Passive Radar Jamming: A Novel Method Using Time-Varying Plasma

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Abstract—Based on the resonance absorption effect of plasma, a novel time-varying plasma passive jamming method against one dimensional range profile of radar detection is proposed in this paper. The jamming mechanism of time-varying plasma structure is presented and verified. Based on the transmission line analogy, an instantaneous method is developed to calculate the radar time domain echo and the pulse compression of a target coated by the time-varying plasma. Then, the distortions of radar waveform and spectrum are numerically calculated. Finally, the jamming effect of the time-varying plasma on the one-dimensional range profile of a target is studied systematically for different regulating amplitude and frequency of electron density, radar bandwidth and pulse width parameters. The range profile result indicates that single radar target coating by time-varying plasma structure will generate cloaking effects and produce two or more false radar targets, and the distance between real and false target as well as reduction of echo intensity are related to the radar and regulating plasma parameters. The results show that this jamming method could have a great impact on the one-dimensional range profile, and the results could provide many useful reference to radar countermeasure.

Index Terms—passive jamming, time-varying plasma, range profile, false target

I. INTRODUCTION

During the last few decades, plasma technology have attracted great attention due to its unusual electromagnetic (EM) property [1–4] which the conventional material does not possess. First, plasma can be applied to stealth technology (act as an EM-wave absorber) since its wide absorbing bandwidth and high absorption efficiency. Considerable efforts [5–12] have been made to study on the reduction of the radar cross section (RCS) by plasma coating. Rokhlenko [5] studied the reflection properties for EM waves normally incident on a flat perfect conductor shielded with semi-infinite plasma. Koretzky [6] demonstrated that plasma torches can effectively attenuate EM waves. Chaudhury [7, 8] calculated microwave scattering from metallic objects shielded by plasma shroud and studied RCS characteristics of a flat plate covered with inhomogeneous plasmas. Yuan [9, 10] proposed an enclosed plasma stealth structure, and verified the stealthy mechanism. Liu et al. [11] studied the influence of plasma induced by α-particles on the decrease of radar echoes. Second, plasma can be used as a kind of passive jammer because of the distortion effects of plasma on the radar echo waveform. Xu et al. [13–15] have proposed a novel jamming technology of plasma based on the resonance absorption effect of plasma, and the results show than it is possible for plasma to jam the detection of radar echo and produce the phenomenon of false target.

Among the above researches, the plasma is only considered as a time-invariant medium, and the effectiveness of absorbing and jamming are both time-invariant and difficult to adapt to changes in the environment. Practically, the plasma electron density which is main physical parameter related to the reflection property of plasma can be adjust as needed quickly [16]. Especially, when the plasma is regulated time-varyingly around the strong resonance absorption effect, the amplitude and phase of radar echo would change greatly in the bandwidth, and the intra-pulse of radar echo will be modulated by plasma. Thus, plasma could be used as a time-varying passive jammer to produce the phenomenon of multi-false target and destroy the radar detection.

However, researchers have mainly focused on the power attenuation of plasma medium, and few work has concentrated on the distortions of the time-varying plasma on the radar echo waveform and the jamming effects on the radar range profile. For this purpose, based on resonant absorption effect of plasma, a novel time-varying plasma passive jamming method against one dimension range profile of radar detection is proposed in this paper. The remainder of this paper is organized as follows. In Section II, physical model and jamming mechanism of the time-varying plasma structure are given, and an instantaneous method is developed to calculate the radar echo and the pulse compression of a target coated by time-varying plasma. In Section III, the distortions of radar waveform and spectrum are numerically calculated, and the jamming effect of time-varying plasma on the one-dimensional range profile of a target is studied systematically for different regulating amplitude and frequency of electron density, radar bandwidth and pulse width parameters. Finally, the conclusion is reported in Section IV.

