Research on High-power Transmission Technology of Satellite Borne RF Connector

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Abstract: The reliability of the communication link shall be affected severely due to failure modes such as multipactor, low pressure discharge, and thermal damage that are commonly found in the RF connector when it performs high-power microwave signal transmission in the vacuum environment of outer space. This paper proposes supporting measures in respect of design against multipactor, low pressure discharge and thermal damage after analyzing mechanisms of failure modes of the RF connectors when it transmits high-power microwave signals in a vacuum environment. Upon tests, these proposed measures can effectively guarantee the reliability of the RF coaxial connector transmitting high-power signals in vacuum.

Keywords: RF connector; high-power transmission; low pressure discharge; multipactor

1. Introduction
RF connector is a precise microwave passive device that transmits communication signals adopting coaxial transmission to implement the impedance matching and energy transfer of the microwave signal transmission path. The RF connector is functioned as a bond linking the whole communication system through establishing a microwave link between microwave components. As the space technology and satellite industry are booming, the rising service power of model satellites has raised a demand for high-power satellite borne RF connectors. At the same time, high reliability of high-power RF connectors being resistant to space environment is also demanded. If RF connectors are designed and produced without considering failure modes and preventive measures for transmitting high-power signals in outer space, it might damage or fail in its subsequent use, thus affecting the operation of the spacecraft as a whole. At worst, it might lead towards the failure of a mission [1]. Hence, it is of great significance to study the failure modes during transmitting high-power microwave signals in the outer space environment, for improving the performance stability and service life of the spacecraft.

2. Failure Mode Analysis
Three failure modes stand out for RF connectors transmitting high-power microwave signals in the outer space environment.

2.1. Multipactor failure
Multipactor, in general, occurs in an environment with the air pressure of \( \leq 10^{-3} \) Pa, and takes place most easily in the process of transmitting high-power signals. The generation of multipactor might result in the detuning of resonant equipment, the rising VSWR, the increments in reflection power and system...
noise, and the detuning of microwave signal. What’s worse, if the inner surface of the component is ablated, it will cause permanent damage to the component with excess local temperature \[^2\].

Figure 1. Multipactor ablating the surface of the RF device

2.2. Low pressure discharge failure
Low pressure discharge typically occurs in the environment with the air pressure ranging from 200Pa to 58kPa. Note that it is more prone to multipactor under the same power. Low-pressure discharge could lead to the detuning of resonant equipment, interference with the coupling and transmission of microwave signals. In severe cases, it might cause damage or partial defects (Fig. 2) to microwave devices, permanently damaging the equipment \[^3\].

Figure 2. Low-pressure discharge sample

Figure 3. Thermal damage sample

2.3. Thermal damage failure
Thermal dissipation conditions are poor in the vacuum environment. When the transmission power is large and the link loss accumulated in the form of heat cannot be dissipated timely, the excessive heat will bring about partial deformation of the connector, or causing ablation to the entire device (Fig. 3).

3. Failure Mechanism Analysis

3.1. Mechanism of multipactor
Multipactor, also known as the multipacting effect, is a strong discharge triggered by secondary multiplication between two conductors in a vacuum environment, which is the resonance discharge occurring (Fig. 4) when the component is at the pressure of \(1 \times 10^{-3}\) Pa or below.

Initiating electrons bombard the upper surface of the metal under the acceleration of the applied RF field. If the secondary electron emission coefficient \(\delta\) of the material is greater than 1, more secondary electrons will be released in comparison to initiating electrons. Then, secondary electrons bombard the lower surface of the metal under the acceleration of negative electric field. The circulation won’t be stopped until the multipactor effect is produced \[^4\].
Low pressure discharge is a gas breakdown effect caused by the avalanche increase of electron number in space after the charged particles in the gas impact neutral particles or stimulate the emission of secondary electrons on the metal surface under the action of the RF field formed by signal transmission in a low-pressure environment (ranging from $10^{-3}$ to $10^5$ Pa) [3]. The mean free path of charged particles in the low-pressure environment is less than or approximately equivalent to the feature size of the gas space. In that case, the charged particles in the gas obtain can obtain sufficient energy under the action of electric field to impact neutral particles for exciting or ionizing electrons and positive ions. Besides, charged particles newly generated lead to new excitation or ionization after being accelerated by the electric field. In consequence, the electron number in space witnesses an avalanche growth (Fig. 5). Thus the originally insulated gas is turned into plasma, generating the low pressure discharge [5].

