to the resonance feature in the polarization conversion, energy attenuation and waveform distortion dual functions can be achieved. For radar, that will strongly reduce the SNR (Signal-to-Noise Ratio) of the matched filter and the probability of detection. A broadband polarization conversion metamaterial structure was designed with multi resonance frequencies. To evaluate the effectiveness, a typical pulse compression radar model was established, the waveform property, correlation loss in the matched filter and probability of radar detection were simulated and calculated. It was found that the metamaterial achieved the function of passive signal modulation, the echo energy was reduced markedly and great distortion was generated near the resonance frequencies, also the correlation loss in the matched filter was significantly increased especially near the resonance frequencies. Finally the calculated probability of radar detection gave furthermore proof of the effectiveness of the method.

INDEX TERMS Polarization conversion metamaterial, single-polarization radar, radar countermeasures, passive signal modulation.

I. INTRODUCTION
Electromagnetic metamaterials are artificially designed media composed of subwavelength structures, which have attracted great attention in recent years due to its extraordinary electromagnetic properties that traditional materials do not possess [1]–[4]. Especially in the area of stealth technology, taking advantage of the function of perfect absorption [5]–[7], anomalous scattering [8], [9], metamaterials have been developed as new technic to counter the radar detection with much potential. The basic principle of these studies is same to the ordinary stealth technics including absorbing coating and special configuration design, aiming at lowering down the reflection energy in the radar direction. Besides the countering in the energy domain, some researchers have paid their attention to the signal property of the radar echo [10]–[13]. The waveform distortion caused by the resonance absorption effect of metamaterials or plasma can destroy the correlation between the transmitted signal and the echo, thus bringing additional jamming effect to the radar detection. However, few works have concentrated on the polarization manipulation ability of metamaterials, which is also an important domain in radar countering. For the receiver of radar system, power loss depends on not only the attenuation in the propagation but also the mismatch of polarization between the echo and the receiving antenna.

There are still a lot of active service radars operate in single polarization, for which effective echo power can be reduced through converting the polarization of the echo to its orthogonal form. Polarization conversion metamaterials just right have the ability to manipulate the polarization of electromagnetic waves [14]–[16]. So it can be employed to reduce the radar’s effective receiving power. What’s more, the realization of polarization conversion is always accompanied by strong resonance and dispersion, which brings great distortion to the signal waveform, reducing the correlation with the original signal. That is to say, polarization conversion metamaterials would counter the radar detection in dual functions of energy attenuation and waveform distortion.

In this paper, metamaterial was used into the field of radar countermeasure in polarization domain and signal domain. We proposed a design of metamaterials that can
converse the incident linear polarized (LP) waves into its cross-polarization counterparts, and keep the helicity for both left circular polarized (LCP) waves and right circular polarization (RCP), as shown in Fig.1. The metamaterial structure was designed with multi resonance frequencies, realizing a broadband polarization conversion effect. The performance of the broadband polarization conversion and the resonance property is simulated. Then, the metamaterial’s influences on the waveform and spectrums of the echo are calculated, where remarkable signal distortion was achieved. Furthermore, the correlation loss in the matched filter caused by the energy attenuation and waveform distortion is calculated with typical pulse compression techniques. The probability of radar detection is calculated in the end, which gives further proof of the countering effectiveness of the metamaterial to single polarization radar.

II. POLARIZATION CONVERSION METAMATERIAL DESIGN

We describe our strategy to realize the function of polarization conversion, starting from discussing the working principle of the metamaterial unit cell. In this work, the metamaterial structure is composed of periodic repetition unit cells, each of which consists of a double-head arrow shaped structure etched on a grounded substrate ($\varepsilon_r = 2.65$, loss tangent is 0.01), as shown in Fig.2(a). The metallic structure on top is constituted of copper with a thickness of 0.036mm. The unit cell has a period of $p = 5.0$mm, and the other geometrical parameters are as follow: $a = 5.6$mm, $b = 2.0$mm, $d = 3.0$mm and $w = 0.3$mm. The metamaterial structure is illuminated by a normal incident plane-wave along the $-z$ direction, which is either LP or circular polarization (CP). In order to facilitate the analysis, a new coordinate system was established along the diagonal direction, as shown in Fig.2(b).

