GU J Sci 30(3): 29-37 (2017)

Gazi University

Journal of Science

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Absorbing Property of Multi-layered Short Carbon Fiber Absorbing Coating

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Article Info

Received: 29/04/2017
Accepted: 12/06/2017

Keywords

Short carbon fiber,
Absorbing coating,
Multi-layered,
Absorbing property.

Abstract

The radar absorbing coating was prepared with short carbon fiber as absorbent and waterborne polyurethane (WPU) as matrix resin. The coating's absorbing property was tested with vector network analyzer, using aramid honeycomb as air layer which was matched with carbon fiber coating. The results demonstrate that the single-layered carbon fiber absorbing coating presented relatively poor absorbing property when the layer was thin, and the performance was slightly improved after the matched air layer was adopted. Then the multi-layered carbon fiber absorbing coating was produced by matching the air layer with absorbing coating of varied carbon fiber content. Consequently, the absorption intensity and the band width of effective absorption were significantly enhanced. According to varied matching methods between carbon fiber coating and air layer, the composite coating's reflectivity reached a minimum of -23dB, and the reflectivity was less than -10dB within the range of 4-13GHz, the band width of effective absorption reached 9GHz.

1. INTRODUCTION

The absorbing coating refers to a type of functional coating that can dissipate the electromagnetic wave by transforming them into heats or other energy forms, or absorb and attenuate the incident waves through destructive interference [1-2]. Carbon fiber has good conductivity and is highly radar-reflective, yet the problem that ordinary carbon fiber cannot be utilized as filler for absorbing coating can be effectively solved by dispersing the shortly-chopped fiber into the matrix resin [3-5]. Wu Honghuan's study over the relations between carbon fiber's length and the absorbing property shows that significant consumption cannot be achieved through too-short carbon fibers because the current's radial flow path along the fiber is also too short, while too-long carbon fiber can easily form a strong reflector that weakens the absorbing property [6]. Researchers like He Fang studied the disperslbility of carbon fiber with varied length and the results imply carbon fiber around 2mm presents good disperslbility, longer fibers can create aggregation because they are easily intertwined [7]. In order to further improve the carbon fiber's absorbing property, current studies mainly focus on their activation treatments [8-9]; modification through Carbonyl Iron Powder, Ni-Fe Alloy and so on [10-12], and preparation of carbon fiber with special structures such as porous carbon fiber and helical carbon nanofiber [13-15], while studies over multi-layered design of carbon fiber absorbing coating is rare. In this paper, the radar absorbing coating was prepared with short carbon fiber (2 mm) as absorbent and waterborne polyurethane (WPU) as matrix resin. The absorbing property was studied through matching the coatings with varied carbon fiber contents and air layer.

2. EXPERIMENT

2.1. Materials

Carbon Fiber: Shanghai Lishuo's LS-CF2-S carbon fiber;

Waterborne polyurethane (WPU): Shanghai yuanhe's Bayhydrol2648 waterborne polyurethane

Thickening agent: Guangzhou Hongrun's RM-8W thickening agent

Aramid Honeycomb: Suzhou Fanglei's AC-NH Mata-aramid Paper Honeycomb

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2.2. Sample Preparation

Waterborne polyurethane and carbon fiber were prepared by a fixed mass proportion. Then the 0.5 wt% thickening agent was added into the waterborne polyurethane which was later processed with a disperser (SF smart dispersing sand mill) at the speed of 300 r/min for 10 mins. After the thickening, the absorbent was put into the resin that was also dispersed at the same speed for 30min. when uniformly dispersed; the mixture was placed into a mold by a fixed thickness. The curing process first proceeded at room temperature for 12 hours, then in oven by 50℃ for 24 hours. After complete curing, the coating was demoulded and the honeycomb was used as air layer to match the carbon fiber coating to produce multi-layered matched radar absorbing coating.

2.3. Testing

The HITCHI-53700N scanning electron microscope (SEM) and SG-51metallurgical microscope were adopted to characterize microscopic morphology of the carbon fiber and the coating. And the Agilent PNA E8363B vector network analyzer was used through NRL-arc method to test the electromagnetic wave's reflectivity with testing frequency range of 2-18 GHz.

3. RESULTS AND CONCLUSIONS

3.1. Microscopic Morphology Analysis

Figure 1is the SEM image of short carbon fiber. According to the image, the carbon fiber has a filamentous structure with an average diameter of 7 μm , and there are several small grooves on the surface which are beneficial to the combination of carbon fiber and matrix resin. Figure 2 is the metallurgical microscope image of short carbon fiber coating. According to the image, the short carbon fibers are randomly distributed in the matrix resin along different directions without obvious entanglement and reunion, and the spacing between carbon fibers is relatively even.

