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Design and characterization for a high-temperature dual-band radome wall structure for airborne applications

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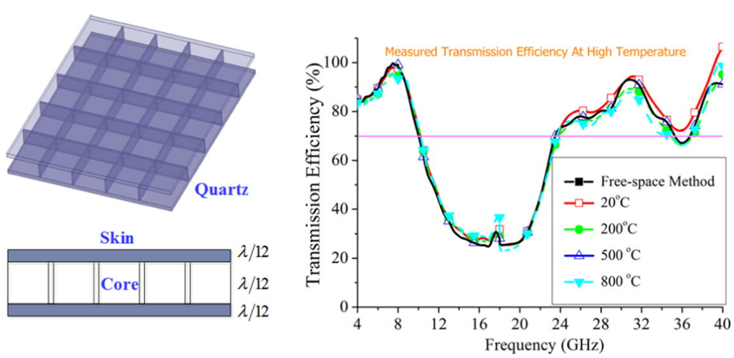
HIGHLIGHTS

- A dual-band A-sandwich radome wall is designed for both centimeter and millimeter wave applications at high temperature.
- A calibration method is proposed to eliminate the temperature-dependent errors of the microwave measurement system.
- Experiments show the radome wall is feasible for the 4–10 GHz and 24–40 GHz frequency spans at temperatures up to 800 °C.
- Experimental and calculation results demonstrate the effectiveness of the dual-band design method.

GRAPHICAL ABSTRACT



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ABSTRACT

Modern aircraft have reached higher and higher flight speed, resulting in the urgent demand of design and characterization for high-temperature airborne radomes, especially for those with dual-band or multi-band properties. In this paper, an A-sandwich radome wall structure made of quartz is designed for both centimeter and millimeter wave applications at high temperatures. Its transmission performance in the 4– 40 GHz frequency range at ambient temperature to 800 °C is characterized by a broadband free-space microwave measurement system, which is mainly composed of a vector network analyzer, spot-focusing lens horn antennas, and a furnace for heating sample. A calibration method is proposed to eliminate the temperature-dependent distortion of microwave signals by the microwave-transparent walls of the furnace, and the errors caused by the wall position variations as well. Transmission measurements show that the radome wall structure is feasible for dual-band applications in the 4– 10 GHz and 24– 40 GHz frequency spans with the transmission efficiency higher than 70% at temperatures up to 800 °C, and demonstrate the effectiveness of the design method. It can be expected that the free-space microwave measurement system in conjunction with the proposed calibration method is capable of damage detection for aerospace structures under high-temperature conditions.

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1. Introduction

A radome, which is electromagnetically transparent at particular microwave frequencies, is applied to protect the fragile antenna system mounted on different types of aircraft or missiles [1–3]. Nowadays, antenna systems are required to have more and more functions, such as communication, imaging, and detection, consequently leading to more than one wave band operated [1,4]. However, the radome must not interfere the utility of the antenna system [5–7], and therefore should have dual-band or multi-band transmission characteristics. Besides, the radome should withstand rain erosion, lightning strike, aerodynamic and also thermal loading [8]. Nowadays, the fight speed of aircraft or missiles has reached supersonic or hypersonic levels, resulting in the temperature outside the radome as high as 1400 °C or even more [9,10]. Thus, the radome material must possess excellent thermal and mechanical properties. High temperatures may also have significant effects on the temperature-dependent dielectric constant and loss tangent of the radome material, as well as geometrical dimensions due to thermal expansion, consequently degrading the transmission performance.

In the literature, most studies were focused on designs of broadband radomes at a particular wave band [11–16], and designs for dual-band dielectric radomes were not commonly seen. A few dielectric radome wall structures have been developed for dual-band applications [4,17–19]. Mackenzie and Stressing proposed a dual-band radome wall structure for X-band and W-band applications [4]. The flat radome wall was designed in an A-sandwich construction with two dense skin layers and a foam core layer. This kind of sandwich structures are widely used in engineering, such as in automobile industry, civil engineering, aviation, and aerospace industry [20–25]. Pei et al. proposed a C-sandwich structure, which was composed of three dense layers and two foam layers, with better dual-band transmission performance [17]. Lee et al. developed a dual-band flat radome, which involved frequency selective surfaces embedded in dielectric material and exhibited a broad passband in 2– 18 GHz together with a narrow waveband at 95 GHz [18]. To the authors' knowledge, most of the dual-band radome structures reported were not developed for high-temperature applications. Besides, some of the designs only took numerical calculations into consideration, and experimental verification was not involved, especially for those for high-temperature dual-band applications. Thus, it is necessary to develop dual-band radomes for high-temperature applications, and experimental verification at high temperatures is also required.

