IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received July 19, 2019, accepted August 4, 2019, date of publication August 16, 2019, date of current version September 9, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2935514

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

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This work was supported in part by the National Natural Science Foundation of China under Grant 61701381, Grant 61431010, and Grant 61627901, in part by the Natural Science Basic Research Plan in Shaanxi Province of China under Grant 2019JM-177, and in part by the Chinese Postdoctoral Science Foundation.

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 inten sity 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 and Kuo [6] demonstrated that plasma torches can effectively attenuate EM waves. Chaudhury and Chaturvedi [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 *et al.* [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

The associate editor coordinating the review of this article and approving it for publication was Zhu Han.

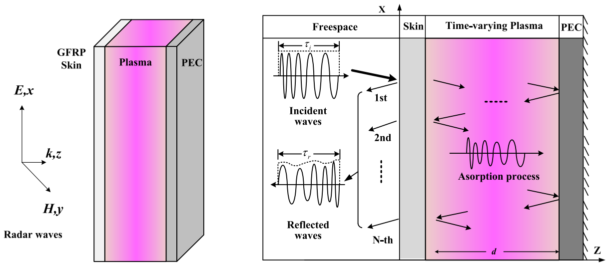


FIGURE 1. Physical model of an enclosed time-varying plasma structure.

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 will 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.

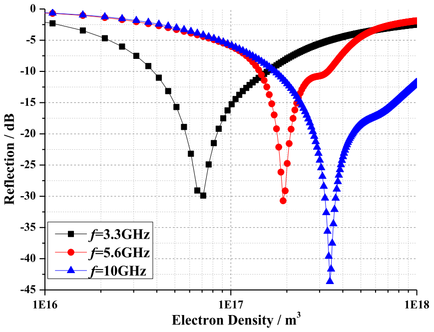


FIGURE 2. The resonance absorption effect of plasma for different radar frequencies.

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 ($N_e = 7{*}10^{16}/\mathrm{m}^3$, $v = 4.4$GHz), ($N_e = 2{*}10^{17}/\mathrm{m}^3$, $v = 4.0$GHz) and ($N_e = 3.4{*}10^{17}/\mathrm{m}^3$, $v = 0.6$GHz), 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.

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

$$N_e(t) = N_{ep}(1+a \cdot \cos(2\pi \cdot f_r \cdot t)), \tag{1}$$

where N_{ep} is the critical electron density, a 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 $E(t_n f_n)$ is defined below:

$$E(t_n, f_n) = \exp(j \cdot 2\pi \cdot f_0 \cdot t_n + j \cdot \pi \cdot k \cdot t_n^2), \tag{2}$$

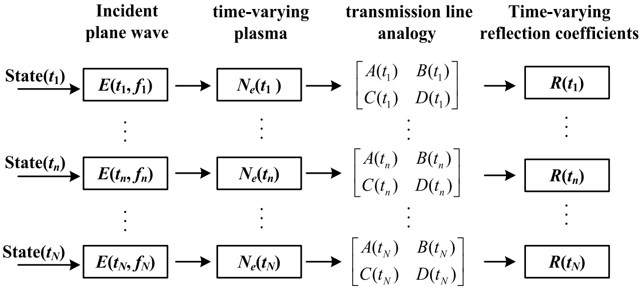


FIGURE 3. **The calculation process for radar echo waveform reflected by time-varying plasma.**

where $t_n = n{\cdot}dt$ is the discrete time of calculation, $f_n = f_0 + k \cdot t_n$ is the instantaneous frequency at the moment t_n, and f_0 is the carrier frequency, k is frequency modulation slope.

Then, the discrete form of plasma electron density $N_{\mathrm{e}}(t_n)$ and dielectric coefficient $\varepsilon(t_n)$ according to discrete time step t_n is obtained by

$$N_{\mathrm{e}}(t_n) = N_{\mathrm{ep}}(1+a \cdot \cos(2\pi \cdot f_r \cdot t_n)) \tag{3}$$

$$\varepsilon(t_n) = [1 - \frac{f_p^2(t_n)}{f_n^2 + \nu^2} - j\frac{\nu}{f_n} \cdot \frac{f_p^2(t_n)}{f_n^2 + \nu^2}] \cdot \varepsilon_0 \tag{4}$$

$$f_p(t_n) = \frac{1}{2\pi}\sqrt{N_{\mathrm{e}}(t_n) \cdot e^2/\varepsilon_0 \cdot m_e}, \tag{5}$$

