Application of high-thermal-conductivity diamond for space phased array antenna

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ABSTRACT
Active phased array antenna typically featured high performance, high device integration, and high heat flux, making it difficult to dissipate heat. Diamond, the substance with the closest arrangement of atoms in nature, has the advantages of high thermal conductivity and strong adaptability to the space environment. The batch applications of high-thermal-conductivity diamonds for the thermal management of the phased array antennas of the inter-satellite links were introduced in this paper. The diamond was developed by the direct-current arc-plasma chemical vapor deposition method. The product size, thermal conductivity, precision, and application scale all met the engineering requirements. The high-precision assembly of the diamond and the structural frame enabled the efficient heat collection and transfer from the distributed point heat sources of multiple transmit/receive (T/R) modules. Verified on the ground, the thermal matching design between the diamond and the metal frame exhibited an outstanding heat dissipation performance. After four satellites using the diamonds were launched, the flight data showed good antenna thermal control, with temperature gradients of the T/R modules less than 2.2 °C, further verifying the rationality and effectiveness of using high-thermal-conductivity diamonds in the thermal design and implementation of antennas.

1. Introduction
The important feature of Chinese space project is the establishment of inter-satellite links among satellites, which is enabled by the Ka active phased array antenna, the most crucial piece of terminal equipment on the satellite. The Ka active phased array antenna on satellite (hereafter referred to as “antenna”) features high performance, high device integration, and high heat flux. Therefore, it is difficult to dissipate accumulated heat in the antenna because a large number of transmit/receive (T/R) modules are densely arranged in a small space. The T/R module, commonly recognized as the essential component of the active phased array antenna, is the key component to facilitate the electronic scanning of the phased array beam [1–3]. Inside the T/R module, a variety of high-performance, high-gain gallium arsenide (GaAs) chips are highly integrated by the low-temperature co-fired ceramic (LTCC) structure, resulting in the increase in the internal heat flux. The heat flux in the micron-scale gallium arsenide chip in the phased array antenna on satellite can be as high as 50 W/cm², far beyond the heat transfer limit of general heat pipes. However, the thermal conductivity of the LTCC material at the bottom of the chip is very low, about 2 W/(m·K), making it difficult for the chip to dissipate heat. In addition, due to the compact structure, the traditional thermal control method has difficulty adapting to the special requirements of the structural and microwave design of the antenna. The T/R modules are compactly arranged on the front and back side of a single transceiver component, with only 2.8 mm of geometric distance between both sides, making it impossible to implement two-phase heat transfer components such as heat pipes. Furthermore, 90% of the antenna heat is concentrated in a relatively small antenna front area. Even worse, the antenna needs to operate continuously in orbit for more than 15 years with the T/R module operating at temperatures ranging from −10 to 50°C, while a low temperature gradient of all the T/R modules (less than 10°C) is required.

Moreover, due to the non-sealed structure of the satellites, there are only two modes of heat transfer: conduction and radiation. Satellite antennas are difficult to dissipate heat compared with ground phased arrays, which generally use convection to dissipate heat. Many application cases in this area show that the thermal control of satellite phased array antennas has suffered substantially [4, 5]. In summary, the heat dissipation of the active phased array antennas on satellites has become...
The DC plasma jet CVD method can fabricate high-quality polycrystalline diamonds with thermal conductivities of up to 2000 W/(m·K) at a moderate price [28, 29]. Based on the requirements of the satellite in terms of product size, thermal conductivity, and batch production capacity, the high-thermal-conductivity diamond investigated in this article was developed by the DC plasma jet CVD method.