4. High-power Transmission Technology

To ensure that the RF connector transmits high-power radio frequency signals stably in the space environment, corresponding measures must be taken to prevent multipactor, low pressure discharge and thermal damage from taking place, according to the above analysis concerning failure modes and mechanism of the RF connector.

4.1. Multipactor suppression measures

1) Optimized clearances between inner and outer conductors

When the multipactor conductor threshold is between 6 and 10dB of transmission power, the multipactor threshold can be improved through optimizing the clearance between inner and outer conductors on the premise of allowable space structure.

To be specific, since the transit time of secondary electrons is dependent of the clearance between
conductors, the longer the electron transit time the fewer electrons will reach the opposite conductor through acceleration when the work frequency is constant. Theoretically, the increasing gap can raise the multipactor threshold. But it is worth noting that this approach has two limitations. First is the requirement of the cut-off frequency. The excessive clearance might reduce the cut-off frequency of the product, or the frequency baseline for second harmonic generation. If the cut-off frequency is lower than the operating frequency, the microwave transmission characteristics will be deteriorated drastically. The second is volume limitation. Components used in space are strictly limited in volume and weight. Increased clearance will result in a corresponding increase in volume and weight of the product.

2) Insulation barriers between inner and outer conductors

When the multipactor conductor threshold is within 6dB of transmission power, it cannot fully meet the requirements through using merely the method of clearance increasing due to the limited connector size. In response to its, non-metallic insulating materials can be introduced between the inner and outer conductors. For instance, the inner conductor can be wrapped with an insulating material in the coaxial section of the air dielectric, which can reduce the kinetic energy during electron impact. More than that, it can also function as a refraction of electrons, that is, electron motion between the inner and outer conductors can be obstructed by the barrier to suppress the secondary multiplication and avoid the destruction of vacuum power. Nevertheless, adding non-metallic barriers also generates step capacitances in addition to the impedance discontinuities, leading to a high-peak electric field. Furthermore, dielectric loss is also introduced to increase the insertion loss of the connector, causing a difficulty in heat dissipation. Aiming at these situations, it is essential for studying new impedance compensation and connector structure optimizing methods with comprehensive considerations in optimizing the S parameters of RF connectors and suppressing vacuum resonance discharge. It includes the following aspects: a) optimizing the design parameters of the high-frequency paths, b) ensuring impedance matching of the RF connector transmission path, c) realizing precise compensation during transmission. Through the above measures to improve the product power performance.

4.2. Low-pressure discharge suppression measures

1) Vent design

As low pressure discharge occurs only when the air pressure reaches a certain threshold, vents can be designed on the enclosure of the RF connector to discharge the gas in the connector cavity as quickly as possible, so that the air pressure in the cavity can be maintained below the discharge threshold, avoiding low pressure discharge. The vent is designed after accurately computing. If the vent is too small, the gas in the inner cavity will be unable to discharge in time. If the vent is too large, it will increase the probability of electromagnetic leakage of the product. Therefore, vents must be set approximately or increased in number according to the electric field energy distribution on the basis of satisfying electromagnetic leakage, so as to achieve the optimum ventilation effect. The size and length of the vent are calculated as per the ventilation air conduction formula, shown in below [4-5].

\[ U = \frac{12.1d^3}{(l + 4d/3)} \]  

(1)

Apart from formula computing, a mathematical model of air pressure in the RF connector in the space environment changing with time should be constructed to design the location and number of effective vents using relevant electromagnetic and microwave technologies.