In this paper, an A-sandwich radome wall structure, which is made of a core layer of grid structure sandwiched by two quartz skin plates, is designed according to a dual-band design method based on the theory of small reflections. The transmission performance of the dual-band structure in the 4– 40 GHz frequency range at ambient temperature to 800 °C is measured by a high-temperature broadband free-space microwave measurement system. A calibration method is also proposed to eliminate the temperature-dependent errors of microwave signals by the front and the back walls of the furnace, which is used for heating the sample. Experimental data show that the radome wall structure is feasible for dual-band applications in the 4– 10 GHz and 24– 40 GHz frequency ranges with the transmission efficiency higher than 70% at temperatures up to 800 °C, and the results are demonstrated to be consistent with calculated results by the transfer matrix method. The high-temperature free-space microwave measurement system combined with the proposed calibration method is a promising tool for damage detection of aerospace structures at high temperatures.

2. Design for the dual-band A-sandwich radome wall structure

2.1. Design method for dual-band structures

In our previous work [26], using the theory of small reflections [27], we have put forward a design method for dual-band radome wall structure with an arbitrary odd number of layers. Calculations were carried out to demonstrate the effectiveness of the design method. However, experimental verification was not conducted in that work. In this paper, an A-sandwich radome wall structure is designed according to this method, and experimental verification will be carried out at both ambient and high temperatures. Because the A-sandwich structure consists of three layers, we will briefly introduce the dual-band design method for three-layer structures as a special case for the general design method [26], which is feasible for a dual-band structure with an arbitrary odd number of layers.

As shown in Fig. 1, the symmetrical A-sandwich radome wall structure comprises three layers ($N=3$) with two dense skin layers and a foam core layer. The dielectric constant and the thickness of each layer are assumed to be $\varepsilon_{r,i}$ and d_i, respectively, where $i=1,2,3$. According to the theory of small reflections [27], the total reflection coefficient of the A-sandwich structure is approximately equivalent to

$$\Gamma = \Gamma_0 + \Gamma_1 \exp(-2j\theta_1) + \Gamma_2 \exp[-2j(\theta_1+\theta_2)] + \Gamma_3 \exp[-2j(\theta_1+\theta_2+\theta_3)], \quad (1)$$

where Γ_i is the reflection coefficient at each boundary as shown in Fig. 1, and the phase thickness of the ith layer θ_i can be expressed as $\theta_i = k_i \cdot d_i$, where k_i is the wave number of the ith layer. As can be seen from Eq. (1), the total reflection of the A-sandwich structure is approximately evaluated as the sum of the first reflections off each boundary with phase delay. This results from the fact that, the theory of small reflections takes the assumption of small discontinuity in the dielectric property between each layer, and multiple reflections can be neglected.

Assume that the A-sandwich structure is to be designed as a dual-band structure with a low operating frequency f_0 and a high one $a \cdot f_0$ ($a>1$). The phase thicknesses of the ith layer for the two frequencies would be $\theta_i(f_0) = 2\pi d_i/\lambda_i$ and $\theta_i(a \cdot f_0) = 2\pi \cdot a d_i/\lambda_i$, respectively, where λ_i is the wavelength within the ith layer corresponding to f_0. It can be seen from Eq. (1) that, if $\theta_i(a \cdot f_0) = \theta_i(f_0) + n\pi$ $(n=1,2,3\cdots)$, the total reflection coefficient would be the same for the two frequencies. This means that the structure can be designed for f_0 for good transmission performance to simultaneously obtain dual-band transmission property for both f_0 and $a \cdot f_0$, if $\theta_i(a \cdot f_0) = \theta_i(f_0) + n\pi$ $(n=1,2,3\cdots)$ is guaranteed. If n is chosen as 1, then we have

$$\Delta\theta = \theta_1(f_0) = \theta_2(f_0) = \theta_3(f_0) = \pi/(a-1). \quad (2)$$

Because the structure is symmetrical, we have $\Gamma_0 = -\Gamma_3$ and $\Gamma_1 = -\Gamma_2$. Thus, the total reflection coefficient of the A-sandwich structure can be derived as

$$\Gamma = 2j\exp(-j3\Delta\theta)[\Gamma_0 \sin(3\Delta\theta) + \Gamma_1 \sin\Delta\theta]. \quad (3)$$

It is seen from Eq. (3) that, if $3\Delta\theta$ lies in the span of $0\sim\pi/2$, $\Gamma_0 \sin(3\Delta\theta)$ would be negative, whereas $\Gamma_1 \sin\Delta\theta$ would be positive,

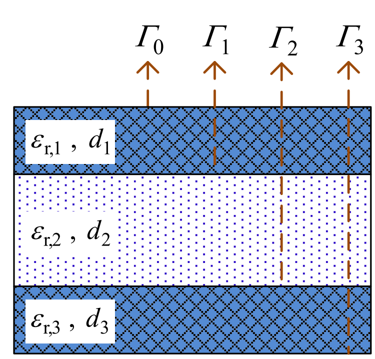

Fig. 1. Schematic diagram of the A-sandwich structure with two skin layers and a core layer.