ANALYSIS OF ECHO CHARACTERISTICS FOR TIME - VARYING SCATTERERS

Junjie Wang [1], Weidong Hu[2] and Dejun Feng[1]

[1]State Key Laboratory of Complex Electromagnetic Environmental Effects on Electronics and Information System, National University of Defense Technology, Changsha, China
[2]College of Electrical Science, National University of Defense Technology, Changsha, China

ABSTRACT

Phase modulation technique is that the phase information of signal varies proportionally with a modulated signal, which is commonly applied in the field of communications. The current processing method mainly uses the active devices to intercept, modulate and repeat, but the devices are complicated and require a certain processing time. In this paper, Phase modulation method based on phase-switched screen (PSS) is studied and the echo characteristics are analyzed. Meanwhile, the realization of PSS time-varying modulation is discussed. Simulation results are utilized to demonstrate the effectiveness of the proposed method.

KEYWORDS

Linear frequency modulation (LFM), frequency spectrum shifting, phase-switched screen (PSS)

1. INTRODUCTION

Signal modulation technologies are widely applied in the field of electronic information by varying the electromagnetic characteristics of electromagnetic waves, including amplitude modulation, phase modulation, polar modulation and so on. As one of them, the phase modulation technique is originally applied in the field of communications, such as binary phase shift keying (BPSK). Phase modulation in digital communication is a kind of nonlinear modulation, which increases the reliability of signal transmission. In the field of radar waveform design, phase coding signal has received extensive attention due to their excellent range and velocity resolution. Phase modulation is currently mainly implemented by active devices, but its processing method is relatively complicated and need a certain response time.

Electromagnetic metamaterial is designed by man-made processing with electromagnetic parameters that are not available in natural materials. With the development of material technology, it provides a novel way to actively control electromagnetic wave, which can effectively process some problems in engineering applications [1-3].

The phase-switched screen (PSS), a novel electromagnetic metamaterial, imposes phase modulation onto the radar reflected signal so that its energy lay outside receiver passband [4-11]. It is shown to be effective in shielding a target as radar absorbing materials (RAM). Earlier works on PSS mainly covered the theoretical aspects from the electromagnetic characteristics to obtain

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excellent absorbing effect. In this paper, the electromagnetic regulation method based on PSS is analyzed in detail from signal level. The PSS modulation device is simple and has real-time response.

The remainder work is demonstrated in following parts. In Section 2, the basic principle of PSS modulation is described in detail. In Section 3, the influence of incident signal on PSS echo characteristics are analyzed. In Section 4, the possible realization of PSS time-varying modulation is discussed. Finally, conclusions are drawn in Section 5.

2. Basic Principle of PSS Modulation

A typical PSS structure is shown in Fig. 1, consisting of an active resistance layer and a conducting surface, separated by a dielectric spacer with thickness d and dielectric constant 1. The active impedance layer is a microwave screen that can switch electromagnetic wave between full transmission and full reflection.

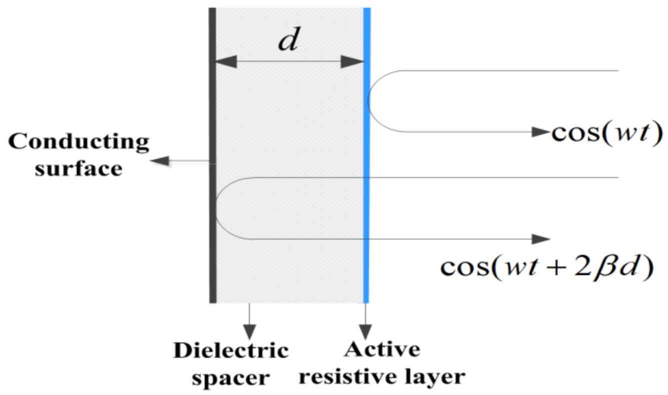
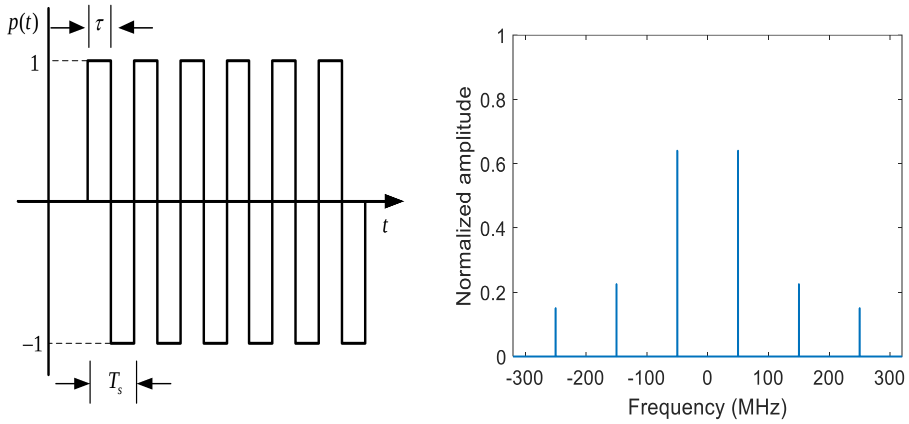