where $f_p(t_n)$ is the plasma frequency, ν is the plasma collision frequency,e is the electron charge, m_e is the electron mass, and ε_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

$$k(t_n) = 2\pi f_0\sqrt{\mu_0 \varepsilon(t_n)} \tag{6}$$

$$Z(t_n) = \sqrt{\mu_0/\varepsilon(t_n)}. \tag{7}$$

where μ_0 is free space permeability. The transmission matrix of the m-th layer at state (tn) is

$$\begin{bmatrix} A(t_n) & B(t_n) \\ C(t_n) & D(t_n) \end{bmatrix} = \begin{bmatrix} \cosh(jk(t_n)d) & Z(t_n) \cdot \sinh(jk(t_n)d) \\ \frac{1}{Z(t_n)} \cdot \sinh(jk(t_n)d) & \cosh(jk(t_n)d) \end{bmatrix}. \tag{8}$$

The reflection coefficient at state (tn) can be expressed as

$$\tilde{R}(t_n) = (B(t_n) - Z_0 \cdot D(t_n)) \big/ (B(t_n) + Z_0 \cdot D(t_n)), \tag{9}$$

where Z_0 is the freespace wave impedance.

Since the $\tilde{R}(t_n)$ is nonlinear modulated by the time-varying plasma, $\tilde{R}(t_n)$ the can be expressed as

$$\tilde{R}(t_n) = \mathrm{A}_0 + \sum_{m=1}^{\infty} 2{\cdot}\mathrm{A}_m \cdot \cos(2\pi \cdot m \cdot f_r \cdot t_n), \tag{10}$$

where A_0 is the mean value of $\tilde{R}(t_n)$ 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:

$$\begin{aligned} S(t_n) &= \tilde{R}(t_n) \cdot rect\left(\frac{t_n}{T_p}\right) \cdot \sin\left(2\pi \cdot \left(f_0 \cdot t_n + \frac{1}{2}k \cdot t_n^2\right)\right) \\ &= rect\left(\frac{t_n}{T_p}\right) \cdot \sin\left(\pi \cdot k \cdot t_n^2\right) \\ &\quad \cdot \left[\mathrm{A}_0 \cdot \sin(2\pi \cdot f_0 \cdot t_n) + \sum_{\substack{m=-\infty \\ m\neq 0}}^{\infty} \mathrm{A}_m \right. \\ &\quad \left. \cdot \cos(2\pi \cdot (f_0 + mf_r) \cdot t_n) \right]. \end{aligned} \tag{11}$$

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 $S(t_n)$ and the impulse response of the matched filter

$$Y(n) = S(t_n - t_0) * H(t_n), \tag{12}$$

where the operation $*$ indicates convolution, $H(t_n) = S_0^*(\text{-}t_n)$ 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]

$$\begin{aligned} Y(n) = \mathrm{A}_0 + \sum_{\substack{m=-\infty \\ m\neq 0}}^{\infty} \mathrm{A}_m \left(1 - \left|\frac{mf_r}{B}\right|\right) \\ \cdot \sin c\left(B \cdot \left(1 - \left|\frac{t_n}{T_p}\right|\right) \cdot \left(t_n + \frac{mf_r \cdot T_p}{B}\right)\right) \end{aligned} \tag{13}$$

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

$$\Delta \mathrm{R}_m = \frac{mf_r \cdot T_p \cdot c}{2B} \tag{14}$$

where c is speed of light.

TABLE 1. Simulation parameters.

Parameter	Symbol	Value
Carrier Frequency	f_0	3.3GHz
Radar Bandwidth	B	10MHz ~ 250MHz
Pulse Width	T_p	10μs ~ 100μs
Target Location	R_0	10km
Plasma Regulating Frequency	f_r	100kHz ~ 1MHz
Plasma Regulating Amplitude	a	0.2 ~ 0.8
Critical Electron Density	N_{ep}	$7.2*10^{16}/m^3$
Plasma Collision Frequency	v	2.75GHz

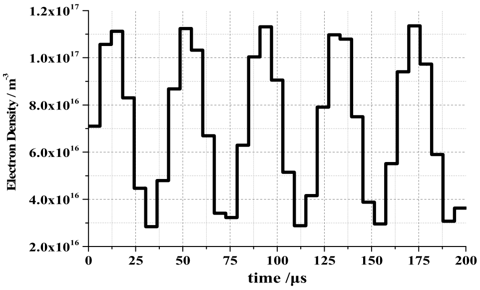


FIGURE 4. An actual curve of time-varying electron density.