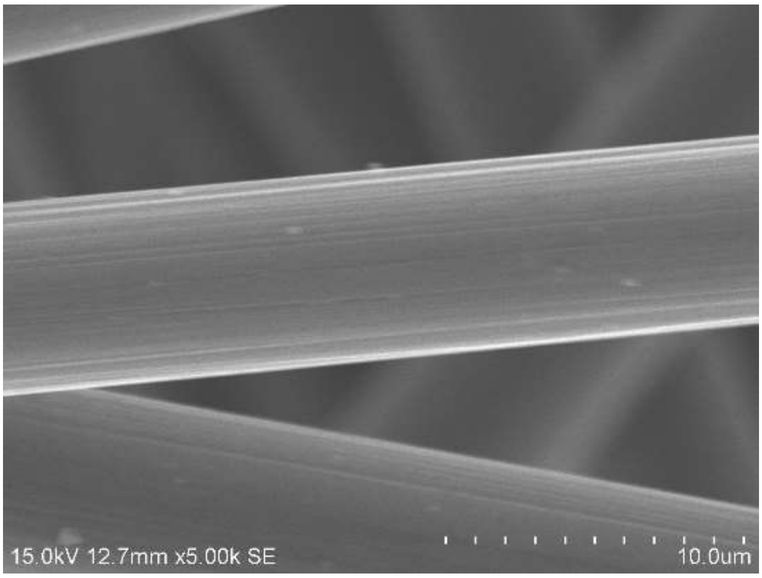

Figure 1. *SEM image of short carbon fiber*

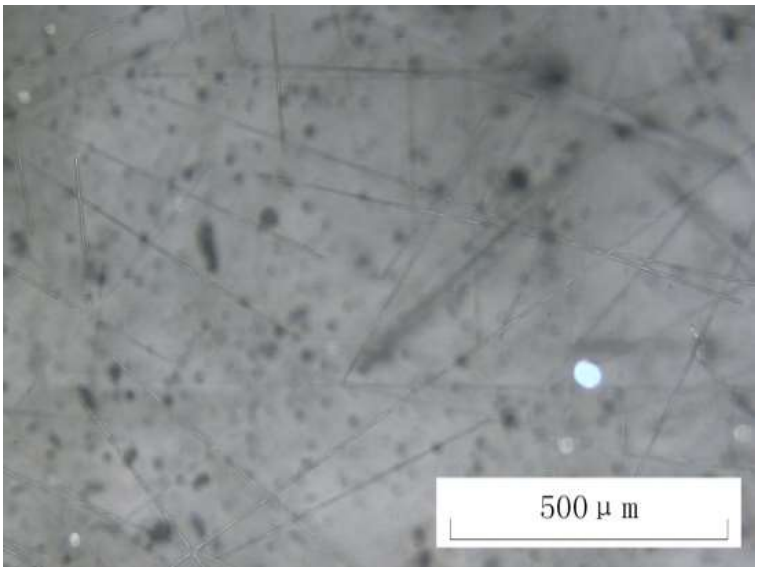

Figure 2. *Metallurgical microscope image of short carbon fiber coating*

3.2. Absorbing Property Analysis

3.2.1. Single layered carbon fiber coating

Figure 3 is the testing curve of single-layered carbon fiber absorbing coating's reflectivity (with 0.5 mm coating thickness and carbon fiber content being respectively 0.1 wt.%, 0.2 wt.%, 0.3%, 0.5 wt.%). According to the Figure, the coating's absorbing performance was improved as the carbon fiber content increased but reached a maximum of merely -2 dB.