Fig. 1. PSS structure diagram.

Assuming an incident electromagnetic wave is with frequency w and wavelength λ. The dielectric spacer has a thickness of $d=\lambda/4$. The reflected signal can be expressed as: $\cos(wt+2\beta d)=-\cos(wt)$ when active resistive layer presents full transmission, $\cos(wt)$ when active resistive layer shows full reflection, where $\beta=2\pi/\lambda$. Thus the incident signal is equivalent to multiplying a bipolar rectangular pulse sequence switched between +1 and -1.

2.1. Periodic Modulation Waveform of PSS

As presented in Fig. 2(a), the signal $p(t)$ is regarded as the amplitude coefficient being periodically switched between +1 and -1, T_s is the switching period, τ is the duration of +1. According to the theory of PSS [4], the modulating signal of PSS can be expressed as



(a) Modulation waveform in time domain. （b）frequency spectrum characteristics.

Fig. 2. The periodic modulation waveform of the PSS.

$$p(t) = \frac{2\tau}{T_s} - 1 + \sum_{n=1}^{+\infty} \frac{2}{n\pi}\left(1 - \cos\left(\frac{2n\tau\pi}{T_s}\right)\right)\sin\left(2\pi n f_s t\right) \tag{1}$$

where f_s is the switching(or modulating) frequency of PSS and satisfy f_s=1/T_s, and τ/T_s is the modulating duty ratio. By Fourier transform (FT), the frequency spectrum of signal $p(t)$ can be written by

$$P(f) = \left(\frac{2\tau}{T_s} - 1\right)\delta(f) + \sum_{\substack{-\infty \\ n\neq 0}}^{+\infty} \left|\frac{2}{n\pi}\right|\left(1 - \cos\left(\frac{2n\tau\pi}{T_s}\right)\right)\delta(f - nf_s) \tag{2}$$

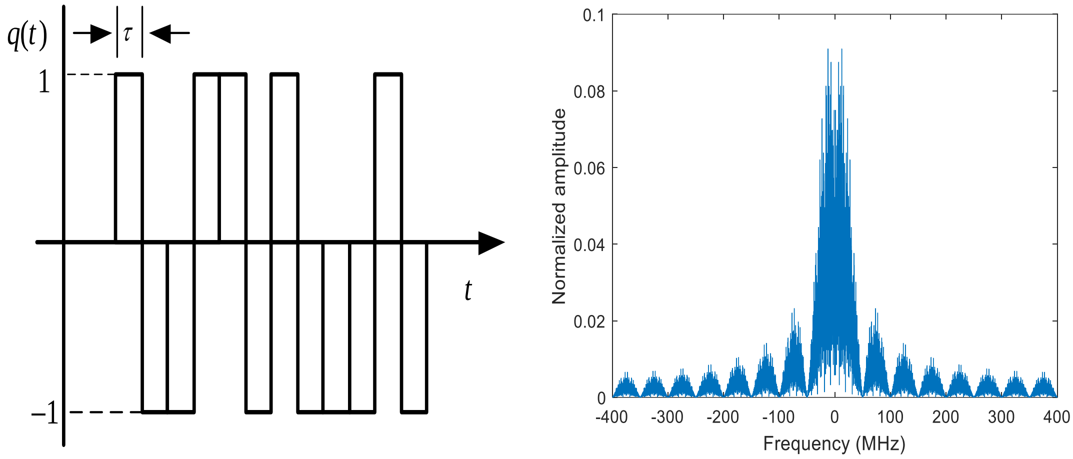
According to (2), the frequency spectrum consists of a number of discrete harmonic components with interval f_s. Its envelope magnitude follows the sinc distribution. In particular, when τ/T_s=0.5, the amplitude of even harmonic is given by.