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 1. 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.

In consideration of practical switching and response time of plasma source, the time step t_p of plasma electron density varied is a great many times of discrete time step t_n. For example, an actual curve of time-varying electron density $N_e(t)$ is shown in Fig.4, where $N_{ep} = 7.2*10^{16}/m^3$, $a = 0.6$, $f_r = 500kHz$, $t_p = 6\ us$. The thickness of plasma slab is 5cm.

A. WAVEFORM AND SPECTRUM DISTORTIONS OF RADAR ECHO

In this section, we set the radar transmitting signal parameter as: $B = 50MHz$, $T_p = 10\mu s$, and the time-varying plasma in Fig.4 is adopted. The time-domain waveforms and spectrums of radar echo are acquired by Equation (10), and the results are shown in **Fig. 5** and **Fig. 6**, respectively.

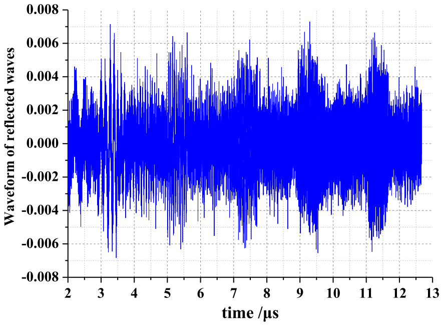


FIGURE 5. Time-domain waveform of radar echo.

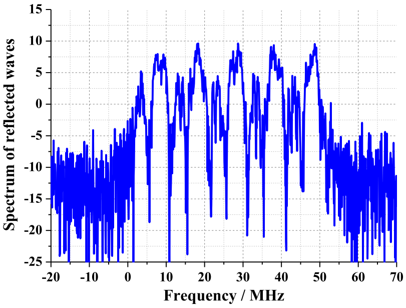


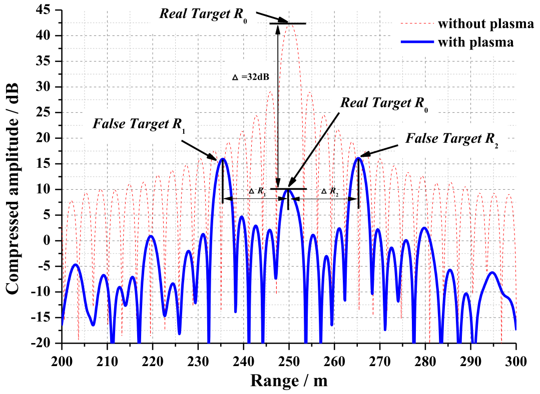
FIGURE 6. Spectrum of radar echo.

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.

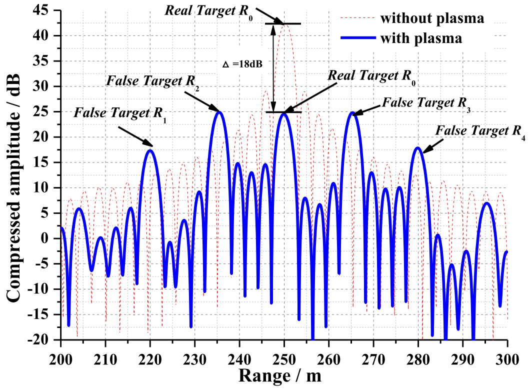
B. THE JAMMING EFFECT OF AMPLITUDE OF ELECTRON DENSITY VARIATION ON THE ONE DIMENSIONAL RANGE PROFILE

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: $B = 50MHz$, $T_p = 10\mu s$, range gate width is 500m, $f_r = 500kHz$ 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)**.

