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Design of Multipactor-free S-band Duplexer Using New Test Method for Space Applications

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Abstract

Multipactor-free S-band duplexer based on inter-digital cavity type filter is proposed and demonstrated by in-house mulitpactor test facility for satellite RF components. Multipactor sensitivity of designed duplexer is analyzed by checking it out the maximum field accumulated region inside duplexer and calculating the electric field intensities at each resonator using 3D EM simulation in order to restrict the minimum gap distance as 2.5 mm which handles 43.13 dBm RF input power. Multipactor threshold was finally detected at 44 dBm in experiment for pulse mode test. The developed multipactor test method is cost effective, simple structure and gives a good agreement compared with the previous high cost MP test methodologies.

Key words : Multipactor, Diplexer, Filter, RF Power Handling.

Ⅰ. Introduction

Especially RF passive components for satellite applications should be taken into account with multipactor (MP) breakdown under extreme high vacuum condition. MP occurring condition is that the mean free path(MPF) of free electrons which is the average distance electrons travel between collisions with other electrons in the gas is greater than the gap spacing. At that condition the free electrons can travel to opposite side wall without any collision among other electrons and only contributed and trapped by input RF E-field. MP is a resonant multiplication of secondary electrons which can occur when a free electron caught in an input RF field that impacts to a surface wall with sufficient energies to release more than one secondary electron at a phase, and the RF field can finally accelerate these secondary electrons. As a consequence, it can affect RF performance degradation such as increasing of spike noise, return loss and noise level in pass band as well as damaging of physical structure of surface[1],[2].

In this letter, the MP free duplexer which can handle the RF input power up to 5 watt (36.99 dBm) with additional 6 dB margin of safety for telecommand and telemetry application of satellite communication is presented in terms of some design techniques, a new MP test method by using 3D EM field analysis and an in-house MP test facility respectively.

The description of designed duplexer is only focused on the downlink BPF part of duplexer rather than that of uplink because the former is located after a transmitter with high RF power and the latter is only receiving path with exactly same configuration.

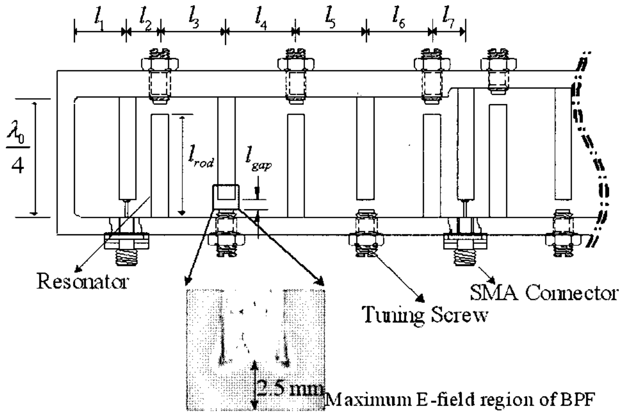

Fig. 1. Configuration of the downlink BPF in a part of duplexer and the identification of maximum E-field accumulated region.

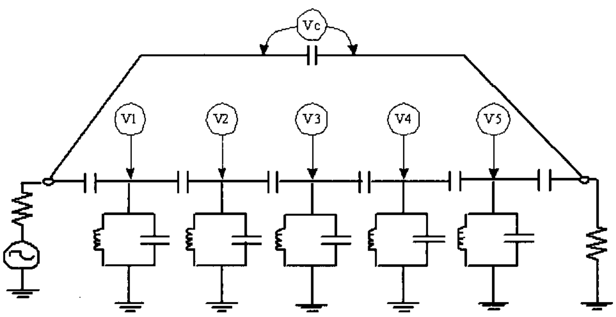

Fig. 2. Electrical equivalent model of Fig. 1.

