Spectrum Modulation of Smart-Surfaces for Ultra High Frequency Radars

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Abstract. Smart surfaces are reconfigurable meta-materials whose electromagnetic characteristics can be altered for applications such as remote identification, stealth, etc. This paper introduces the spectrum modulation of smart-surfaces for long range radars. Applying controlling signals onto the tunable lumped elements loaded on smart-surfaces, modulations can be achieved on reflecting signals illuminating on smart surfaces. Changing the spectral characteristics of the modulated signals, radar receivers can only detect the limited information of the target. This paper introduces the operation mechanism of smart surfaces and analyzes two specific modulating signals, the square wave signal and the pseudo-random Gaussian white noise signal. The spectrum of reflecting signals will change accordingly, making it difficult for the radar receiver to detect. Simulations and results show that the proposed method can change the reflecting echo of the radar and reduce the probability of the target being detected.

Keywords: Radar Cross-Section (RCS) · Spectrum modulation · Metamaterial · Remote identifications

1 Introduction

The rapid development of radar technology poses a great need in remote identifications of various civil and military objectives. The main objectives of the remote identifications are to reduce technique of the radar cross section (RCS) and to eliminate the possibility of detection, identification and tracking. The radar cross section is related to the shape, size, structure and material of the target, as well as the frequency, polarization and angle of incidence of the incident electromagnetic wave [1]. The traditional method of reducing RCS mainly includes two categories. One is to design a special shape to make the target-reflected radar wave deviate from the radar emission direction [2], but this method will affect the objects aerodynamic performance; another is Radar Absorbing Materials (RAM)

X. Liu et al. (Eds.): ChinaCom 2018, LNICST 262, pp. 405–413, 2019.
https://doi.org/10.1007/978-3-030-06161-6_40

[3,4], which uses coating or structural materials to absorb incident electromagnetic waves. Consequently, the electric field strength of the target scattering can be decreased and the RCS will be reduced. Obviously, this method has good performance in absorbing the incident wave. Unfortunately, it is sensitive to the frequency of incident waves and cannot cope with the complicated electromagnetic environment.

Ultra-High Frequency (UHF, 300 MHz−3000 MHz) radar is mainly used to detect the speed and angle of long-distance moving targets due to its relatively long wavelength. Radars in this frequency band have flexible working modes, large bandwidth (>20%), and are likely to adopt multi-frequency or Linear Frequency Modulation (LFM) waveforms, which poses a considerable challenge for designing RCS reduction materials. In recent years, artificial materials have been used to manufacture ultra-thin and wide-band radar absorbers [5,6]. Electromagnetic metamaterials are a new type of artificially composite electromagnetic materials which can controlled dielectric constants and magnetic permeability [7]. The frequency response of metamaterials is affected by cell size, arrangement, dielectric substrate, incident angle and other factors [8]. A variety of radar absorber structures based on Metamaterials have been proposed in the literatures, such as single-layer resistive reflection absorbers [9], multilayer metal metamaterial absorbers [10], non-magnetic broadband radar absorbers [11]. These structures have their own advantages and disadvantages, each with different absorbing properties and are suitable for a specific operating frequency and working bandwidth. The electromagnetic characteristics will be fixed once the radar absorbing surface based on metamaterials is designed and manufactured. However, smart-surfaces [12] can dynamically adjust their electromagnetic characteristics, and the surface does not only absorb the wave but also changes the electromagnetic characteristics of the electromagnetic wave irradiated on the surface, such as the amplitude, the phase, the direction of the reflected wave. It will affect the judgment of the radar receiver and reduce the possibility that the target is detected, therefore the function of RCS reduction can be realized.

In our previous contribution [13], we introduce active meta-surfaces to mitigate the windmill clutters. This paper studies the operation of smart surfaces for UHF radars. The active-surfaces consist of reflecting elements loaded with voltage-controlled elements. Controlling the voltage applied on the elements, the impedance of surfaces could be ideally switched between zero and extreme high impedance. If selecting appropriate modulating signals, we can design the signals arrived at the radar receivers. The content focus on the spectrum of the reflection signal modulated by the square wave signal and the pseudo-random Gaussian white noise signal. Actively modulating to the incident signal, the spectral characteristics of the reflected signal are changed. Not only the power of the reflection signal within the radar operation frequency band will be reduced, but also the power outside the frequency will be altered. This are possible to provide a new dimension in radar coating technology such as smart friend and foe identification, full-band RCS reduction, remote sensing, etc.