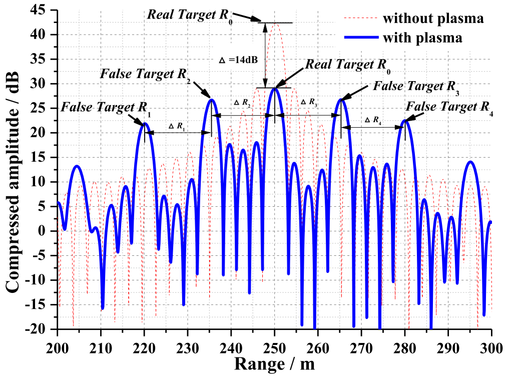
For the variation amplitude $a = 0.2$, results in Fig.7(a) indicate that the pulse compressed amplitude of the real target coated by time-varying plasma is decreased by 32dB comparing with the pulse compressed amplitude of the real target without plasma. Meanwhile, two false targets appear about 15m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



(a) variation amplitude a=0.2



(b) variation amplitude a=0.6

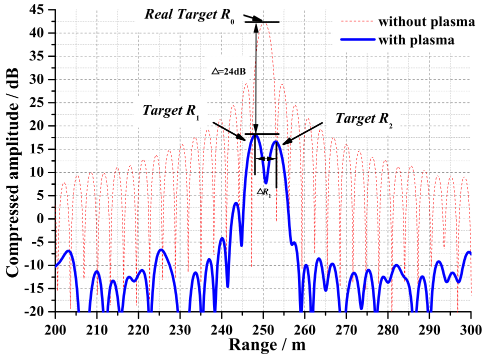


(c) variation amplitude a=0.8

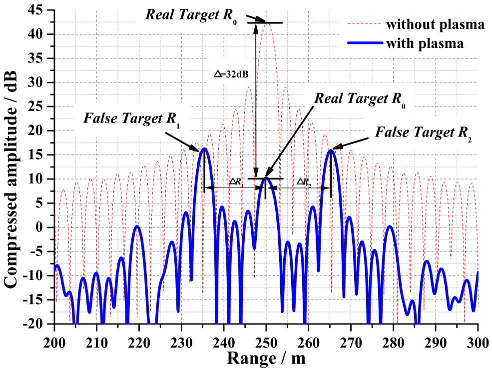
FIGURE 7. **The jamming effect of different plasma variation amplitude.**

For the variation amplitude $a = 0.6$ and $a = 0.8$, results in Fig. 7(b)-Fig.7(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 $a = 0.6$.

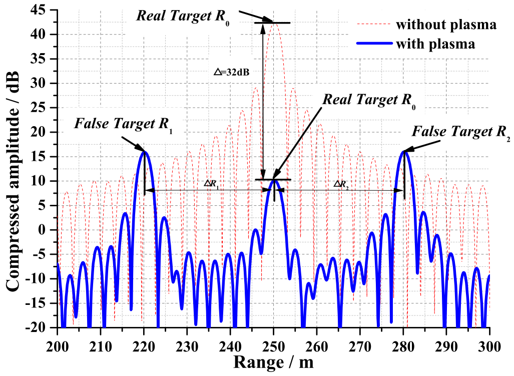
Moreover, by comparing the above results, we can conclude that the larger the variation amplitude of plasma density is, the smaller the echo pulse compressed amplitude attenuation is, but the more false targets are. When the variation amplitude a is small, the real target would hide in the false targets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



(a) regulating frequency f_r=100kHz



(b) regulating frequency f_r=500kHz



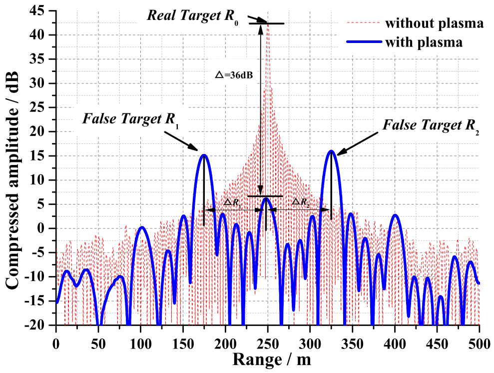
(c) regulating frequency f_r=1MHz

FIGURE 8. **The jamming effect of different plasma regulating frequency.**

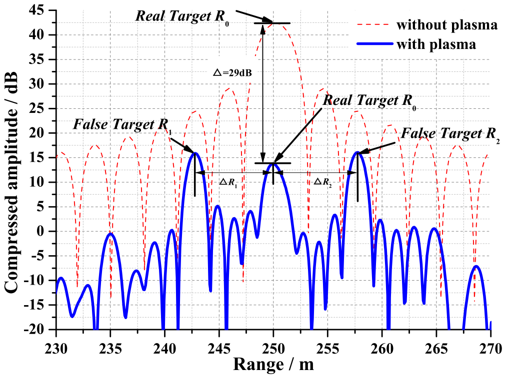
C. THE JAMMING EFFECT OF FREQUENCY OF ELECTRON DENSITY VARIATION ON THE ONE DIMENSIONAL RANGE PROFILE

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: $B = 50\text{MHz}$, $T_p = 10\mu\text{s}$, $a = 0.2$ 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.

