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Active Scattering Cancellation Using a Microstrip Antenna Element

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Abstract

A technique for reducing the scattering (i.e., radar cross section) of a given object in a fixed direction is presented, which makes use of a radiating microstrip patch antenna element. The system is designed so that the radiation from the patch cancels a radar signal reflected from the object in a specified direction at the carrier frequency of the radar signal, and therefore reduces the time-varying radar signal that is scattered from the object in the specified direction for an incident time-varying radar pulse that arrives from a known direction. Applications include spectral coexistence and EMI reduction from radars.

1 Introduction

The most common method that is applied for the reduction of the radar cross section of an object is RAM, i.e., radar absorbing material, which is coated over the surface of the object and reduces its radar cross section (RCS) by absorption of the incident radar signal [1]. Among other techniques, metamaterials have also been used to implement RCS reduction [2 – 4], but this usually suffers from the limitation of being narrow band. Another way to reduce the RCS of an object is to alter its shape so that there is less reflection from the object in the direction of the radar detector. These techniques are effective at high frequencies [1].

The method of "active cloaking", to reduce the radar cross section of an object using radiation from antennas has been demonstrated theoretically in [5 – 9]. Some of the practical implementations of active RCS reduction have been covered in [10].

In the method proposed here [11, 12] the time-varying radar signal that is reflected from a fixed object is cancelled by radiation from a patch antenna placed on the object. An electronic system is proposed to implement this scheme, and results are presented to explore its effectiveness for practical radar pulses. It is assumed that the direction of arrival for the incident signal is known, and the direction for which cancellation is desired has also been specified.

2 Theoretical Analysis

For studying the proposed method of RCS reduction and evaluating it, the system is chosen to consist of a metallic plate, which is the object that needs to be hidden from the radar, with a rectangular patch antenna on the surface of the plate, along with a sensor for detecting the amplitude of the incident radar signal. Behind the plate there is a phase shifter and amplifier that connects the sensor and the antenna. This system is represented in Figure 1 and the schematic diagram of Figure 2. Here we have considered the simplest case (the object is a simple metal plate) to demonstrate the capabilities and limitations of this method. The radar signal impinging on this system is taken to be a time-varying plane wave that is incident normally on the metal plate (though other incidence angles could have been used). The sensor is realized here as a vertical probe with one or more orthogonal horizontal branches, and it is small compared to a wavelength.

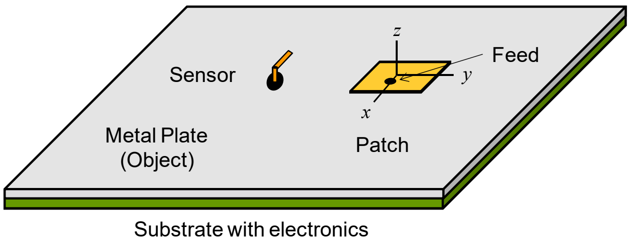

Figure 1. The layout of the patch antenna and sensor on an object, with the object taken to be a metal plate for simplicity. The electronics is shown in Figure 2.

The amplitude of the incident radar signal is picked up by the sensor and then transformed through the phase shifter and amplifier circuit shown in Figure 2, and then fed to the patch antenna. The gain of the amplifier and the phase shift are adjusted to ensure that the scattered signal from the plate is exactly cancelled by the radiation from the patch antenna for a single frequency wave, corresponding to the carrier frequency ω_0 of the radar pulse.

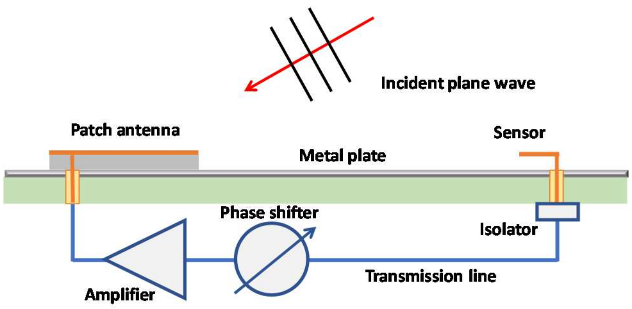

Figure 2 Geometry of a patch on an object (metal plate), connected by a transmission line to a sensor via an isolator, amplifier and phase shifter.