For the LP incidence, which is either horizontal ($x$-) or vertical ($y$-) polarized, the electric field vector can be decomposed into $u$ and $w$ direction. It has been demonstrated that the symmetry was broken in $u$ and $w$ direction, which causing the modification of the polarization of the reflected wave [17], [18]. Without loss of generality, here we give a detailed discussion for the $x$-polarized incidence. As shown in Fig.2(b), the incident field $E_i$ can be decomposed into $u$ and $w$ direction, $\vec{E}_i = E_{i\parallel} \hat{u} + E_{i\parallel} \hat{w}$. It can be easily got that $E_{iu} = E_{iw}$. All the incident energy will be reflected back by the metal plate at the bottom, that means the reflected field has the same amplitude to the incidence, i.e. $E_{rw} = E_{iw}$ and $E_{rw} = E_{iw}$, where $E_{rw}$ and $E_{rw}$ is the amplitude of the $u$ and $w$ component of the reflected field, respectively. However, the reflected phases are different for $u$ and $w$ polarization. For the $u$-polarization incidence, electromagnetic resonance can be generated along the metal arrow structure. The phase of reflected field will remain unchanged. Thus the composed reflected wave $\vec{E}_r = E_{ru} \hat{u} + E_{rw} \hat{w}$ will change its polarization to the $y$ direction. For the $w$-polarization incidence, the structure generates no resonance at above frequencies. The field is reflected by the metal back, $E_{rw}$ obtain phase change of $\pi$, which will change its direction into the opposite of $E_{rw}$. Under the same principle, the $y$-polarized incidence will be converted into $x$-polarized reflection.

The proposed structure also works for the CP waves. If a single metal plate illuminated by the CP waves which also can be decomposed into $u$ and $w$ directions, as shown in Fig.2(c), both $E_{rw}$ and $E_{rw}$ will obtain phase change of $\pi$. But the phase difference between $E_{rw}$ and $E_{rw}$ remain unchanged. Because the propagation direction of the reflected wave is changed to the opposite direction as the incidence, the polarization of the wave will become its cross-polarization counterparts, i.e. LCP (RCP) incidence corresponds to RCP (LCP) reflection. So the CP radars need two antennas with different polarization, one for transmitting, the other for receiving. It can be inferred that if the CP waves illuminate onto the proposed structure, $E_{rw}$ will obtain phase change of $\pi$, while the phase of $E_{rw}$ will remain unchanged because of the resonance along the metal structure. Thus the reflected CP waves will be co-polarization counterparts, i.e. LCP (RCP) incidence corresponds to LCP (RCP) reflection. Therefore, the CP radar will receive only little echo energy.

The reflection property was studied by employing the software CST Microwave Studio, as shown in Fig.3 and Fig.4. In Fig.3, it can be found that the unit cell provides a broadband high efficient cross-polarization reflection for LP wave, where the reflectivity keeps larger than 90% from 7.8GHz to 21.5GHz. The broadband polarization conversion effect results from the superposition of multiple resonance peaks around 9.25GHz, 13.52GHz, and 19.52GHz, where three descending peaks arise for the co-polarization reflected waves. Correspondingly, sharp reflection phase variation of the co-polarization reflected waves can be found at these
FIGURE 3. Reflection property of (a) amplitude, and (b) phase of the metamaterial for LP (horizontal and vertical polarized) incidence.

FIGURE 4. Reflection property of (a) amplitude, and (b) phase of the metamaterial for CP (LCP and RCP) incidence.

FIGURE 5. Time-domain waveform and spectrum of transmitted wave.