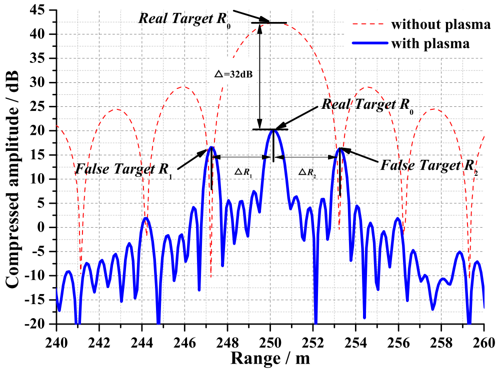
For the plasma regulating frequency $f_r = 100\text{kHz}$, 500kHz and 1MHz, the false targets appear about 3m, 15m, 30m away from the real target, respectively. That is, the larger the regulating frequency f_r is, the farther the false target is from



(a) radar bandwidth B=10MHz



(b) radar bandwidth B=100MHz



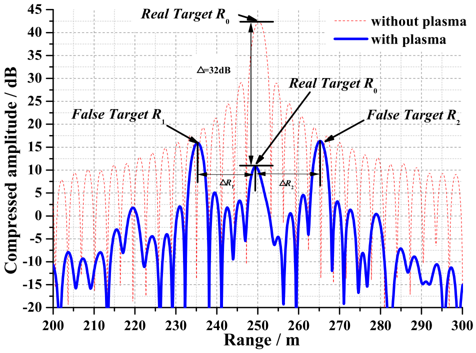
(c) radar bandwidth B=250MHz

FIGURE 9. **The jamming effect of different radar bandwidth.**

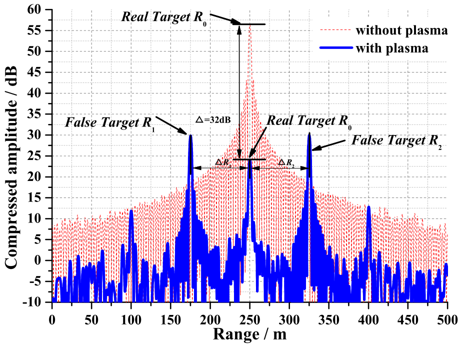
the real target. Moreover, to generate false targets, the basic requirement is that the plasma regulating frequency f_r should larger than $1/T_p$ which is the reciprocal of radar pulse width.

D. THE JAMMING EFFECT OF RADAR BANDWIDTHS ON THE ONE DIMENSIONAL RANGE PROFILE

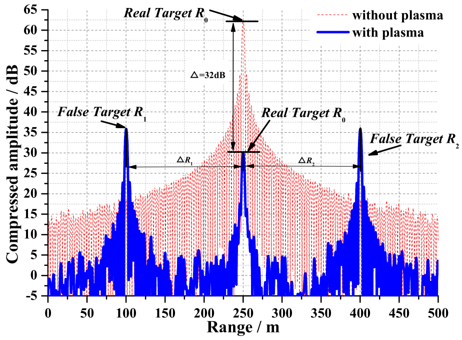
The jamming effect of regulating time-varying plasma on the pulse compression radar with different parameters will be quite different. In this section, by setting the plasma with a same time-varying characteristic, the jamming effect on the radar one dimensional range profile with different frequency bandwidth is studied. The parameters of regulating time-varying plasma are set as: $a = 0.2$, $f_r = 500$kHz. The radar signal parameters are set as: $T_p = 10\mu$s, and the bandwidth range is 10MHz to 250MHz. The results of different radar bandwidth are shown in **Fig. 9(a)~(c)**, respectively.



(a) radar pulse width T_p=10μs



(b) radar pulse width T_p=50μs



(c) radar pulse width T_p=100μs

FIGURE 10. **The jamming effect of different radar pulse width.**

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 $10\mu s$ to $100\mu s$. 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 $T_p = 50\mu s$, $100\mu s$ 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 $T_p = 10\mu s$, $50\mu s$, $100\mu s$ are both 32dB.

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.

(2) 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.

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

(4) 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.

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