II. PHYSICAL MODEL AND ANALYSIS METHODS

A. Physical Model and Jamming Mechanism of Time-varying Plasma Structure

As shown in Fig.1, an enclosed plasma jamming structure is composed of a glass fiber reinforced plastic (GFRP) skin and a time-varying plasma slab. The GFRP skin could enclose the
plasma and block off the visible glow. The inductively coupled plasma (ICP) producing technology is adopted to create time varying plasma slab. The main components of discharge device are discharge power supply and RF matching system, vacuum pumping system, discoid discharge coil and discharge cavity. The discharge coil is placed at the bottom of the cavity, and the plasma is produced in closed cavity, which has the advantages of stable discharge state and high electron density. The electron density of ICP is proportional to the input discharge power. By controlling the variation of input power with time, the electron density would vary with time and the time-varying plasma is produced consequently. The geometric sketch of typical radar waves (linear Frequency modulated LFM waves) incident on the time-varying plasma jamming structure is shown in Fig. 1. As is well-known, the electron density is the main parameter which can affect the reflection characteristic of EM waves in plasma. Thus, when the radar wave is incident on the structure, the multi-interactions of LFM waves and time-varying plasma are complicated and would lead to intrapulse distortion of radar echo. Further, the radar signal processing would be disrupted and the one-dimensional range profile of radar detection would be jammed.

Fig. 1. Physical model of an enclosed time-varying plasma structure

According to ref.[13], [14], each radar carrier frequency has a critical plasma parameter including the electron density \( N_e \) and collision frequency \( v \) to generate a satisfying resonance absorption effect. For example, the critical plasma parameters for three typical radar frequencies 3.3GHz, 5.6GHz and 10GHz are \((N_e=7 \times 10^{16}/m^3, v=4.4GHz)\), \((N_e=2 \times 10^{17}/m^3, v=4.0GHz)\) and \((N_e=3.4 \times 10^{17}/m^3, v=0.6GHz)\), respectively, and the resonance absorption effect is presented in Fig. 2. The mechanism of time-varying plasma jamming technology is that the electron density is regulated around the critical parameter and the amplitude difference within radar echo intra-pulse will reach dozens of decibels, causing the radar intra-pulse modulation effect which will influence radar signal processing and produce false targets deceptive jamming.

Fig. 2. The resonance absorption effect of plasma for different radar frequencies

B. Analysis Method of radar echo Time-varying Plasma

The time-varying characteristic of plasma can be all kinds of functions. Taking the most fundamental and typical sinusoidal variation as example, the electron density \( N_e(t) \) is defined as

\[
N_e(t) = N_{ep}(1 + \alpha \cdot \cos(2\pi f_r \cdot t)),
\]

where \( N_{ep} \) is the critical electron density, \( \alpha \) is the extent of variation, \( f_r \) is the regulating frequency, \( t \) is time.

Because, the transmitting time of radar waves in plasma is much greater than plasma varying time. Thus, when the LFM radar wave incident on the jamming structure, the time-varying plasma and LFM waves could be divided into large numbers of static state according to the discrete time sequence. For each static state, the reflection properties of instantaneous wave can be determined by the transmission line analogy [17], [18]. Then, the radar time-domain echo could be obtained by synthesizing all the computation results of discrete time sequence.

The calculation process for radar echo waveform reflected by time-varying plasma is shown in Fig. 3. First, the LFM wave is adopted as the transmitted radar signal, and its instantaneous discrete form \( E(t_0, f_0) \) is defined below:

\[
E(t_0, f_0) = \exp(j \cdot 2\pi f_0 \cdot t_0 - j \cdot \pi \cdot k \cdot t_0^2),
\]

where \( t_0 = m \cdot dt \) is the discrete time of calculation, \( f_0 = f_0 + k \cdot t_0 \) is the instantaneous frequency at the moment \( t_0 \), and \( f_0 \) is the carrier frequency, \( k \) is frequency modulation slope.