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Ⅱ. Design and MP Analysis for Duplexer

2-1 Design of Duplexer

The structure of the proposed duplexer is a conventional one employed with an interdigital cavity type as shown in Fig. 1. Inner rectangular size is a quarter-wavelength long at a mid band and is short circuited at one and open circuited at the other end alternating in parallel. The duplexer however should be a MP free structure operated in space handled with high RF power, so more detail design analysis are needed such as following. The downlink BPF with five resonators is shown in Fig. 1 and to design the filter the external quality factor Q_{ext} and the inter-resonator coupling coefficient k_{ij} between i_{th} and j_{th} resonators and fringing capacitance C_f between each end of resonator and surface of wall are calculated[3],[4]. The Q_{ext} and k_{ij} are controlled by changing the diameter and location of each rod and by adjusting the height of inner rectangular cavity, respectively. Using these calculated the external quality factor Q_{ext} and the coupling coefficient k_{ij}, 0.1 dB-ripple five-pole Chebyshev band pass filter with a 2.7 % bandwidth centered at 2.23 GHz is initially designed.

In order to get the MP free structure up to 20 watt RF input power, the duplexer was designed without any performance degradation as following; the first is the length of resonator was more 3.68 mm shorter than the initial quarter-wave length value (33.63 mm) to increase the gap spacing up to more than 2.5 mm, the second is the diameter of rods (5 mm) was more bigger to get the same fringing capacitance C_f and the last is the duplexer was designed as the cavity length is about 1.32 mm larger than that of initial value.

Based on well-known filter synthesis technique[3] and some design modifications as above, the Q_{ext} is found to be 37.1 and the lengths of l_1, $l_2(=l_7)$, $l_3(=l_6)$, $l_4(=l_5)$ and l_{rod}, l_{gap} are 15.68 mm, 9.75 mm, 19.57 mm, 20.73 mm and 29.95 mm, 2.5 mm, respectively.

2-2 MP Sensitivity Analysis

The MP susceptibility curve is employed by [1], [5]. From this curve, the threshold gap voltage (V_{th}) is about 496.7 voltage calculated by 5.58 GHz×mm of F×d product with 2.23 GHz and 2.5 mm gap spacing for silver plated surface. To define the maximum field accumulated region and to find E-field intensity, 3D EM simulation, finite element method(FEM), was employed and E-field distribution was shown in Fig. 1 and the equivalent model of downlink filter is shown in Fig. 2. The gap voltage of each pole is calculated by integral of E-field through the critical gap distance, 2.5 mm as in (1), (2)[6].

$$E(t) = \mathrm{Re}\left(\sum_i E(f_i) e^{j(2\pi f_i t + \phi_i)} \right) \tag{1}$$

$$V_{gap} = \max_{x \in (0, \varpi_i)} \int_l E_y(x, y, z = z_i; \varpi) \cdot dy \tag{2}$$

Next to evaluate the power handling capability of the device, MP free maximum RF input power is defined as in (3).

$$P_{i,\max}(\varpi) = \frac{V_{th}^{\,2}(h_i, \varpi)}{2 Z_0(\varpi) (V_{gap} / V_{in})^2 (z_i, \varpi)} \tag{3}$$

Above calculations, the most field accumulation regions are 2nd and 4th pole and moreover the gap voltage and MP free RF input power in each rod over the interesting frequency ranges are shown in Fig. 3 and 4. These figures show finally the worst MP free RF input power as 20.58 watt (43.13 dBm) at 2.23 GHz.

Ⅲ. MP Sensitivity Test

3-1 In-house MP Test Facility

It is difficult to define exactly the MP threshold RF input power by experiment because it depends on the type of device, surface treatment, test facility environment and so forth[7]. The in-house MP test facility is a new test method called a phase detecting system that is simple and one of local test methods as shown in Fig. 5. The additional test methods are adapted; one is a phase nulling system as one of global methods that is a well-known method and the other is a high cost electron current detection method as a local system to verify and use as a cross-reference test method for our one.

The proposed MP test method is low cost with simple configuration based on DBM(Doubly Balanced Mixer) as a phase detector compared with previous test methods; the one of well known methods is the phase nulling system which is so expensive and complex method composed by several precise variable phase shifters and variable attenuators[7] and it is also difficult to make the RF power nulling of input and return signals at each RF power incremental step. The second is the electron current detection by faraday cup which should be needed to make some holes of DUT and physically connected the faraday cup as electron detector to DUT, so this method is not recommended to test a high cost device such as flight model. The last popular one is to monitor the noise level at in/out put port. This method require some additional post-processing, not a real time solution.