The paper is organized as follows. Section 2 introduces the principle of spectrum modulation based on the smart surfaces, including numerical model and transmission line analysis of Smart Meta-surfaces. Section 3 analyzes the performance of reflecting signals using periodic square wave and Gaussian white noise. Finally, Sect. 4 is the conclusion.

2 Spectrum Modulation of Smart Surfaces

2.1 Numerical Model of Smart Surfaces

Generally, spectrum modulation of smart surfaces is the way that modulating the incident radar signal to make the reflecting signal is different from the original incident signal in spectral characteristics, consequently, reducing the power of radar reception and processing. The modulated signal tends to change in characteristics such as spectral bandwidth, amplitude, and frequency.

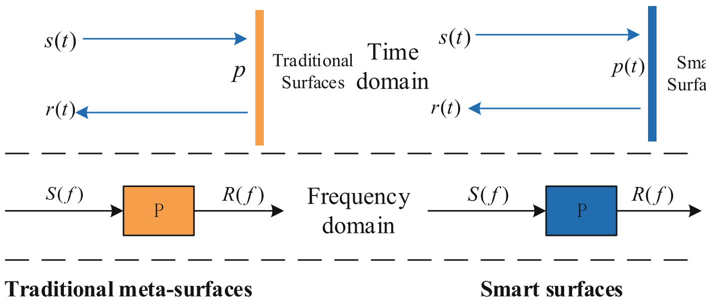

Fig. 1. Principle of traditional meta-surfaces and smart surfaces

Shown in Fig. 1, conventional meta-surfaces reduce the power of reflection signals using a radio wave absorbing structure, which approximately equals to multiply a static coefficient before the reflecting signals. The proposed smart surfaces can change its reflection coefficient dynamically that spectrum modulation can be applied on the reflecting signals. When the incident wave signal $s(t)$ irradiates onto the smart surface, the incident signal will interact with the smart surface and be modulated by the modulating signal $p(t)$ to form a reflecting signal with expected spectral characteristics. The relationship between the three kinds of signals at the time domain can be expressed as:

$$r(t) = s(t) \times p(t) \tag{1}$$

According to the Fourier transform, their relationship at the frequency domain can be depicted as:

$$R(f) = S(f) \otimes P(f) \tag{2}$$

where $s(t)$, $p(t)$, and $r(t)$ represent the frequency response of the incident signal, the modulating signal and the reflecting signal, respectively. $\otimes$ indicates a convolution operation.

For radar receivers, it is assumed that the widely used matched filter is adopted which can be expressed as $\omega(t) = s^*(-t)$. Then, the incident signal can reach the radar receiver without loss in an ideal situation, therefore $r(t) = s(t)$, and the output signal power of the radar receiver is expressed as:

$$P = \frac{1}{T}|\sigma_0|| \int_0^T [s(t) \otimes s^*(-t)]^2 dt| \tag{3}$$

where σ_0 denotes a time-invariant coefficient which represents the combined effect of the gains obtained in various stages of signal transmission, propagation, reflection and reception. After passing through the modulation board, the output signal of radar receiver is first multiplied by the modulating signal. Then the Eq. (3) becomes:

$$P = \frac{1}{T}|\sigma_0|| \int_0^T [s(t) \times p(t) \otimes s^*(-t)]^2 dt| \tag{4}$$

Therefore, it can be seen from the above equation that the received power within the bandwidth of the radar receiver will be greatly decreased as long as there is an appropriated modulating signal to change the spectral characteristics of the incident signal.

In order to reduce the output power of the receiver filter, it is necessary to design the modulating signal $p(t)$ or $P(f)$. There are two designed ideas as follows:

(1) Using the concept of frequency modulation to shift the spectrum of reflecting waves to other frequencies.

From the traditional analog modulation technique, it is known that the modulating signal will have a shifting effect on the spectrum when one signal is used to modulate another signal. Based on the similar principle, we can design an appropriated $p(t)$ so that the incident signal $s(t)$ can be shifted in the spectrum.

Assume that p(t) is a single frequency signal:

$$p(t) = exp(2\pi f_1 t) \tag{5}$$

Its spectrum $P(f)$ is equivalent to an impulse response at the corresponding frequency f_1. Then, after the incident signal is modulated, the echo signal spectrum is shifting f_1 on the basis of the incident signal frequency. The frequency of the reflecting signal can be shifted outside the bandwidth of the radar receiver when f_1 is designed reasonable so that the output power of the receiver is minimized.

(2) Using the idea of a filter to design a set of modulating signals, making the power spectrum of the reflected wave approximates Gaussian white noise.