Then, the discrete form of plasma electron density \( N_e(t_n) \) and dielectric coefficient \( \varepsilon(t_n) \) according to discrete time step \( t_n \) is obtained by

\[
N_e(t_n) = N_{ep}(1 + \alpha \cdot \cos(2\pi f_r \cdot t_n)),
\]

\[
\varepsilon(t_n) = 1 - \frac{2\pi}{f_r^2} \cdot \left( \frac{f_p(t_n)}{f_p(t_n) + v^2} \right),
\]

where \( f_p(t) \) is the plasma frequency, \( v \) is the plasma collision frequency, \( e \) is the electron charge, \( m_e \) is the electron mass, and \( \varepsilon_0 \) is the free space dielectric constant, respectively.

Based on the transmission line analogy, a transient method is developed to calculate the time-varying reflection coefficient of the EM wave incident on the time-varying plasma structure. In this method, the propagation constant \( k(t_n) \) and the intrinsic wave impedance \( Z(t_n) \) of EM wave in the plasma slab at moment \( t_n \) is expressed as
where $\mu_0$ is free space permeability. The transmission matrix of the $m$-th layer at state $(t_0)$ is
\[
\begin{bmatrix}
A(t_0) & B(t_0) \\
C(t_0) & D(t_0)
\end{bmatrix} = \begin{bmatrix}
\cosh(\beta(t_0) d) & \sinh(\beta(t_0) d) \\
\frac{1}{Z(t_0)} \sinh(\beta(t_0) d) & \cosh(\beta(t_0) d)
\end{bmatrix}.
\]

The reflection coefficient at state $(t_0)$ can be expressed as
\[
R(t_0) = \frac{B(t_0) - Z_0 \cdot D(t_0)}{B(t_0) + Z_0 \cdot D(t_0)},
\]
where $Z_0$ is the free space wave impedance.

Since the $R(t_0)$ is nonlinear modulated by the time-varying plasma, $R(t_0)$ can be expressed as
\[
R(t_0) = A_0 + \sum_{m \neq 0} n A_m \cdot \cos(2\pi m f \cdot t_0),
\]
where $A_0$ is the mean value of $R(t_0)$ amplitude, $A_m$ is $m$-th order modulation which is relate to the extent of variation $a$.

Finally, the radar echo expression of a PEC surface coated with time-varying plasma structure can be expressed as below:
\[
S(t_0) = R(t_0) \cdot \text{rect} \left( \frac{t_0}{T_p} \right) \cdot \sin \left( 2\pi \cdot \left( f_0 \cdot t_0 + \frac{1}{2} k \cdot t_0^2 \right) \right)
= \text{rect} \left( \frac{t_0}{T_p} \right) \cdot \sin \left( \pi \cdot k \cdot t_0^2 \right),
\]
where $T_p$ is radar pulse width, $k$ is chirp constant.

Because the electron density is changed around the critical parameter, it can be concluded that the amplitude and phase of the radar echo intrapulse changes greatly with time, making the modulation effect and be possible to jam radar detection.

C. One Dimensional Range Profile of Target Coated with Time-varying Plasma Jamming Structure

The one-dimensional range profile of a target coated with time-varying plasma jamming structure is acquired by the pulse compression processing of the radar echo, and the output of pulse compression processing $Y(n)$ can be described by the convolution operation [19] between $S(t_0)$ and the impulse response of the matched filter
\[
Y(n) = S(t_0 - t_0) * H(t_0),
\]
where the operation $*$ indicates convolution, $H(t_0) = S_0(t_0)$ is the impulse response of matched filter, and $t_0$ is the propagation time delay of radar echo. By combination (11) and (12), the impulse response of matched filter is deduced as [20]
\[
Y(n) = A_0 + \sum_{m \neq 0} n A_m \left( 1 - \frac{m f}{B} \right) \cdot \sin c \left( B \left( 1 - \frac{t_0}{T_p} \right) \left( t_0 + \frac{m f}{B} \cdot t_0 \right) \right)
\]
where $B$ is radar bandwidth. Thus, the one-dimensional range profile is consists of many spikes and can be regarded as a number of point-like false targets. Each point-like false target corresponds to a sinc function peak. $A_0$ represents the radar echo intensity of real target, and $A_m$ is the radar echo intensity of $m$-th false targets on both sides of real target. The range of false targets away from the real target is given by
\[
\Delta R_m = \frac{m f}{2B} \cdot c
\]
where $c$ is speed of light.