The analysis is done in the frequency domain and the resulting scattered signal from the system is then transformed into the time domain. The complete cancellation of the scattered signal with the radiation from the antenna is done at the carrier frequency of the radar pulse. The scattered field component E_p^{sca}, which is the electric field in the p direction (i.e., the polarization of the scattered field) at (r, θ, ϕ) from the system, at frequency ω, can be expressed as

$$E_p^{sca}(\omega,\theta,\phi) = \left(\frac{e^{-jk_0 r}}{r}\right)\left[E_i^{inc} S(\omega) + R(\omega) V_p(\omega)\right]. \quad (1)$$

Here $S(\omega)$ is a scattering coefficient defined as the scattered field from the given object (metal plate) with the patch antenna present but short-circuited at the feed port, when a unit-amplitude plane wave E_i^{inc} (polarized in the i direction) is incident on the object. (Since we assume normal incidence here, both i and p are taken to be in the x direction.) A short-circuited patch radiates and scatters very little, so this situation becomes equivalent to the patch being absent, and $S(\omega)$ can then be considered to be the scattering coefficient for the object alone. The term V_p is the voltage at the feed port of the patch antenna. The radiation coefficient $R(\omega)$ gives the radiated field by the patch on the object, when the voltage at the feed port of the patch is $V_p = 1$V.

The patch feed voltage depends on the output of the sensor, and it includes a term to account for the mutual coupling between the patch and the sensor. Therefore, the patch feed voltage is

$$V_p = V_s A\left(\frac{Z_{in}}{Z_{in}+Z_{out}}\right) + E_i^{inc} O\left(\frac{Z_{out}}{Z_{out}+Z_{in}}\right). \quad (2)$$

where the $O = O(\omega)$ coefficient is defined as the open-circuited feed port voltage due to a unit-amplitude incident plane wave, i.e., E_i^{inc} = 1 V/m, Z_{in} is the input impedance of the patch and Z_{out} is the output impedance of the amplifier. The coefficient $A = A(\omega)$ is the complex gain of the electronic system, i.e., the combination of the amplifier, the phase shifter, and the transmission line connecting the components together. Therefore, combining Eq. (1) and (2), the scattered field is given by

$$E_p^{sca} = \begin{bmatrix} E_i^{inc} S(\omega) \\ +R(\omega) E_i^{inc}(\omega) O(\omega)\left(\dfrac{Z_{out}}{Z_{out}+Z_{in}(\omega)}\right) \\ +R(\omega) A(\omega) V_s(\omega)\left(\dfrac{Z_{in}(\omega)}{Z_{out}+Z_{in}(\omega)}\right) \end{bmatrix} \left(\frac{e^{-jk_0 r}}{r}\right). \quad (3)$$

In the above expression, the coefficient $A(\omega)$ is taken as

$$A(\omega) = A_0 \exp\left(-j\left(k_0(\omega) - k_0(\omega_0)\right)\sqrt{\varepsilon_r^{eff}} L\right).$$

Here L is the delay length of the connecting transmission line and ε_r^{eff} is the effective relative permittivity for the line. The amplitude term A_0 is chosen so that the third term in (3) exactly cancels the first two terms at the carrier frequency ω_0 of the radar pulse. The scattered signal from a time-varying incident plane wave will not be exactly zero since the incident pulse has a frequency spectrum and is not localized to exactly ω_0.

3 Results

3.1 Scattered Signal

An analysis based on the formulation in Section 2, together with a CAD model of a patch antenna, is performed for the system in Figure 2. The object is taken to be a rectangular perfect electric conducting plate of size 20 cm × 20 cm, with the patch antenna placed at the center of the plate. The rectangular patch antenna has dimensions of 6.255 cm and 9.383 cm in the x and y directions, respectively, with a substrate of height 1.524 mm and a relative permittivity of 2.2. The patch has a quality factor Q of 5 and is resonant at 1.575 GHz, the carrier frequency of the radar pulse.