The design of the modulating signal to convert $R(f)$ into a white noise-like spectrum and make R(f) does not contain the original incident signal, as shown in the following equation:

$$R(f) = \xi_1 + j\xi_2 \tag{6}$$

$$p(t) = \frac{r(t)}{s(t)} = \frac{ifft[R(f)]}{s(t)} \tag{7}$$

where ξ_1 and ξ_2 are both mutually independent, zero-mean normal distribution variables.

Thus, the information of $s(t)$ has disappeared in $r(t)$, therefore the radar receiver cannot recover the information of the incident signal and consequently reduce the probability of the target being found.

2.2 Transmission Line Analysis of Smart Meta-Surfaces

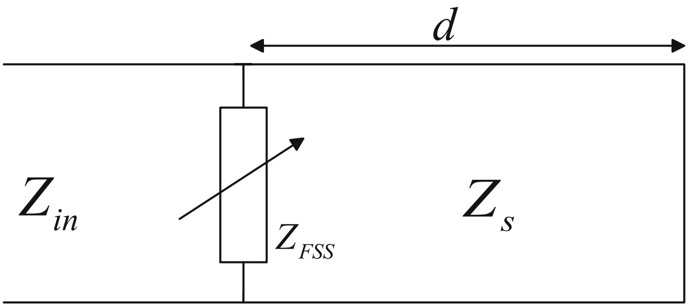

Fig. 2. Transmission line model of smart meta-surfaces

Similar to the conventional modulated surface, the proposed smart meta-surface consists of periodic structures. However, active components are introduced in modulated signals to manage the impedance of the array. The arrays consist one layer of active wideband frequency selective surfaces (FSS) and a perfect electric conductor (PEC) ground plane. Shown in Fig. 2, assume the active FSS and the ground plane are distanced by d, the transmission line model of the active layer can be described using the time varying impendence of FSS $Z_{FSS}(t)$, the medium impendence Z_s, and the propagation constant β, across whose input terminals is placed a time-varying admittance $Z_{in}(t)$, where $Z_{in}(t)$ defined as Z_{in}

$$Z_{in}(t) = \frac{jZ_{FSS}(t)Z_s tan(\beta d)}{Z_{FSS}(t) + jZ_s tan(\beta d)} \tag{8}$$

The results in reflection coefficient, which is related to $Z_{in}(t)$ by

$$\rho(t) = \frac{Z_{in} - Z}{Z_{in}(t) + Z} \tag{9}$$

where $Z = Z_0 \cos\theta$ or $Z = Z_0/\cos\theta$ for parallel or perpendicular polarization, respectively, and Z_0 represents the impedance of free space. Since $Z_{FSS}(t)$ is arbitrary and dependent on the status of active controlling components, then $\rho(t)$ is generally complex number whose absolute value is from 0 to 1. Assume one radar signal $s(t)$ arrive at the smart-surfaces, the reflected radar signal can be described by

$$r(t) = s(t) \times \rho(t) \tag{10}$$

If $\rho(t)$ can be controlled by the periodic square wave or designed in the form of Gaussian white noise, the reflecting signal will difficult to be detected by the radar receiver.

3 Simulation and Result Analysis

3.1 Binary Phase Modulation

First considering the active layer switches impendence by a periodic square wave with an equal duty cycle, it is possible to achieve binary phase modulation of the incident signal. The single frequency signal and LFM signal are considered as incident radar signals and the switching frequency of square wave is 20 MHz. The frequency of the single frequency signal is 1.2 GHz, the simulation results are shown in Fig. 3. It can be seen from the figure that the spectrum of the reflected signal passing through the smart surfaces is evenly distributed to other frequencies with an interval of 40 MHz. There is no spectrum information at the original frequency, its power loss is to be 52 dB after calculation, and other RCS reduction techniques are generally less than 20 dB.

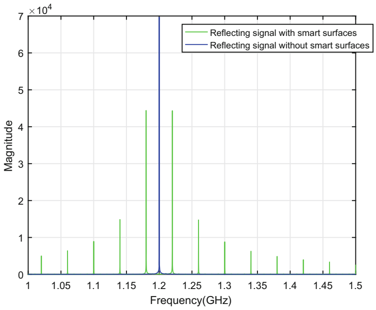

Fig. 3. Single frequency signal

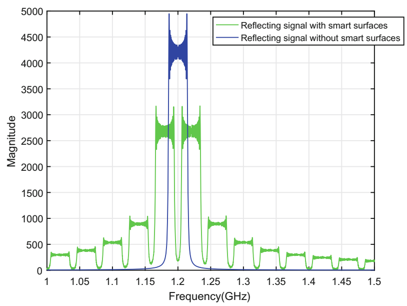

Fig. 4. LFM signal(switching frequency is 20 MHz)

Figure 4 shows the spectral variation of the reflected signal when the incident signal is the LFM signal. The center frequency is 1.2 GHz and the bandwidth is 30 MHz of the incident signal, the switching frequency of the square wave is still 20 MHz. It can be seen from the simulation results that reflected signal produces a lot of the same reflected signal spectrum distributed near the original signal, and there is still have spectrum of the reflected signal within the bandwidth of the original signal, the power loss is only 5 dB. In this case, false echo information appears around the original spectrum, which also affects the judgment of the radar receiver.