$$\underset{n=0,\pm 2,\pm 4\cdots\cdots}{P(f) = 0} \tag{3}$$

Assuming f_s =50MHz and τ/T_s =0.5. As presented in Fig.2(b), the frequency domain peaks are discretely distributed. Multiple harmonic components appear at odd multiples the position of modulating frequency f_s, and peaks in even order are concealed.

2.2. Random Code Modulation Waveform of PSS

Switch the PSS reflection coefficient in a random manner, so the modulating signals are controlled by random code sequence $a_m \in \{+1,-1\}$. Random code modulating signal $q(t)$ is shown in Fig. 3(a) and can be regarded as a random bipolar rectangular waveform, the total code number is M, the number of +1 code is M_1, code width is τ, modulating frequency f_s=1/τ, and the duty ratio is α=M_1/M. The $q(t)$ can be expressed by



(a) Modulation waveform in time domain. （b） frequency spectrum characteristics.

Fig. 3. The random code modulation waveform of the PSS.

$$q(t) = rect\left(\frac{t-m\tau}{\tau}\right) * \sum_{m=0}^{M-1} a_m \delta(t-m\tau) \tag{4}$$

where δ(·) is the impulse function, ∗ is the convolution operation, rect(t/τ) yields 1 when $|t/\tau|<0.5$, otherwise is 0. Carrying out FT to (4), the frequency spectrum $Q(f)$ of the modulating signal can be given by

$$Q(f) = \tau \sin c(\tau f) \sum_{m=0}^{M-1} a_m \exp(-j2\pi m\tau f) \tag{5}$$

Q(f) cannot be further simplified due to the randomness of a_m, and some unique characteristics of the modulating be obtained by (5). When $f=kf_s$, Q(f)=0, where k is a non-zero integer. The main-lobe width of frequency spectrum can be calculated by

$$B_{main} = \frac{2}{\tau} \tag{6}$$

Particularly, the spectrum output in f=0 is written by

$$Q(0) = M\tau|1-2\alpha| \tag{7}$$

Assuming that the modulating signal is with code width τ=0.02us and duty ratio α=0.5. Fig. 3(b) presents the frequency spectrum of PSS random code waveform. The frequency spectrum is continuous with B_{main}=100MHz and $Q(0)$=0.

3. Influence of Incident signal on PSS Echo Characteristics

In addition to the form of the modulating signal, the incident signal is also one of the main factors affecting the performance of the PSS. It must be pointed out that a necessary condition for PSS to obtain excellent spectrum shifting performance is that the carrier frequency of incident signal must correspond to the interval between the active impedance layer and conducting surface, i.e., $d=\lambda_0/4=c/4f_0$, where f_0 is the carrier frequency of signal and λ_0 is the wavelength of signal.