2. Application requirements

2.1. Temperature requirements of satellite phased array antennas

The temperatures of RF chips and electronic devices on a phased array antenna are closely related to the reliability and electrical performance. The failure rate of the microwave RF components in the T/R module increases exponentially with the increase in temperature, and the electrical performance of the microwave RF components deteriorates as the temperature rises. In addition, the phase of the transceiver component on the phased array antenna is affected by the temperature. To ensure phase control of the entire antenna array, the temperature consistency of microwave radio array is strictly required. To ensure that the antenna can function normally in orbit for a long time during its full lifespan, it is necessary to maintain the operating temperature of the antenna with a thermal control design. The temperature requirements of the satellite Ka phased array antenna are mainly the following: ① the temperature of the T/R module and other RF modules ranges from −10 to 50 °C, and ② the temperature gradient of all T/R modules is ≤10°C.

2.2. Antenna requirements for high-thermal-conductivity materials

As shown in Figure 1, the antenna T/R modules were integrated in the active transceiver component, where multiple T/R modules were densely installed on the front and back side of the transceiver. It was difficult to reduce the temperature difference of the T/R modules in a single transceiver component. It was even more difficult to maintain the temperature gradient of all T/R modules at ≤10°C. The main bottleneck was the geometric distance of only 2.8 mm between the front and back side of the T/R module, while China’s current aerospace grade heat pipes measure a minimum geometric size of 3.1 mm. Therefore, it is not feasible to utilize heat pipes. Instead, solid high-thermal-conductivity materials can be considered. The average heat consumption of the T/R module was 1 W. If an aluminum alloy material were used, based on the layout size and the locations of the T/R modules, the temperature difference between the center and the edge of the transceiver component would be approximately \[\Delta t = Q\delta/(\lambda A) = 2 \times 0.16/(121 \times 0.04 \times 0.0028) = 23.6°C,\] where \(Q\) is the heat consumption, \(\delta\) is the thermal conductivity, and \(A\) is the layout size.
which far exceeds the target temperature gradient of 10 °C. If the thermal conductivity could be increased 10 times from 121 W/(m·K) of the aluminum alloy, the temperature difference of the T/R module could be roughly estimated to be about 2.3 °C. Therefore, it is imperative to use high-thermal-conductivity materials.

A preliminary thermal analysis model of the antenna that takes into account the internal radiation and heat transfer was built. The temperature results obtained with various thermal conductive materials were shown in Table 1. The use of high-thermal-conductivity materials could effectively decrease the temperature gradient of the T/R modules inside the antenna and reduce the temperature. The higher the thermal conductivity of the material was, the lower the temperature of the T/R module and the smaller the temperature gradient became. Specifically, both the temperature level and the temperature gradient when using diamond were 22 °C less than those when using an aluminum alloy material, showing the significant advantages of diamond. The thermal conductivities of aluminum–diamond materials, copper–diamond materials, and high-thermal-conductivity bulk graphite were all above 400 W/(m·K), meeting the temperature requirements. However, investigations showed that there was a certain degree of discreteness in the mechanical properties and the thermal conductivities of the aluminum–diamond and copper–diamond materials. It was difficult to ensure that metal and diamond powder were uniformly mixed during the fabrication, easily resulting in non-uniform distributions of the crystal grain size as well as structure and stress at each position. In addition, metal-based diamond composites are prone to high internal stresses during the fabrication, requiring further study and verification on the long-term stability. The application of bulk graphite, with low mechanical strength, is also limited in engineering applications of the high-precision processing and assembly of T/R modules due to its tendency to generate excess surface materials. Therefore, high-thermal-conductivity diamond has become the first choice for resolving the problem of antenna heat dissipation.

### 3. Application

#### 3.1. Structural design and implementation

High-thermal-conductivity diamond plates were embedded on the front and back sides of the frame structure of each transceiver component of the antenna in Figure 1. The diamond plate was installed on every antenna. The diamond film was fabricated by the DC arc plasma CVD method and cut by a high-power laser, simultaneously making several performance test samples from the original film. The surface roughness

### Figure 1. Schematic diagram of the thermal control design based on a diamond film and a photograph of the high-thermal-conductivity diamond film.
and flatness of the diamond films were controlled within an effective and reasonable range by polishing [25].