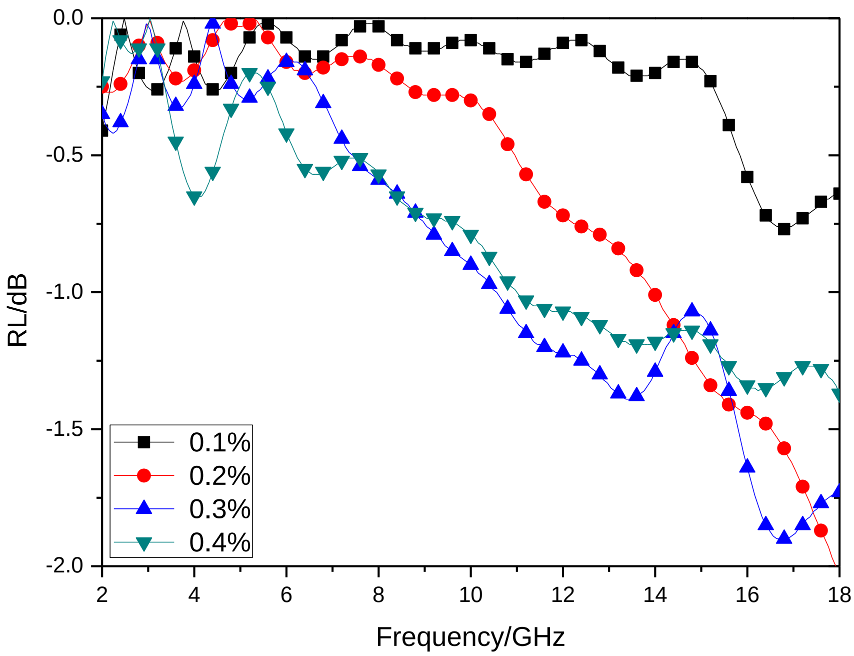

Figure 3. *Reflectivity's testing curve of single-layered carbon fiber absorbing coating*

According to the single layer penal absorbing coating's reflecting and absorbing model, when the EM wave Ei reached the single layer coating's front surface, part of the wave Er would be reflected back into the air by the surface, the other part would penetrate into the coating and reach the coating's rear surface after going through consumption process by the absorbent. Again, the wave then would go through a second round of consumption process after being reflected back into the coating by the metal penal and the leftover energy Ee would be bounced back into the air. If the consumed energy is assumed to be El, then the entire process will be like Figure 4, and the energy relations are: $E_i = E_r + E_t = E_r + E_l + E_e$.

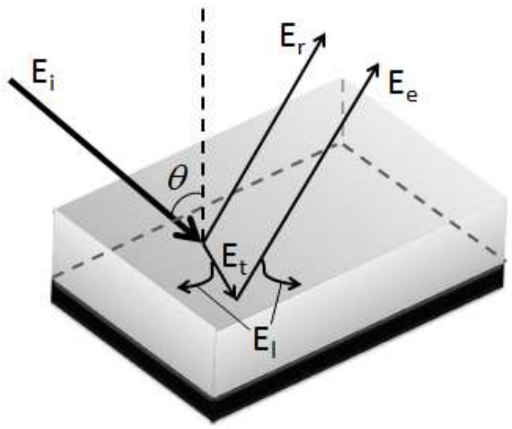

Figure 4. *Single layer penal absorbing coating's reflecting and absorbing model*

The analysis above shows that the coating's absorption for EM wave is mainly due to 2 parts: 1, the absorbent consuming the part of EM wave that has traveled through the coating; 2, the destructive interference caused by reflection with coating's front surface and rear metal penal. Therefore, the single-layered coating's failure of effective consumption for EM wave may be explained by 3 reasons:1, most of the EM wave was reflected back and failed to penetrate into the coating;2, the absorbent failed to achieve effective consumption for EM wave after it went inside the coating;3, effective interference consumption was not achieved due to the fact that the phase position and vibration amplitude of the waves reflected by the coating's front surface and rear metal penal did not match with each other. Considering these factors, the single-layered coating could be matched with the air layer to further study the coating's absorbing property.

3.2.2. The matching between carbon fiber coating and air layer

The aramid honeycomb's permittivity and permeability are close to the air's. Figure 5 is the testing curve of 1/8-bore-diameter AC-NH Mata-aramid Paper Honeycomb (with the thickness being respectively 2 mm, 4 mm, 6 mm, 10 mm)'s reflectivity. In the Figure, it can be seen that the reflectivity curve of honeycomb of varied thickness does not change a lot and is almost the same as the air's reflectivity curve.