Therefore, the radar echo intrapulse is drastic fluctuant, the jamming effect of time-varying plasma on the one dimensional range profile of the target can be inferred according to the distortion of pulse compression.

III. SIMULATION RESULTS AND DISCUSSIONS

In this section, we take a typical S-band radar as an example and adopt the LFM wave as the transmitting wave, the radar parameters range and plasma regulating parameters adopted in the following simulations are specified in Table I. Then, the distortions of radar waveform and spectrum are numerically calculated. Finally, the jamming effect of time-varying plasma on the one dimensional range profile of a target is studied for different amplitude and frequency of electron density variation, radar bandwidth and pulse width parameters.

<table>
<thead>
<tr>
<th>TABLE I SIMULATION PARAMETERS</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Carrier Frequency</td>
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<td>Radar Bandwidth</td>
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<td>Pulse Width</td>
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<td>Target Location</td>
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<td>Plasma Regulating Frequency</td>
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<td>Plasma Regulating Amplitude</td>
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<td>Critical Electron Density</td>
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<td>Plasma Collision Frequency</td>
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In consideration of practical switching and response time of plasma source, the time step $t_0$ of plasma electron density varied is a great many times of discrete time step $t_0$. For example, an actual curve of time-varying electron density $N(t)$ is shown in Fig.4, where $N_{ep}=7.2*10^6/m^3$, $a=0.6$, $f_r=500kHz$, $t_0=6us$. The thickness of plasma slab is 5cm.

![Fig. 4. An actual curve of time-varying electron density](image-url)
Fig. 5 and Fig. 6, respectively.

![Waveform of reflected waves](image)

**Fig. 5.** Time-domain waveform of radar echo.

![Spectrum of reflected waves](image)

**Fig. 6.** Spectrum of radar echo.

It is found that waveform and spectrum of the radar echo fluctuate greatly within the pulse width and the radar bandwidth. In the radar bandwidth, the difference of the echo intensity of different frequencies will be as high as 20 dB, and this will lead to the mismatch between the radar echo signal and the matched filter greatly.

### B. The Jamming Effect of Amplitude of Electron Density Variation on the One Dimensional Range Profile

The amplitude of electron density variation is an important factor for regulating radar echo, and it is necessary to analyze the jamming effect of variation amplitude of electron density on the one dimensional range profile. In this section, we set the radar transmitting signal parameter as: $B=50$MHz, $T_p=10\mu$s, range gate width is 500m, $f_r=500$kHz and the range of variation amplitude of plasma electron density is 0.2 to 0.8. The one dimensional range profile of a target coated with time-varying plasma jamming structure are acquired by Equation (10), and the calculated results of different plasma variation amplitude are shown in Fig. 7(a)–(c).

![Compressed amplitude](image)

**Fig. 7.** The jamming effect of different plasma variation amplitude

For the variation amplitude $a=0.2$, results in Fig. 7(a) indicate that the pulse compressed amplitude of the real target coated by time-varying plasma is decreased by 32dB comparing with the pulse compressed amplitude of the real target without plasma. Meanwhile, two false targets appear about 15m from the real target, and the pulse compressed amplitude of the false target is 7dB larger than that of the real target.

For the variation amplitude $a=0.6$ and $a=0.8$, results in Fig. 7(b)-(c) indicate that several false targets appear integer multiple 15m away from the real target. The pulse compressed amplitudes of the false target and real target of $a=0.8$ are larger than that of $a=0.6$, and the number of false targets of $a=0.8$ is more than that of $a=0.6$.

Moreover, by comparing the above results, we can conclude that the larger the variation amplitude of plasma density is, the smaller the echo pulse compressed amplitude attenuation is, but the more false targets are. When the variation amplitude $a$ is small, the real target would hide in the false targets to make it detected difficulty.