The proposed MP test method is very simple and cost effective configuration, almost real time solution and can test one port device as well as multi-port device without any physical destruction. The detail operations and/or explanations for our developed test method are followings.

The DC output voltage of the developed phase detecting system using a doubly balanced mixer as a phase detector is measured by the variation of a reflected signal V_{re} of DUT with a reference signal V_{in} which is no variation for all testing and mathematical operating is described in (4) to (7).

$$V_{in} = A_1 \cos(\varpi_{in} t + \phi_{in}) \tag{4}$$

$$V_{re} = A_2 \cos(\varpi_{re} t + \phi_{re}) \tag{5}$$

$$V_{out} = \alpha \cos(\phi_{re} - \phi_{in}) + \beta \cos(2\varpi t) + HOT \tag{6}$$

$$V_{out}\big|_{filtered} \approx \beta \cos(\phi_{re} - \phi_{in} + \phi_\theta) \tag{7}$$

β is a maximum amplitude of mixer and $\cos(\phi_{re} - \phi_{in} + \phi_\theta)$ is a initial phase difference. In out test system, ϕ_{in} is fixed, ϕ_{re} can vary with MP occurring, so if MP occurs, ϕ_{re} should be changed and β is about 0.000629 (V_{rms}) for 30 dBm RF input power. ϕ_θ is initial phase deviation and its value depends on the configuration of test setup or test aid and DUT and the initial phase deviation of our system is about −87.8 degree under high vacuum condition.

3-2 Measured Results

The proposed MP test method is a phase detecting system in conjunction with an electron current detection and a phase nulling system as a reference. The test mode is a pulsed mode as pulse repetition frequency (PRF) of 1 kHz with 3 % duty cycle under 10^-5 torr and the RF input step of 0.5 dB scale and MP sensitivity is measured by DC output voltage of Agilent 34401A, nulling spectrum of Agilent E4440B and electron current of Keithley 6485.

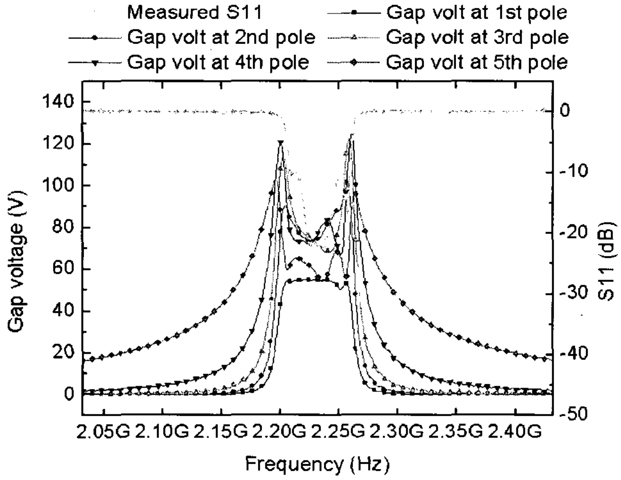


Fig. 3. Measured S_{11} and calculated gap voltage at each resonator.

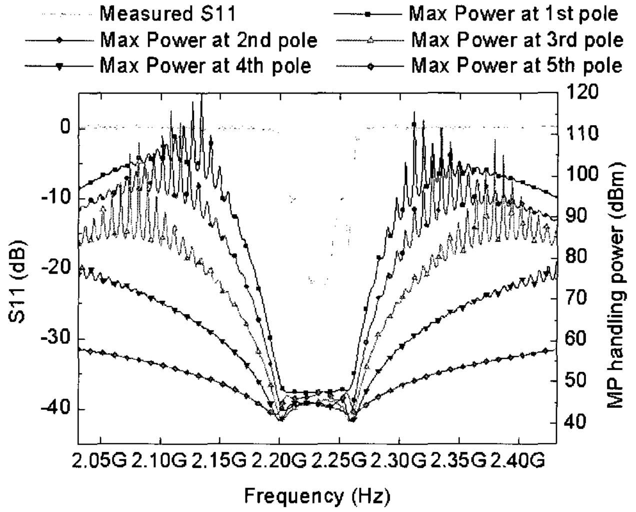


Fig. 4. Measured S_{11} and calculated multipactor free maximum RF input power at each resonator.