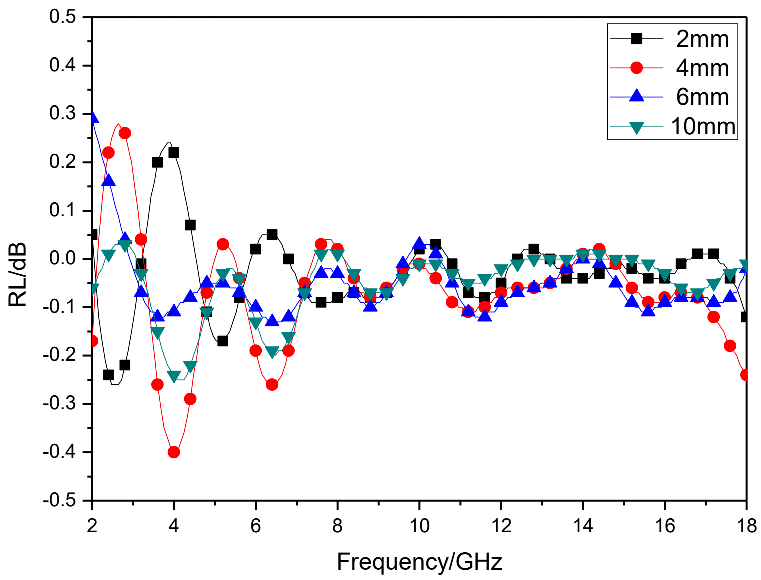

Figure 5. *Reflectivity's testing curve of AC-NH Mata-aramid Paper Honeycomb*

Table 1 gives the mechanical properties of the aramid honeycomb due to be used in this paper. According to the data, the due-to-be-used aramid honeycomb has low density, high strength and does not present obvious mass increase after being matched with the coating and can contribute to the strength to some level. The analysis above shows that the 1/8-bore-diameter AC-NH Mata-aramid Paper Honeycomb can be used as air layer to match with the carbon fiber's coating.

Table 1. *Mechanical properties of AC-NH Mata-aramid Paper Honeycomb*

Product	Cell Size (inch)	Density (kg/m^3)	Bate compressive strength (MPa)	plate shear（MPa）			
				strength L	modulus L	strength W	modulus W
AC-KH	1/8	48	2.40	1.39	88	0.97	65

Figure 6 is the reflectivity's testing curve after the coatings of varied carbon fiber content (0.1 wt.%, 0.2 wt.%, 0.3 wt.%, 0.5 wt.%) were matched with the aramid honeycomb of varied thickness (2 mm, 4 mm, 6 mm, 10 mm), according to the Figure, the testing curve has been significantly improved after the coatings were matched with the honeycomb, compared with the one before matching.