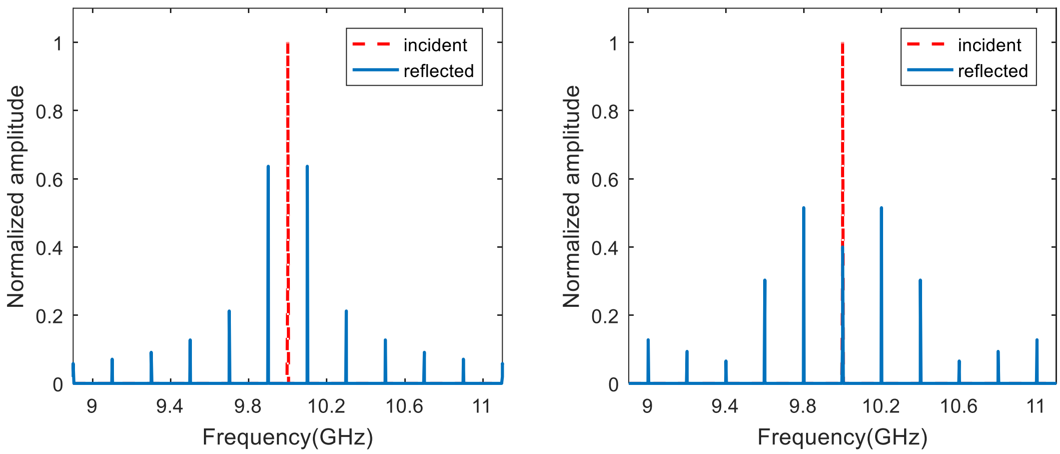
The influence of the incident signal form on the PSS echo characteristics is specifically analyzed below, including single frequency signal and wideband linear frequency modulation (LFM) signal.

3.1. Single Frequency Signal

Suppose that the incident signal is $A\sin(2\pi f_0 t)$, and the signal reflected by PSS can be expressed as

$$r(t) = A\sin(2\pi f_0 t)\cdot\left[\frac{2\tau}{T_s} - 1 + \sum_{n=1}^{+\infty}\frac{2}{n\pi}\left(1-\cos\left(\frac{2n\tau\pi}{T_s}\right)\right)\sin\left(2\pi n f_s t\right)\right]$$
$$= \left(\frac{2\tau}{T_s}-1\right)A\sin(2\pi f_0 t) + A\sum_{n=1}^{+\infty}\frac{1}{n\pi}\left(1-\cos\left(\frac{2n\tau\pi}{T_s}\right)\right)\left(\cos\left[2\pi(f_0 - f_s)t\right] + \cos\left[2\pi(f_0 + f_s)t\right]\right) \quad (8)$$

According to (8), the echo contains a number of harmonic components $\sin(2\pi f_0 t)$, $\cos[2\pi(f_0-f_s)t]$, $\cos[2\pi(f_0+f_s)t]$, so PSS can realize spectrum shifting of the incident signal. When τ/T_s=0.5, the reflected signal only contain odd harmonic components. As shown in Fig. 4(a), the incident signal is single frequency signal with f_0=10GHz, PSS modulating parameters with f_s=100MHz, τ/T_s=0.5. It can be seen that the energy at the original incident frequency is completely suppressed, and many discrete peaks are formed at odd harmonics. When the PSS modulating parameter is with f_s=200MHz, τ/T_s=0.3, zero-order and even-order peaks appear in Fig. 4(b), and the interval between each peak varies with the modulating frequency f_s.



(a) f_s=100MHz, τ/T_s=0.5 (b) f_s=200MHz, τ/T_s=0.3

Fig. 4. The frequency spectrum of single frequency signal based on PSS modulation.

It can be seen from the above analysis that when the incident signal is a single frequency signal, the PSS can fully exert its phase modulation and exhibit an ideal spectrum shifting effect.

3.2. LFM Signal

The wideband LFM signal is widely applied in modern radar systems for its excellent performance. Assuming that the carrier frequency is f_0, the wavelength is λ_0, the LFM rate is K_r, the pulse duration is T_P, and the signal bandwidth is $B=K_rT_P$. The coverage of the LFM signal is $[f_0-B/2, f_0+B/2]$, and the portion of the signal faring away from f_0 is incident on PSS. When the active resistive layer appears to be fully transparent, the incident wave reaches the PSS conducting surface, and the extra phase brought by the scattering is no longer π. So the corresponding amplitude coefficient is no longer -1. Then the influence on the PSS modulation is analyzed on this condition. The signal reflected by the conducting surface under the single frequency is

$$r(t)=\cos\left(2\pi f_0 t+\frac{4\pi d}{\lambda}\right)=-\cos\ 2\pi f_0 t \tag{9}$$