The diamond plate was embedded in an aluminum frame of the transceiver component, with the interface filled with conductive epoxy adhesive that was later cured at a high temperature. The height difference between the secured diamond plate and the frame of the transceiver component was less than 100 μm to satisfy the high-precision assembly design. A higher filling rate that ensured good heat transfer between the T/R module and the heat transfer interface of the diamond film was obtained by filling the installation interface between the T/R module and the diamond film with a conductive epoxy adhesive at a lower curing temperature. The abovementioned design enabled the accumulated heat of the T/R module to diffuse quickly through the diamond film to the entire transceiver frame, reducing the temperature gradients of the T/R modules. To improve the electrical conductivity between the T/R module and frame, gold was coated on the surface of diamond film by controlled sputtering. Thus, the surface of insulating diamond film could be electrically conductive while the binding force between the conductive adhesive and the diamond film was enhanced.

### 3.2. Ground test and experiment verification

A series of ground tests and experiments were carried out on the diamond plate, ensuring the aerospace product quality. An optical microscope (OLYMPUS BX-51) was used to observe the surface of diamond. A Dektak150 surface profiler was used to measure the roughness, and a coordinate-measuring machine was used to measure the flatness. The characterization of diamond quality was developed using a RenishawinVia confocal laser Raman. A Netzsch LFA 467 Hyper-Flash was used to measure the thermal conductivity of diamond, and a DF-500 diamond film mechanical property testing machine was used to measure the fracture strength of the diamond by a three-point flexural test. The experimental temperature cycled between −40 and 140 °C with 100 alternating heating and cooling cycles. After the ground tests and experiments, the surface of the high-thermal-conductivity diamond was free of defects such as cracks, burrs, dirt, pores, scratches, or pits. The shape and flatness of the diamond met the requirements of the blueprint, with a surface roughness less than 6.4 μm and flatness and parallelism lower than 40 μm. The fracture strength was higher than 400 MPa, and the thermal conductivity was higher than 1600 W/(m·K).

**Figure 2** shows the fracture morphology and laser

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**Figure 2.** (a) Fracture morphology and (b) laser Raman spectrum of the diamond film.
Raman spectrum of the diamond film. The Raman spectrum showed a sharp diamond characteristic peak near $1332.5 \text{ cm}^{-1}$, with a full-width-at-half-maximum of less than $6 \text{ cm}^{-1}$, indicating that the diamond was of high quality. The deposited gold layer on the diamond surface exhibited a bright and uniform metallic luster, without spots, areas with missing coatings, bubbles, peeling, cracks, or shedding. After the temperature cycle tests from $-40$ to $140 \degree C$, there were no changes in the surface morphology of the high-thermal-conductivity diamond and gold layer. The sputtered gold layer showed no blistering, peeling, cracking, or shedding. The adhesion test showed that the bond was strong between the deposited gold layer and the diamond before and after the temperature cycle tests, meeting the temperature cycle resistance requirements of the diamond.

The measured masses and thermal conductivities of the batch-produced diamond films were shown in Figure 3. The diamond quality was stable with a thermal conductivity at room temperature greater than 1600 W/(m·K), reaching up to 1900 W/(m·K).