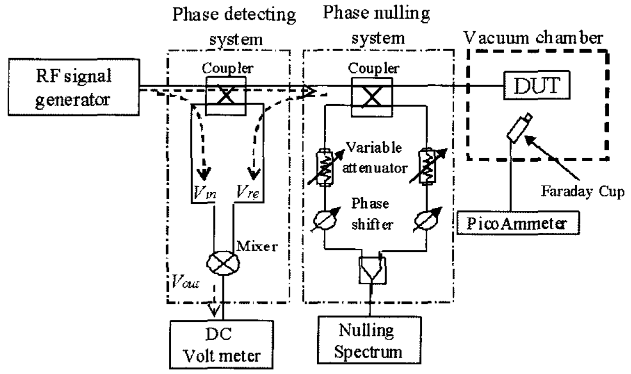


Fig. 5. In-house developed MP test facility.

The final test results are shown in Fig. 6 that give the MP occurred in 44 dBm±0.25 dB RF input and exactly good agreement compared with that of electron current measurement. At that time the spike noise was detected by the phase nulling spectrum analyzer shown in Fig. 7. The final fabricated duplexer is show in Fig. 8 with a silver plated aluminum body and the total dimension is 240×47.78×15 mm.

3-3 Aging Test

To verify the operating of the duplexer, the additional aging test is performed at CW mode which is much worse than pulsed mode in terms of MP breakdown.

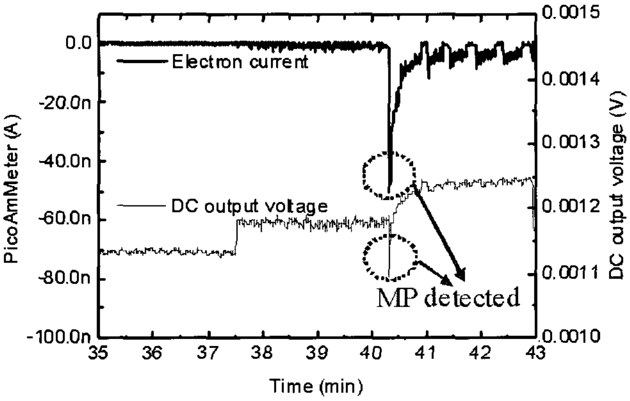
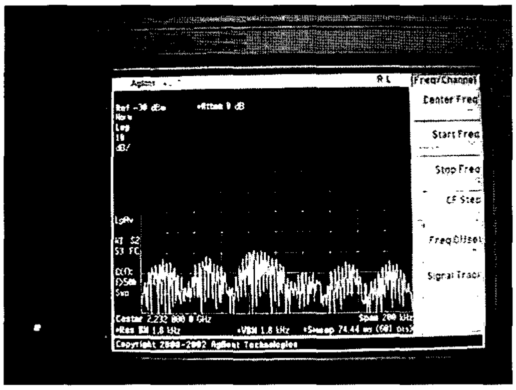
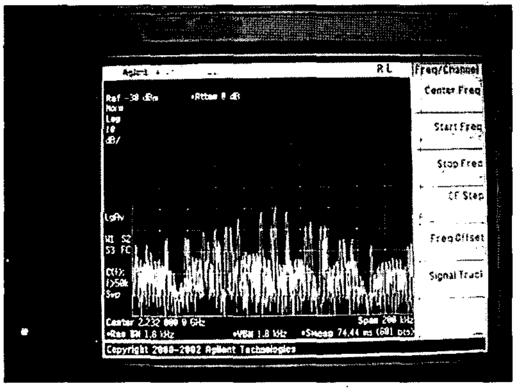


Fig. 6. The measured DC output voltage and electron current.