The amplitude coefficient is -1. Assuming that the PSS amplitude modulation factor of a signal under non-single frequency conditions can be expressed as

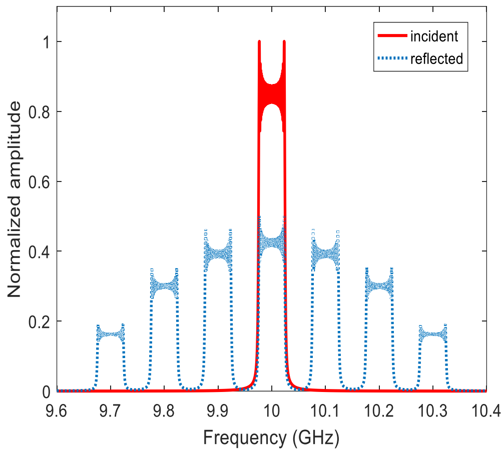
$$r'(t)=\cos\left(2\pi f'_0 t+\frac{4d\pi}{\lambda'}\right)=\cos\left(2\pi f'_0 t+\frac{f'_0\pi}{f_0}\right) \tag{10}$$

where $f'_0=f_0+K_rt$, $\lambda'=c/f'_0$. Perform trigonometric function expansion on (10)

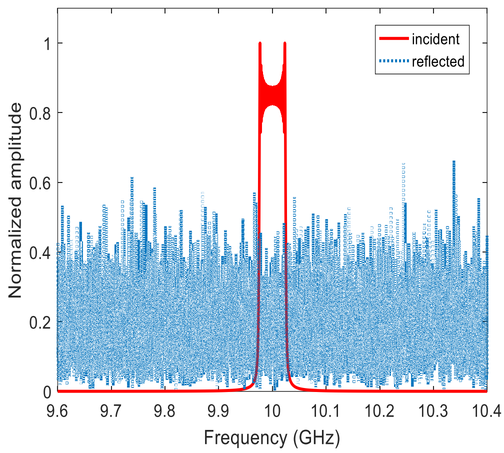
$$\begin{aligned} r'(t)&=\cos(2\pi f'_0 t)\cos\left(\frac{f'_0\pi}{f_0}\right)-\sin(2\pi f'_0 t)\sin\left(\frac{f'_0\pi}{f_0}\right)\\ &=-\cos(2\pi f'_0 t)\cos\left(\frac{K_r t\pi}{f_0}\right)+\sin(2\pi f'_0 t)\sin\left(\frac{K_r t\pi}{f_0}\right) \end{aligned} \tag{11}$$

So the echo signal is that the ideal echo signal is multiplied by amplitude factor $\cos(K_rt\pi/f_0)$, and plus a signal term $\sin(2\pi f'_0t)\sin(K_rt\pi/f_0)$. Since these two amplitude factors are determined by K_rt/f_0, the modulation of the LFM signal ultimately depends on the ratio of the signal bandwidth to the carrier frequency, i.e., B/f_0. For most radars, the relationship between is basically satisfied $B\leq0.05f_0$. Assuming $B=0.05f_0$, $\cos(K_rt\pi/f_0)=0.9877\rightarrow1$, $\sin(K_rt\pi/f_0)=0.1564\rightarrow1$. Considering that the conditions $B\leq0.05f_0$ can generally be satisfied, so ±1 signal modulation can be obtained for LFM signal.

Fig. 5(a) shows the spectrum of the reflected signal modulated by PSS. The energy of incident signal is discretely redistributed within the entire sideband on the periodic modulation. On the contrary, the frequency spectrum is continuous with random code modulation and most of reflected energy spreads outside the pass-band, as presented in Fig. 5(b).



(a) Periodic modulation.



（b）Random code modulation.

Fig. 5. The frequency spectrum of LFM signal based on PSS modulation.

4. *REALIZATION OF PSS TIME-VARYING MODULATION*

In the previous introduction to the PSS structure, we mentioned that the active resistive layer needs to be switched between a fully transmissive and a fully reflective state. In practical applications, the active frequency selective surface (AFSS) has such function. The bias voltage of the AFSS is adjusted by the control circuit to switch the two states.