The signal transmitted from the radar is a rectangular chirped pulse signal that has a 2% variation in frequency across the width of the pulse, with a center frequency of 1.575 GHz. The frequency starts at a beginning frequency that is 1% lower than 1.575 GHz at the beginning of the pulse, and linearly increases to a frequency that is 1% higher than 1.575 GHz at the end of the pulse, and the width of the rectangular chirped pulse is 317.46 ns. This incident radar signal at the surface of the plate is shown in Figure 3. Figures 4 and 5 show the normalized scattered signal from the plate with the scattering cancellation scheme implemented as shown in Figure 2, for different delay lengths L in the system. Figure 4 gives the normalized scattered signal from the plate with no delay in the system, which is not a practical scenario. Figure 5 gives the normalized scattered signal from the plate with a delay in the system of five guided wavelengths at ω_0.

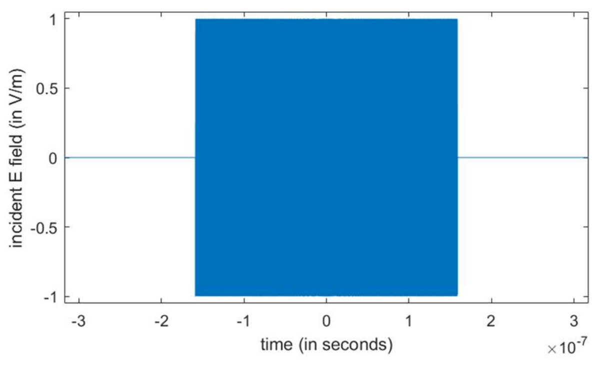

Figure 3. The incident rectangular chirped pulse signal.

Comparing Figures 4 and 5 shows that for a higher delay in the circuit, the RCS reduction degrades. Also, the strongest part of the scattered signal is at the leading and trailing edges of the pulse. This is consistent with causality, as the system cannot instantaneously adjust the patch radiation to cancel changes in the incident signal. The cancellation is best at the middle of the signal.

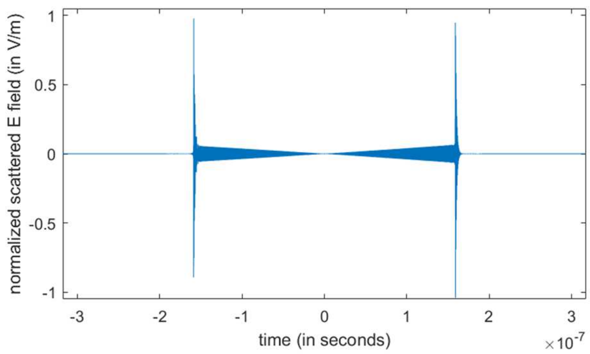

Figure 4. The rectangular chirped pulse scattered signal with scattering cancellation implemented, for no delay in the circuit.

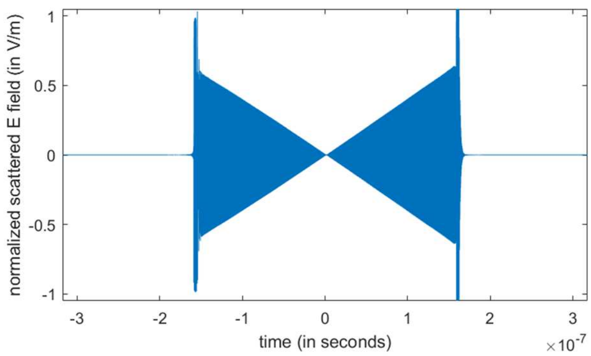

Figure 5. The rectangular chirped pulse scattered signal with scattering cancellation implemented, for five wavelengths delay in the circuit.

3.2 Figure of Merit

The efficacy of the RCS reduction achieved due to the proposed method can be measured using a figure of merit (FoM) [12]. The FoM is defined as the ratio of the energy in the scattered signal when the proposed RCS reduction technique is applied, to the energy in the scattered signal from the same object without any RCS reduction in effect. Results from the study show the effects of the delay in the system, and the relative bandwidth BW of the patch antenna, and are presented in Table 1. Table 1 shows the calculated FoM for the same rectangular chirped pulse in Section 3.1. The FoM values for the chirped rectangular pulse are given for different delays in the system and different values of antenna Q, where $BW = 1/(\sqrt{2}Q)$.