III. JAMMING EFFECTIVENESS ON ECHO WAVEFORM

The scattered echo signal carries the information of the target. Owing to the electromagnetic resonance effect in the polarization metamaterial structure as shown above, the waveform and spectrum of the echo will be vigorously modulated. Here, we adopt the linear frequency modulation (LFM) signal to study this effect. LFM signal is a typical kind of pulse compression signal, which has been widely used in modern radar system; it can enhance the SNR of radar receiver and has high distance resolution at the same time [19], so it is generally difficult to jam the pulse compression radars. The transmitted LFM pulse signal can be expressed as

\[ s_0(t) = A_0 \cos(2\pi f_0 t + \pi \mu t^2) \text{rect}(t/T) \]

where \( A_0 \) is the peak amplitude, \( f_0 \) is the initial frequency, \( \mu \) is the frequency modulation slope, \( T \) is pulse width. The rectangular window function is \( \text{rect}(t/T) = 1 \) for \( 0 \leq t \leq T \) and zero otherwise. The bandwidth of LFM signal can be calculated as \( B = \mu T \).

For stationary target without jamming material, the echo signal contains attenuation of the amplitude and time delay from the target, which can be expressed as [19]

\[ e_1(t) = A_1 \cos[2\pi f_0 (t - T_1) + \pi \mu (t - T_1)^2 \text{rect}((t - T_1)/T)] \]

where \( A_1 \) is the echo amplitude, \( T_1 = 2R_1/c \) is the delay time, here \( R_1 \) represents the target distance, \( c \) is the light velocity in vacuum.

Obviously, the echo has the same waveform with the source, they are highly correlated.

While for the target covered with the proposed metamaterial, the echo gets strong distortion, resulting from the co-polarization energy loss and phase abrupt change. For LP radar, the echo spectrum can be calculated as convolution of the normal echo \( S_1(f) \) and the co-polarization reflectance \( r_{hh}(f) \), or \( r_{vv}(f) \). For CP radar, it can be calculated as convolution of \( S_1(f) \) and the cross-polarization reflectance \( r_{RL}(f) \), or \( r_{LR}(f) \).

\[ E_2(f) = S_1(f) \otimes r_{hh}(f), \quad \text{or} \quad E_2(f) = S_1(f) \otimes r_{vv}(f), \]

\[ E_2(f) = S_1(f) \otimes r_{RL}(f), \quad \text{or} \quad E_2(f) = S_1(f) \otimes r_{LR}(f) \]
where ⊗ represents the inverse Fourier operation. Then the echo can be got from the inverse Fourier transform.

\[ e_2(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E_2(f) e^{j2\pi ft} df \]

Owing to the highly symmetry of the metamaterial structure, the reflectance for co-polarization LP cross-polarization CP incidence and are almost the same. The horizontal polarization was chosen as the representative to study the jamming effect. In order to evaluate the effect in the broad polarization conversion band, we take 5 signal samples in different carrier frequencies, as listed in Table 1. These 5 sample signals are with the same pulse width \( T = 2\)us, and the same bandwidth \( B = 100\)MHz. The base band waveform and the spectrum of the transmitted signal are shown in Fig.5. The spectrum varies from 0 to 100MHz. The positions of these frequencies are marked in Fig.2. It can be perceived that they represent 5 different types situation: 9.50GHz locates on the reflectivity rising section, 18.25GHz locates on the reflectivity decline section, 13.42GHz, 13.47GHz and 13.52GHz locate near the resonance frequency 13.52GHz. For the signal sample No.4, \( f_0 = 13.47GHz \), with the additional modulation bandwidth 100MHz, the central of the spectrum are right located in the resonance frequency 13.52GHz.

Then the echoes of the 5 sample signals are shown in Fig.6 - Fig.10, the results indicate that both the waveforms and spectrums are distorted besides the amplitude attenuation. Fig.6 shows the echo at 9.50GHz, the amplitude for both the waveform and the spectrum have tiny upward sloping. That can be explained from Fig.3, which shows the co-polarization reflectivity goes up slowly, and the reflection phase varies gently at 9.50GHz. So the echo got mainly attenuation of the amplitude and a little distortion.