The T/R module was a high-precision product. In addition to the strict error control over the flatness of both the diamond film surface and the structural frame of the transceiver component, the assembly of diamond film between the structural frame and T/R module is strictly controlled. All are realized by automation to ensure the microwave precision and good heat transfer of the contact interface, and reduce the temperature difference caused by the contact thermal resistance. Laser grating was used to measure the topographic characteristics to ensure the high-precision assembly of the diamond and the structural frame after diamond film was secured in the frame of transceiver component by the conductive adhesive, which was cured at high temperatures. The linear expansion coefficient of the diamond film was $1 \times 10^{-6}/\degree C$ while the linear expansion coefficient of the metal material of the transceiver component was $21 \times 10^{-6}/\degree C$. A mismatch in the thermal expansion between the two materials emerged. To solve the problem of thermal matching between the diamond film and the metal material, a conductive adhesive with a certain degree of elasticity was selected. And a certain thermal deformation tolerance was reserved at both ends of the diamond assembly, preventing the diamond film from being stressed due to thermal deformation. The curing temperature was experimentally verified, and a curing temperature as low as possible was selected to achieve a reliable connection between the diamond film and the structural frame. After the diamond film was assembled with the antenna structure, it could withstand 100 thermal cycle tests at $-20$ to $70 \degree C$ and a test at a higher temperature of $120 \degree C$ for 4h. In addition, Industrial Computed Tomography was used for non-destructive testing to check the contact on the installation interface between the diamond film and the antenna frame.

Figure 4 shows a photograph of the whole antenna in the vacuum chamber during the thermal balance test. The whole-system-level thermal balance test of the antenna was carried out in a thermal vacuum chamber. The test results showed that the temperature level of all T/R modules was in the range of 15.3–19.3\degree C, with a maximum temperature gradient of 1.9\degree C. Ground tests verified the efficient heat collection and transfer from multiple distributed point heat sources of the T/R modules. The thermal matching design of the diamond and the metal frame proved to be valid with the T/R module temperature gradient of 1.9\degree C, showing an outstanding heat dissipation performance. Figure 5 shows a thermal analysis temperature mapping based on thermal results.
3.3. Flight results

The Ka phased array antenna developed by the China Academy of Space Technology was launched into orbit with the satellite and performed well in orbit. The flight temperature results of the phased array antennas on four satellites in one orbital period were shown in Figure 6. The analysis of recent telemetry data showed that the telemetry temperature of the antenna T/R module was in the range of 6.2–17.2 °C, and the maximum temperature gradient was 2.2 °C on all the T/R modules, exceeding the requirement of ≤10 °C.

In addition, as the antenna operated in full-transmission mode for 20 min, the heat accumulated in a single T/R module increased from 1 to 1.5 W, and the heat accumulation of the entire antenna increased 1.6-fold. In contrast, the temperature of the antenna T/R modules increased only 2.3 °C (Figure 6), which indicating that the diamond film exhibited a good heat diffusion performance and was capable of quickly diffusing the heat of the T/R module to the outside. It further verifies the effectiveness of thermal design and the implementation of high-thermal-conductivity diamonds in the antenna.

4. Conclusions and prospects

(1) The batch applications of DC arc plasma CVD diamonds for the thermal management of the phased array antenna of the inter-satellite link on satellite met the engineering requirements of the characteristics, quality, thermal conductivity, precision, and application scale.

(2) A plan for embedding diamond films in the antenna frame was proposed and carried out, enabling the efficient heat collection and transfer from the distributed point heat sources of multiple T/R modules. Ground tests verified that the thermal matching design of diamond and metal frame was effective, yielding an outstanding heat dissipation performance. The temperatures of all T/R modules were in the range of 15.3–19.3 °C, with a temperature gradient of the T/R modules no greater than 1.9 °C.
(3) Flight verification indicated that the telemetry temperature of the antenna T/R modules was in the range of 6.2–17.2 °C, and the maximum temperature gradient of all the T/R modules was 2.2 °C, exceeding the requirement of ≤10 °C. Furthermore, as the antenna operated in full-transmission mode for 20 min, the temperature rise of antenna T/R modules was only 2.3 °C. The heat diffusion performance of diamond film, quickly diffusing the heat of T/R module to the outside, proved to be very good which further verified the rationality and effectiveness of the design and the implementation of high-thermal-conductivity diamonds.

As a typical ultra-high-performance material and extreme functional material, diamond has outstanding optical, mechanical, thermal, and electrical properties, as well as excellent radiation resistance and chemical inertness. Thus, a wide range of applications for diamond are anticipated in the aerospace field.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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