Table 1. The Figure of Merit (FoM) (in percent) for a rectangular chirped pulse as the incident radar waveform.

***Q*/Delay**	**0**	**0.5 λ_g**	**2 λ_g**	**5 λ_g**
***Q* = 5**	0.59%	0.91%	3.3%	14.3%
***Q* = 10**	1.1%	1.4%	3.9%	15.1%
***Q* = 20**	2.5%	2.9%	5.6%	17.4%
***Q* = 50**	12.6%	13.4%	17.3%	32.4%

From Table 1 we see that in order to get a good RCS reduction, i.e., a small FoM, the bandwidth of the patch must be larger than that of the radar signal. When there is no delay in the system, the RCS reduction keeps getting smaller as the patch bandwidth increases (Q decreases). However, for a fixed delay in the system, the amount of RCS reduction levels off as the patch bandwidth increases, with the lowest value of the FoM that is achievable depending on the delay in the system. The larger the delay, the larger is the smallest FoM that can be achieved. Also, for a given patch bandwidth (i.e., Q), the RCS reduction consistently gets worse as the delay in the system increases.

4 Conclusions

The scattering from an object can be reduced using the present technique. The bandwidth of the patch antenna that is used should be greater than that of the radar signal, and the delay in the system should be kept small.

5 Acknowledgements

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6 References

[1] P. Y. Ufimtsev, "Comments on diffraction principles and limitations of RCS reduction techniques," *Proc. of the IEEE*, vol. 84, no. 12, pp. 1830-1851, Dec. 1996.

[2] Kun Li, Ying Liu, Yongtao Jia, and Y. J. Guo, "A circularly polarized high-gain antenna with low RCS over a wideband using chessboard polarization conversion metasurfaces," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 8, pp. 4288-4292, Aug 2017.

[3] Jianxun Su, Chuiyong Kong, Zengrui Li, Hongcheng Yin, and Yaoqing Yang, "Wideband diffuse scattering and RCS reduction of microstrip antenna array based on coding metasurface," *Electronics Letters*, vol. 53, no. 16, pp. 1088-1089, Aug 2017.

[4] A. Kord, D. L. Sounas and A. Alù, "Ultrathin active cloak with balanced loss and gain," *2016 IEEE International Symposium on Antennas and Propagation*, pp. 369-370, Fajardo, Puerto Rico, 2016.

[5] D. A. B. Miller, "On perfect cloaking," *Optics Express*, vol. 14, no. 24, pp. 12457–12466, 2006.

[6] F. Guevara-Vasquez, G. W. Milton, and D. Onofrei, "Active exterior cloaking for the 2D Laplace and Helmholtz equations," *Phys. Rev. Lett*., 103, 073901, 2009.

[7] F. Guevara-Vasquez, G.W. Milton, and D. Onofrei, "Broadband exterior cloaking," Optics Express, vol. 17, Issue 17, pp. 14800-14805, 2009.

[8] H. H. Zheng, J. J. Xiao, Y. Lai, and C. T. Chan, "Exterior optical cloaking and illusions by using active sources: A boundary element perspective," *Physics Review B*, vol. 81, no. 19, 2010.

[9] D. Onofrei, "Active manipulation of fields modeled by the Helmholtz equation," *Journal of Integral Equations and Applications*, vol. 26, no. 4, 2014.

[10] Hema Singh, Rakesh Mohan Jha, *Active Radar Cross Section Reduction: Theory and Practice*, 1st Edition, Cambridge University Press, Mar. 2015.

[11] S. Sengupta, D. R. Jackson, D. Onofrei, and H. Council, "Reduction of radar cross section using active microstrip antenna elements," *2017 IEEE Antennas and Propagation Society Intl. Symposium*, 9-14 July, 2017.

[12] S. Sengupta, H. Council, D. R. Jackson, and D. Onofrei, "Active Radar Cross Section Reduction of an Object using Microstrip Antennas," *Radio Science Journal*, vol. 55, no. 2, Feb. 2020.