2) Labyrinth structure design

After the RF connector is fully inserted, a coaxial air section where the inner and outer conductors are exposed to the air can be easily found at the end surface. Low pressure environment will be formed partially in this section, leading to low pressure discharge, once the released gas cannot discharged in time. Hence, a special intersecting structure can be designed at the front end of the insulating support in the connector to form a "labyrinth" structure (Fig. 6) in the inserting section, avoiding the phenomenon from happening. To be concrete, the proposed structure is just like adding the creepage distance and avoiding inner and the outer conductors of the connector from directly facing each other due to
processing errors. In this way, low-pressure discharge can be effectively suppressed.

![Figure 6. Labyrinth structure](image)

4.3. Preventive measures against thermal damage

Measures for preventing thermal damage from RF connectors are composed of:

(i) Coaxial cables and insulating support materials with low dielectric loss (tanδ) should be selected to lower the thermal loss of the entire connector. Also, the design of structural parameters of the RF connector should be optimized to reduce the loss value as a whole. In this way, the transmission efficiency of high-power RF connector can be guaranteed. In other words, thermal loss can be lowered to avoid excessive temperature rise.

(ii) Simulation calculation should be conducted on the electric field strength of the connector cavity to locate the distortion point of the cavity power density for parameter optimizing. By doing so, the power density of the connector cavity can be evenly distributed, preventing the accumulation of heat at local points due to the microwave information with heavy loss in the local position during transmission.

(iii) Thermal field simulation analysis is performed on the working state of the RF connector (Fig. 7). More precisely, the proven 3D finite element thermal field analysis technology is applied to analyze the thermal field distribution of the structure when the RF connector transmits high-power signals in steady state and transient analysis, so that the parts with excessive temperature can be located for structure optimization to enhance its heat dissipation potential.

![Figure 7. Thermal field simulation result](image)

5. Verification

Structure optimization and design improvement are conducted on the TNC RF connector that causes low pressure discharge and multipactor when 100W microwave signals are transmitted in the L-band in accordance with the preventive measures proposed in Section 4. The improved TNC RF connector prototype is shown in Fig. 8. The connector is verified in conformity with the following tests:

1) Multipactor-resistant verification test: When the ambient temperature of the vacuum tank is 90°C, its vacuum degree is lower than 1.3×10⁻³ Pa, with the loading power consisting of 200W continuous waves (CW) and 800W pulses (2% duty cycle). The test is conducted at the frequency of 1.15GHz with the holding time of 30 minutes. No discharge phenomenon is found during the test.

2) Verification test of resisting to low pressure discharge: The test environment temperature is first increased to 90±2°C. And then 220W CW is loaded under normal pressure. The test is conducted at the frequency of 1.15GHz. The time decreasing from normal pressure to 1.3Pa shall be no less than 20 minutes. The process is circulated for 3 times. No discharge phenomenon is found during the test.

3) Verification test of resisting to thermal damage: When the ambient temperature of the vacuum tank is 90°C, the vacuum degree is lower than 1.3×10⁻³ Pa, with loading power of 240W CW. The test is conducted at the frequency of 2GHz with the holding time of 30 minutes. No discharge phenomenon is
found during the test.

Based on the above test verification, the improved and optimized TNC RF connector has the rated power tolerance capacity of up to 200W (@L-wavelength) in the space environment, which is increased more than twice the original one, less than 100W. Apparently, the improved RF connector is provided with the ability to transmit high-power signals during satellite application.

6. Conclusions
Multipactor, low pressure discharge and thermal damage are major failure modes of satellite borne high-power RF connectors, which should be prevented in the initial design of the connector in order to safeguard the reliability and service life of satellite high-power RF connectors in the space environment. According to the study, multipactor, low pressure discharge and thermal damage can be effectively suppressed with the help of insulation barrier, vent design, thermal field analysis and the like technologies, contributing to enhancing the reliability and stability of RF connector transmitting high-power signals in the space environment.

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