(a) No MP detected



(b) MP detected

Fig. 7. Phase nulling spectrum in pulse mode MP test.

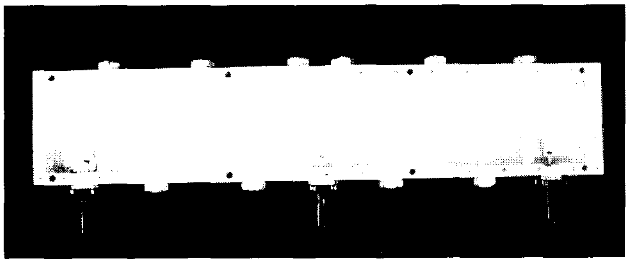


Fig. 8. Fabricated duplexer without top cover.

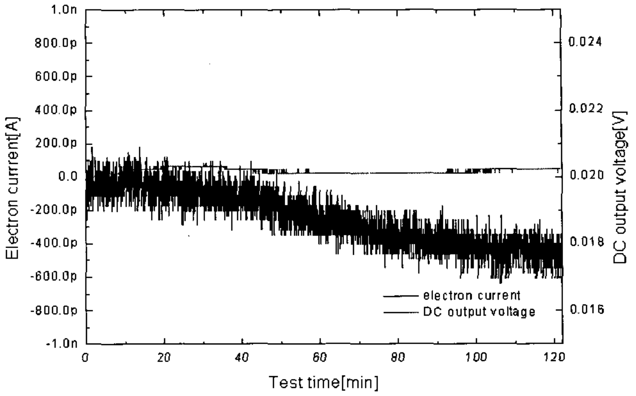


Fig. 9. Aging test results of electron current and DC output voltage.

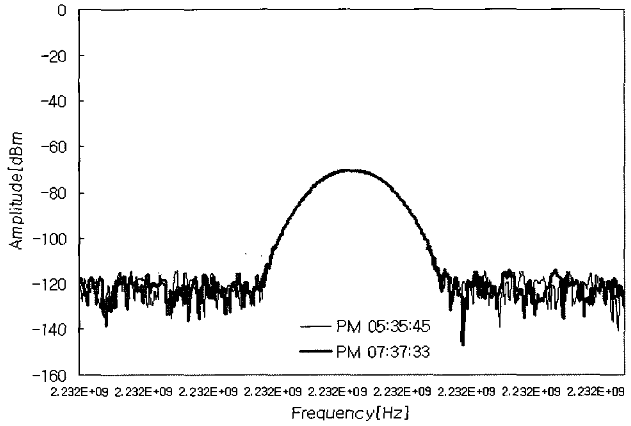


Fig. 10. Aging test result of phase nulling spectrum.

The aging test time is more than 2 hours and testing RF power is just 1 dB below than that of CW mode MP detected. The test results are shown in Fig. 9 to Fig. 10 and no abnormality is detected.

Ⅳ. Conclusion

AMP free duplexer based on interdigital cavity type is proposed and demonstrated by the in-house MP test facility at S-band. A fabricated duplexer five pole Chebyshev filter exhibits an insertion loss of 0.76 dB with 2.7 % and the return loss is better than 18 dB in the passband. The downlink BPF is analyzed by the maximum handling RF power at each resonator pole and carefully designed with no MP breakdown up to 43.13 dBm. The MP breakdown is verified with no abnormality up to 44 dBm for pulse mode test. The developed MP test methods powerful for applying of one port device such as antenna as well as more than 2 port devices and is low cost, simple structure and gives a good agreement. The proposed duplexer is a MP proven one and ready to fly.

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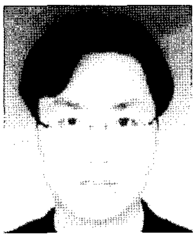

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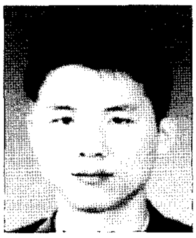

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