### C. The Jamming Effect of frequency of electron density variation on the One Dimensional Range Profile

The regulating frequency of plasma electron density is also an important factor for regulating radar echo, and the jamming effect of regulating frequency of electron density on the one dimensional range profile is studied. In this section, we set the radar transmitting signal parameter as: $B=50$MHz, $T_p=10\mu$s, $a=0.2$ and the regulating frequency range of electron density is 100kHz to 1MHz. The results of different plasma regulating frequency are shown in Fig. 8(a)–(c), respectively.
The jamming effect of different radar bandwidths on the one dimensional range profile

For the narrowband signal, shown in Fig. 9 (a), the pulse compression of the real target echo is reduced by 36dB, and the false target is most far away from the real target which is about 75m. Meanwhile, the false target echo intensity is 8dB larger than the real target.

For the broadband signal, shown in Fig. 9 (b)–(c), the larger the radar bandwidth, the closer the distance between the false and the real target is. In practical applications, for the high range resolution radar system which bandwidth is larger than 1GHz, the regulating time-varying plasma would lead to the expansion and distortion of the one dimensional range profile characteristic of the target, which will produce jamming effect on radar recognition.

E. The Jamming Effect of radar pulse widths on the One Dimensional Range Profile

In this section, the jamming effect of regulating time-varying plasma on the one dimensional range profile of different radar
pulse widths are studied. Parameters of regulating time-varying plasma are set as: \( a=0.2, f_r=500\text{kHz} \). The S-band LFM radar signal parameters are set as: \( B=50\text{MHz} \), and the pulse width range is 10\( \mu \text{s} \) to 100\( \mu \text{s} \). The results of different radar pulse width are shown in Fig. 10(a)–(c), respectively.

From the results, we can conclude that the larger the radar pulse width, the larger the distance between the false and the real target is. For example, the distance between the false and the real target for \( T_p=50\mu \text{s} \), 100\( \mu \text{s} \) is 75m, 150m, respectively. Meanwhile, by comparing the pulse compression results, the reductions of the echo intensity of real and false targets with plasma is consistent for different pulse width. For example, the reductions of the echo intensity of the real target for \( T_p=10\mu \text{s} \), 50\( \mu \text{s} \), 100\( \mu \text{s} \) are both 32dB.

Fig. 10. The jamming effect of different radar pulse width.

IV. CONCLUSION

Based on resonant absorption effect of plasma slab, a novel plasma passive jamming method against one dimension range profile of radar detection is proposed in this paper. First, a regulating time-varying plasma is adopted as the jamming structure. The jamming mechanism of the time-varying plasma structure is presented and verified. Based on the transmission line analogy, an instantaneous method is developed to calculate the radar echo and the pulse compression of a target coated by time-varying plasma. Then, the distortions of radar waveform and spectrum are numerically calculated. Finally, the jamming effect of time-varying plasma on the one-dimensional range profile of a target is studied for different regulating amplitude and frequency of electron density, radar bandwidth and pulse width parameters. The range profile result indicates that:

1. The original single radar target becomes a real target and two or more false radar targets. When the variation amplitude \( a \) is small, the reduction of the real target echo intensity is very large which cannot be detected easily by shielding in many false targets. Meanwhile, the larger the variation amplitude of plasma density is, the more false targets are. For different regulating frequency, the larger the regulating frequency \( f_r \) is, the farther the false target is from the real target.

2. To generate false targets, the basic requirement is that the plasma regulating frequency \( f_r \) should be larger than \( 1/T_p \) which is the reciprocal of radar pulse width.

3. For different radar signal, the smaller the bandwidth and the larger the pulse width is, the farther the false target is from the real target. The regulating time-varying plasma could also distort the one dimensional range profile characteristic of the target for high range resolution radar, which will produce jamming effect on radar recognition.

The simulation results and laws could provide many useful data to radar countermeasure. In practical use, the regulating parameter of time-varying plasma could set based on the enemy radar parameters acquired by the electronic reconnaissance. Furthermore, more complex regulating rule of time-varying plasma and more slab-widths would be taken into account to realize more fantastic jamming effect on radar detection.

REFERENCES