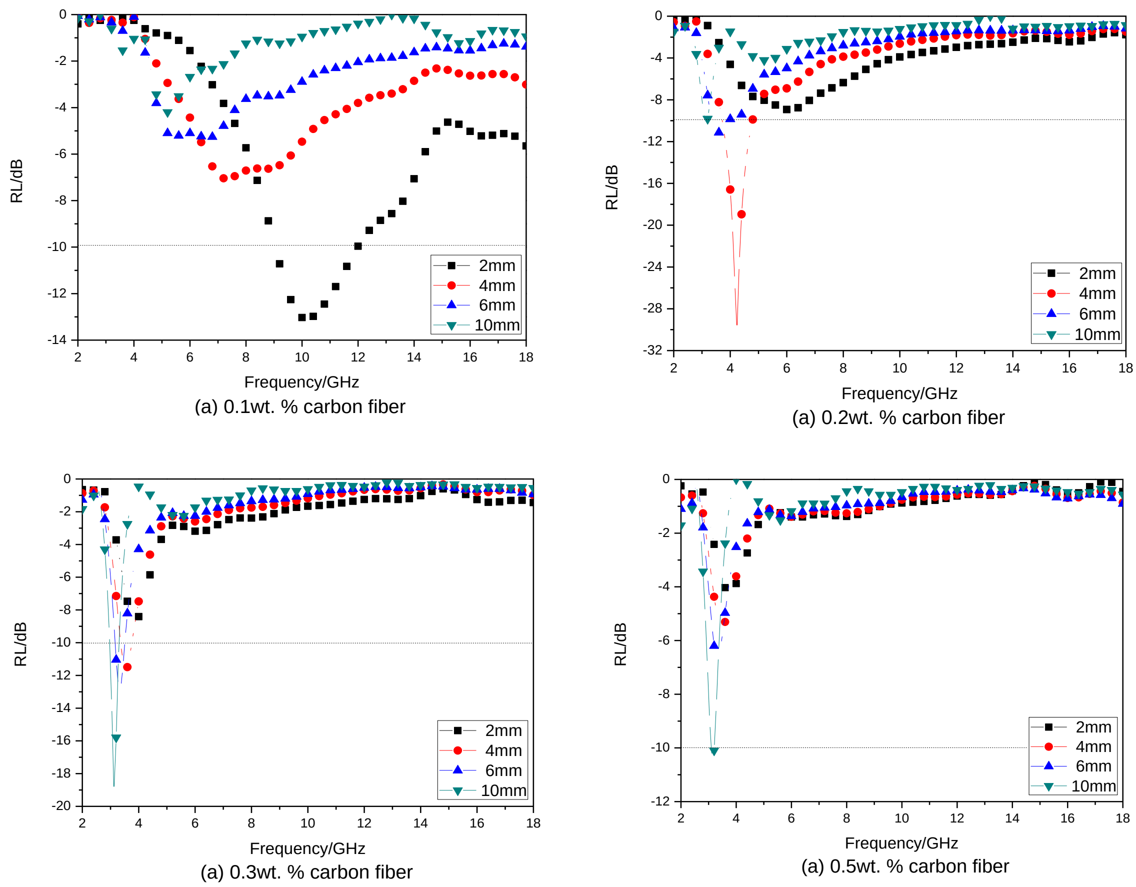

Figure 6. *Reflectivity's testing curve of carbon fiber absorbing coatings matched with air layer*

According to the transmission theory of plain EM wave, when EM wave travel from one medium to another, the surface's reflectivity R was jointly determined by the mediums' magnetic properties, incidence angle θ and incidence wave's polarization direction. When the polarization direction is perpendicular with the surface:

$$R_1 = \frac{Z_2/Z_1 \cos\theta - [1-(k_1/k_2)^2 \sin^2\theta]^{1/2}}{Z_2/Z_1 \cos\theta + [1-(k_1/k_2)^2 \sin^2\theta]^{1/2}} \tag{1}$$

When the polarization direction is within the surface:

$$R_2 = \frac{Z_1/Z_2 \cos\theta - [1-(k_1/k_2)^2 \sin^2\theta]^{1/2}}{Z_1/Z_2 \cos\theta + [1-(k_1/k_2)^2 \sin^2\theta]^{1/2}} \tag{2}$$

In formula (1) and (2), Z_1、 Z_2 represent the medium's intrinsic impedance, $Z = \sqrt{\mu/\varepsilon}$. The vacuum's permittivity and magnetic permeability are the same as 1. Therefore, its intrinsic impedance is Z=1, and the air's intrinsic impedance is almost the same. k_1、 k_2 represent the EM wave's wave number in the medium, and

$$k_1/k_2 = \sqrt{(\mu_1\varepsilon_1)/(\mu_2\varepsilon_2)}\ .$$

If the incidence wave is perpendicular with the coating's surface, the reflectivity can be both simplified into one figure:

$$R = R_1 = R_2 = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{3}$$

According to formula (3), when the EM wave traveled through one medium to another, a lower reflectivity on the surface was demonstrated in smaller intrinsic impedance changes. Therefore, the coating's intrinsic impedance must be close to the air's to make it easier for the EM wave to penetrate in the absorbing coating. In Figure 5, the coating's consuming capacity for high-frequency EM wave was generally weakened as the carbon fiber's content increased. After the content reached 0.3 wt. %, the coating presented poor absorbing capacity in X band and Ku band and was influenced by the matched air layer's thickness in a limited manner. This phenomenon can be explained with carbon fiber's role as electricity-consuming material lacking magnetic-consuming capacity. The carbon fiber's increase was followed by permittivity's increase with permeability remaining closed to 1. When the intrinsic impedance's variation scope between the coating and air increased, effective consumption cannot be achieved as most energy cannot penetrate into the coating.

According to Skin Effect in EM wave's transmission, the field strength will be attenuated exponentially after EM wave transmit into conductor. We assume the depth to be shin depth δ when the EM wave's field strength is lowered to $1/e$ of its original level.

$$\delta = \sqrt{\frac{1}{\pi \sigma \mu f}} \tag{4}$$

According to formula (4), the EM wave presented larger skin depth at lower frequency level in the same medium. In Figure 5, when the carbon fiber content was large, the short carbon fiber could not be completely separated by matrix resin and then a conductive network with conductor properties was established within the coating. Due to the fact that thin coating allows larger skin depth at lower frequency level, part of the EM wave can travel through the coating. After the penetration, the EM wave presented weaker field strength and unchanged frequency, and was reflected back into the air through the coating by the metal penal. During the process, a certain level of consumption for EM wave was realized, and meanwhile, the consumption was enhanced by repeated reflections between the metal penal and absorbing coating, although in a limited way.