Fig.7 shows the echo at 18.25GHz, the amplitude for both the waveform and the spectrum have tiny downward sloping. Similarly, Fig.3 shows the co-polarization reflectivity goes down slowly, and the reflection phase varies gently at 18.25GHz. So the echo also got mainly attenuation of the amplitude and a little distortion at 18.25GHz.

![FIGURE 6. Time-domain waveform and spectrum of echo with carrier frequency \( f_0 = 9.50GHz \).](image)

![FIGURE 7. Time-domain waveform and spectrum of echo with carrier frequency \( f_0 = 18.25GHz \).](image)

![FIGURE 8. Time-domain waveform and spectrum of echo with carrier frequency \( f_0 = 13.42GHz \).](image)

![FIGURE 9. Time-domain waveform and spectrum of echo with carrier frequency \( f_0 = 13.47GHz \).](image)

![FIGURE 10. Time-domain waveform and spectrum of echo with carrier frequency \( f_0 = 13.52GHz \).](image)

Table 1. Carrier frequencies of the 5 signal samples.

| No. | 1   | 2   | 3   | 4   | 5   |
|-----|-----|-----|-----|-----|-----|
| \( f_0 \) (GHz) | 9.50 | 18.25 | 13.42 | 13.47 | 13.52 |

Fig.8-10 shows the frequencies near the middle resonant frequency 13.52GHz. As shown in Fig.8, the spectrum for \( f_0 = 13.42GHz \) lies in the left side of the resonance frequency 13.52GHz, so the amplitude for both the echo waveform and the spectrum present upward sloping. Similarly, as shown in Fig.10, the spectrum for \( f_0 = 13.52GHz \) lies in the right side of the resonance frequency, so the amplitude for both the echo waveform and the spectrum present downward sloping. While the spectrum for \( f_0 = 13.47GHz \), whose center coincides with the resonance frequency, presents two peaks.

It can be confirmed that due to strong polarization conversion effect, the echoes got huge distortion for both the waveforms and the spectrums, especially for the signals near the resonance frequency. This distortion will result in mismatch between the radar echo and the transmitted signal, reduction of the SNR in the matched filter, and then lowering down the radar detection, that will be talked in the followings.

IV. JAMMING EFFECTIVENESS ON RADAR DETECTION

We take a typical signal processing model of pulse compression radar to evaluate the metamaterial jamming effect to single-polarization radar. The simulated signal processing procedure is shown in Fig.11, after down conversion, echo signal enters the matched filter. The output of the matched
FIGURE 10. Time-domain waveform and spectrum of echo with carrier frequency \( f_0 = 13.52\text{GHz} \).

FIGURE 11. Radar signal processing flow path.

The filter can be got by the cross-correlation function of the transmitted signal and the echo.

\[
y(t) = \int_{-\infty}^{\infty} e^{2(\tau)} s_0(t - \tau) d\tau
\]

This result corresponds to the conditions without noise, but the practical radar detection is to seek the target in the background of noise. The value of SNR determines the performance of the detection. To simplify the calculation of SNR, first we achieved the SNR loss by comparing the outputs of the matched filter with and without metamaterial.

\[
\text{SNR}_{\text{loss}} = X_1 - X_2
\]

where \( \text{SNR}_{\text{loss}} \) is the loss of instantaneous SNR in dB, \( X_1 \) is the peak value of the matched filter output of the target echo without metamaterial, \( X_2 \) is the peak value of the matched filter output with metamaterial coating on the target.