When the switching frequency is increased to 30 MHz, and the simulation result is shown in Fig. 5. It is obvious that the reflecting signal with smart surfaces not only has the decreased magnitude but also the spectrum transferred to other frequencies, and the spectrum has no component at frequency of incident signal. In this case, the power loss of the reflected signal is increased to 24 dB. Consequently, proposed method can get better performance when the switching frequency is greater than the bandwidth of LFM signal owing to the reflecting signal can be moved outside the bandwidth of the radar receiver.

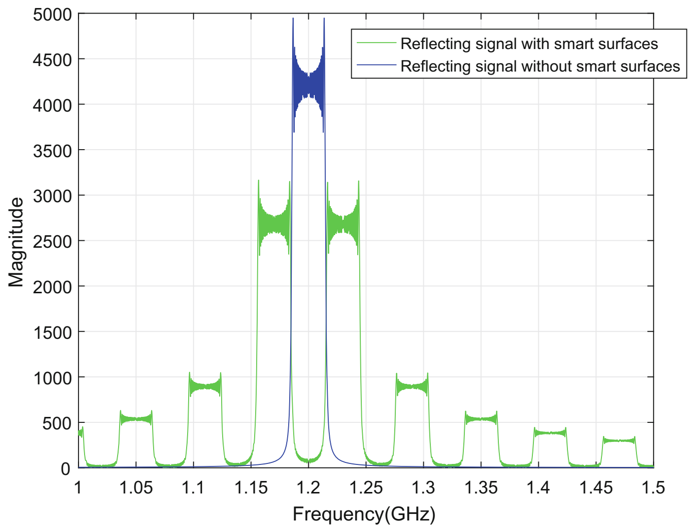

Fig. 5. LFM signal(switching frequency is 30 MHz)

3.2 Pseudo-Random Gaussian Modulation

If $\rho(t)$ can be designed in the form of Gaussian white noise, another way to modulate the incident signal can be obtained. The simulation results are as follows. Figure 6 shows the case that the incident signal is single frequency. After passing through the smart-surfaces, the reflected signal becomes the noise signal and the signal energy is evenly distributed within the frequency band. When such the form of reflected signal arrives at the radar receiver, it will be ignored as the noise signal. And the probability of the target is detected is greatly reduced. Similarly, when the LFM signal as the incident signal irradiates on the smart surfaces, the reflecting signal also becomes a form of a noise signal. The simulation result is shown in Fig. 7. The radar receiver does not detect echo information about the target.

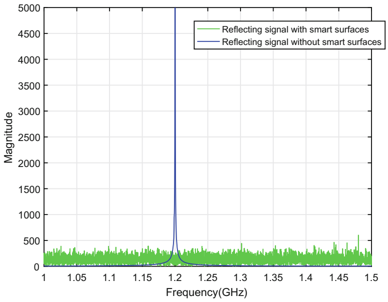

Fig. 6. Single frequency signal

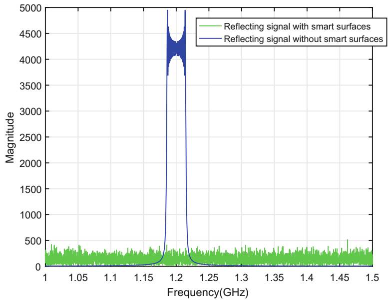

Fig. 7. LFM signal

In summary, the former is that shifting the spectrum to other frequencies but does not change the shape of the signal; and the latter directly converts the radar signal into a noise signal, it has more advantages in the application but it is harder to implement.

4 Conclusion

This paper presents the spectrum modulation of radar signal using smart meta-surfaces. The smart meta-surfaces are active metamaterial whose impedance can controlled by the voltage applied on the lumped elements loaded on the surfaces, so we can control its reflection coefficient at will. The simulated results show that using the square wave signal or Gaussian white noise as the control signal can escape from detection radar but the latter has the better performance. The more comprehensive analysis and prototype will be presented in the future work.

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