The adjustment of phase-difference between the waves reflected by the coating's front surface and rear metal penal can be done by adjusting the thickness of matched air-layer and then interference effect can be produced between the waves. When the reflectivity hit the lowest, destructive interference led to maximum consumption and the air layer's thickness reached optimal matching thickness. According to 5(a), the coating presented best absorbing performance with 2mm matched air layer and 0.1 wt. % carbon fiber content and reached a maximum reflectivity of -13 dB at 10 GHz, the band width of effective absorption was 3 GHz; according to 5(b), the coating presented best absorbing performance with 4mm matched air layer and 0.2 wt. % carbon fiber content and reached a maximum reflectivity of -30 dB at 4.2 GHz, the band width of effective absorption was 1GHz; according to 5(c) and 5(d), a 0.3 wt. % and 0.5 wt. % carbon fiber content at optimal matching air layer thickness with similar effective absorption's frequency range to 0.2 wt.% carbon fiber content but present lower absorbing strength.

3.2.3. Multi-layered carbon fiber absorbing coating

The conclusion in 2.2.2 demonstrated that the absorbing performance was improved when single-layered carbon fiber coating was matched with air layer and a certain level of EM wave consumption can be achieve by adjusting the air layer's matching thickness with relatively narrow band width of effective consumption. The coating presented best absorbing performance at X band and Ku band with 0.1 wt. % carbon fiber content and at S band and C band with 0.2 wt. % carbon fiber content. Therefore, the frequency band of effective absorption can be extended by matching coatings with varied carbon fiber content. Figure 7 is the testing curve of multi-layered carbon fiber absorbing coating's reflectivity with the upper layer containing 0.1 wt. % carbon fiber content(thickness of matched air layer being 2 mm) and lower layer 0.2 wt.% carbon fiber content (thickness of matched air layer respectively being 2 mm, 4 mm, 6 mm and 10 mm). According to the Figure, the composite coating demonstrated best absorption performance with a 4mm matched air layer at nether coating and reached a minimum reflectivity of -23 dB at 4.8 GHz and -14 dB at 10.5 GHz and a reflectivity of less than -5 dB at C band, X band and Ku band, and a reflectivity of less than -10 dB with range of 4-13 GHz. The band width of effective absorption was 9 GHz.

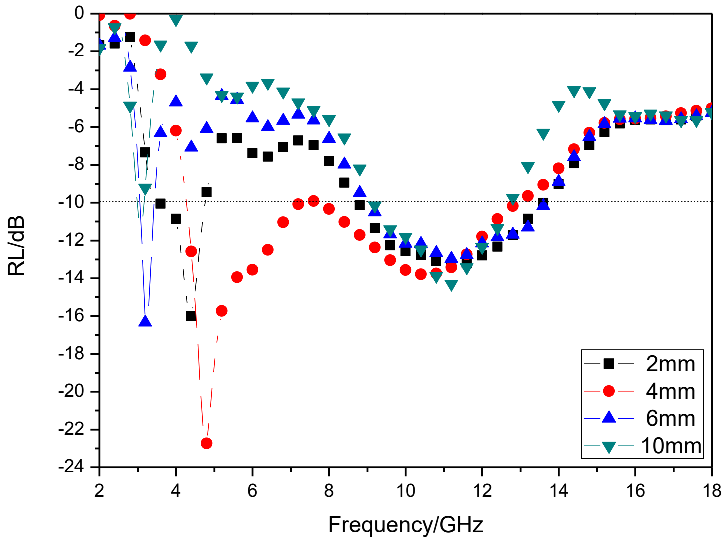

Figure 7. *Reflectivity's testing curve of multi-layered carbon fiber absorbing coating*

4. CONCLUSION

1) The absorbing performance of single layered coating was relatively poor and was significantly improved when it was matched with air layer. The coating presented best absorbing performance with 2 mm matched air layer and 0.1 wt. % carbon fiber content at X band and K band, and with 4mm matched air layer and 0.2 wt. % carbon fiber content at S band and C band.

2）The coating's absorbing performance was effectively improved by matching coatings of varied carbon fiber content to produce multi-layered matched carbon fiber absorbing coating. The best matching solution (from upper level to lower level) is 0.1 wt. % carbon fiber coating, 2 mm air layer, 0.2 wt. % carbon fiber coating, 4 mm air layer, the coating reached a minimum reflectivity of -23 dB at 4.8 GHz, a reflectivity of less than -5 dB at band C, X and Ku and a reflectivity of less than -10 dB within 4-13 GHz. The effective band width of effective absorption was 9 GHz.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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