Then, the output SNR with metamaterial coating on the target can be calculated as

\[
\text{SNR}_{\text{meta}} = \text{SNR}_0 - \text{SNR}_{\text{loss}}
\]

where \( \text{SNR}_0 \) is the output SNR in dB of the target echo without metamaterial. Afterwards, according to the principle of CFAR (Constant False Alarm Ratio) detection, the radar detection results can be achieved using one approximation formula from North [20].

\[
P_d = 0.5 \text{erfc}(\sqrt{-\ln P_{fa}} - \sqrt{\text{SNR}} - 0.5)
\]

where \( \text{erfc}(z) \) is the complementary error function,

\[
\text{erfc}(z) = 1 - \frac{2}{\sqrt{\pi}} \int_{z}^{\infty} e^{-v^2} dv
\]

and \( P_{fa} \) is probability of false alarm, which is chosen to be different value within the range of \( 10^{-6} \sim 10^{-9} \) for different radar systems [21]. In this paper, \( P_{fa} = 10^{-6} \) is adopted in the simulation.

We simulated the 5 aforementioned signal samples, comparisons of matched filtering results with and without metamaterial are shown form Fig.12 to Fig.16, respectively.

Fig.12 shows the results of the matched filter for \( f_0 = 9.50\text{GHz} \). Because the signal distorts a little as talked in Fig.4, the loss in the matched filter mainly comes from the energy attenuations of the co-polarization echo. Similarly, as shown in Fig.13, for \( f_0 = 18.25\text{GHz} \), the loss also mainly comes from the energy attenuations of the co-polarization echo. The SNR loss values for these two are 8.4dB, 7.7dB, respectively.

Fig.14 and Fig. 16 show the results of the matched filter for \( f_0 = 13.42\text{GHz} \) and \( f_0 = 13.52\text{GHz} \), respectively. Because these two frequencies are near the resonance frequency, simultaneous high efficiency polarization conversion and signal distortion are got. The SNR loss can be up to 23.1dB and 22.3dB, respectively.

Fig.15 shows the results for \( f_0 = 13.47\text{GHz} \), when the resonance frequency lies in the center of the spectrum of the signal, as talked in Fig.9. The SNR loss can be up to 25.7dB, and what is more, the main beam is split into two parts, that means single target becomes two false targets several meters apart and the real target is suppressed.

According to the performance of the metamaterial polarization conversion, we then simulated the SNR loss in a broad frequency band from 5GHz to 25GHz. As shown in Fig. 17,
the three peaks of SNR loss appear which is corresponding to the three resonance frequencies in the polarization conversion of the metamaterial. The peak values can be more than 20dB. In the very broad band from 8.43GHz to 20.29 GHz, SNR loss keeps more than 7dB.

The output SNR without metamaterial is set $SNR_0 = 15$dB, for which the probability of radar detection $P_d$ nearly equals 1, that means the target can be identified from the noise very easily. While SNR loss comes from the metamaterial will reduce the performance of radar detection. According to a more prescriptive rule in electronic countermeasures, $P_d \leq 0.1$ is adopted as a valid criterion of the jamming effectiveness. We calculated the probability of detection under the jamming of metamaterial, as shown in Fig.18. Over the polarization conversion band from 8.34GHz to 20.42GHz, the radar lost the efficiency of detection for the target.

V. CONCLUSION

In conclusion, a scheme of countering single polarization radar based on polarization conversion metamaterial was proposed. A metamaterial structure for broadband polarization conversion was designed with multi resonance frequencies. High efficiency polarization conversion was achieved from 7.8GHz to 21.5GHz. During the whole band, co-polarization reflected energy of LP waves and cross-polarization reflected energy of CP waves were markedly reduced, resulting in the attenuation of the amplitude of the echo, correlation loss in the matched filter and reduction of the probability of radar detection. What’s more, near the resonance frequency, the strong resonance and dispersion effect bring about significant waveform distortion and correlation loss, even false targets were generated. Correspondingly, the probability of radar detection was reduced to be nearly zero. It is worth noting that the working frequency can be manipulated through the geometry design of the metamaterial. These results indicate that the polarization conversion metamaterials provide effective countering technic to single polarization radar.
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