To digitally regulate the current of control circuit in AFSS, a control device based on FPGA is discussed. The control device can digitally switch the output waveform by changing voltage status, which further control the "ON" and "OFF" states of the AFSS control circuit, as presented in Fig. 6.

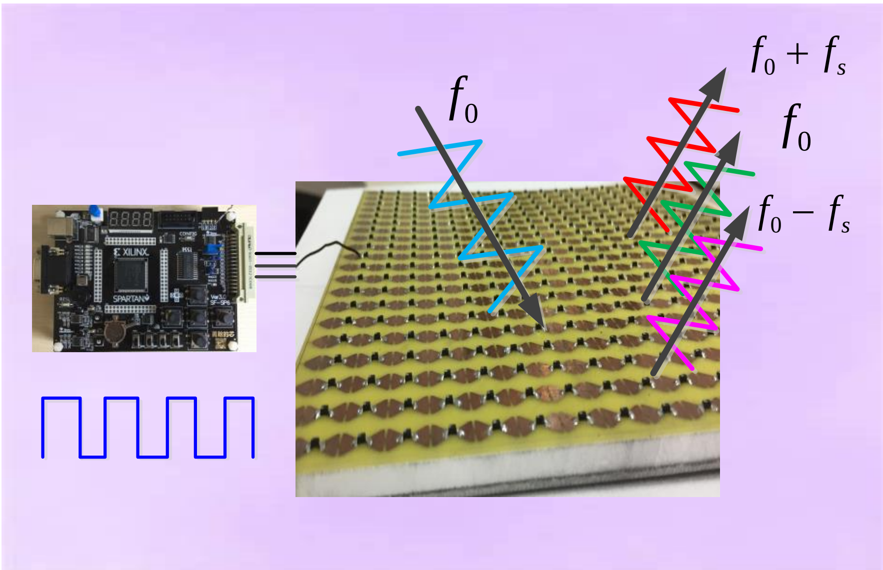


Fig. 6. Control device to PSS modulation diagram.

Here, we only give a possibly implementation of PSS modulation, and some details have not been discussed too much.

5. CONCLUSIONS

In this paper, the electromagnetic regulation method is proposed based on PSS. The spectral characteristics of the PSS modulating waveform are specifically analyzed, including periodic and random code modulation. Next, the condition of the incident signal are discussed, and research shows that PSS can realize the frequency spectrum shifting on both single frequency and LFM signal. Finally, the possible implementation of PSS modulation is studied. From simulation results, the validity and correctness of the proposed method is verified. The proposed method may be applied in communication or radar systems from microwaves and optics.

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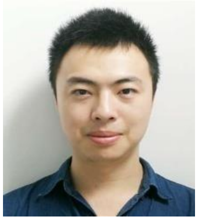
AUTHORS

JUNJIE WANG was born in Hunan, China, in 1991. He received the B.S. degree in communication engineering from Hunan University, Changsha, China, in 2014, and the M.S. degree in information and communication engineering from the National University of Defense Technology, Changsha, China, in 2016, where he is currently pursuing the Ph.D. degree at State Key Laboratory of Complex Electromagnetic Environmental Effects on Electronics and Information System. His research interests include radar imaging and radar signal processing.



WEIDONG HU was born in Liaoning, China, in 1967. He received the B.S. degree in microwave technology and the M.S. and Ph.D. degrees in communication and electronic system from the National University of Defense Technology (NUDT), Changsha, China, in 1990, 1994, and 1997, respectively. He is currently a Full Professor with the Automatic Target Recognition Laboratory, NUDT. His research interests include radar signal and data processing.

DEJUN FENG was born in Hunan, China, in 1972. He received the M.S. degree from the Naval University of Engineering, Nanjing, China, in 2002, and the Ph.D. degree from the National University of Defense Technology, Changsha, China, in 2006, respectively. He is currently an associate Professor with the National University of Defense Technology. His fields of interest include radar signal processing, radar system simulation and inverse synthetic aperture radar.