Multipactor Simulation and Suppression in High-power Ferrite Circulators

Yun Li[1], Hongguang Wang[2], Jing Yang[1], Wanzhao Cui[1]
1 National Key Laboratory of Science and Technology on Space Microwave
China Academy of Space Technology (Xi'an)
2 School of Electronic and Information Engineering
Xi'an Jiaotong University,
Xi'an 710049, China
Email: genliyun@126.com

Abstract—**High-power multipactor effect always leads to high risk of passive intermodulation and electromagnetic compatibility problems. In this paper, multipactor in ferrite circulators has been simulated, analyzed, and measured. Using the Electromagnetic Particle-In-Cell method, the discharge breakdown thresholds of multipactor in circulators with electron-blocking dielectric and without electron-blocking dielectric have been predicted and verified by simulations. To improve the simulation accuracy of electron emission and collision on the ferrite dielectric, Secondary Electron Emission properties have been measured and fitted into the numerical models. Through power scanning method, transient evolution of electron numbers has been obtained and threshold predicted. Simulation results show that the threshold power of these circulators with and without electron-blocking were 1000W and 9700W, respectively. It demonstrates that multipactor breakdown power in ferrite circulators have been improved more than 900% utilizing the electron-blocking dielectric, which is promising for high-power applications, especially in space industry.**

Keywords-Multipactor, Simulation method, Ferrite circulators.

I. INTRODUCTION

Multipaction discharge resulting from the continual increase of secondary electrons due to the secondary electron emission (SEE) phenomenon under vacuum condition is a fundamental and influential phenomenon in many significant applications such as satellite transceiver system[1], ultra high-power antenna[2], accelerators[3-4], and high power microwave (HPM) systems[5-6]. When multipactor discharge breakdown occurs, it brings about many nonliear effects, such as contactive nonliearity, electron noise and signal distortion. In addition, when secondary electrons during multipaction accumulate, the multi-carrier transmission signals are blocked and may lead to harmonic components[7]. Apparently, these defects caused by multipactor lead to high risk of passive intermodulation and electromagnetic compatibility problems, especially for space industry applications.

Effective simulation and threshold anaylysis of multipactor in high power microwave component set the basis for its suppression. Since 1960s, many space agencies and institutes have been studied on it. For traditional multipactor threshold analysis, when the radio frequency electric field is normal to the material surface and the resonant conditions of electron multipactor have been satisfied, the susceptibility curve based on the parallel approximation was proposed and utilized[8-9]. And experimental data on the SEE of some common materials can be found in the literature and used in multipactor analysis[10].

With the rapid development of numerical calculation technologies, especially the Electromagnetic Particle-In-Cell(EM-PIC) method, it brings new technical approach for multipactor analysis in components with increasingly complex structures. Using EM-PIC method, practical microwave devices are divided into tens of thousands of small grids, in which the trajectories of electrons are tracked in nanosecond scale. According to different EM computing techniques and PIC algorithms, some analysis platforms have been invented for multipactor simulation in metal devices[11-12].

For multipactor simulation and suppression in ferrite components, however, there is few literature studies on it. Difficulties come from many aspects. At first, the huge differences in SEE of various ferrite materials lead to difficulties in test and analysis. Then, external bias field makes it hard to simulate the field and the electron trajectory accurately. Especially, the discontinuity at the edge of the ferrite sheet lead to the need for higher accuracy of field calculation to drive the electron motion.

In this paper, SEEs of different ferrite materials have been measured and used in multipactor simulation. Combined with the EM-PIC method, multipactor threshold of circulators has been analyzed and predicted. In addition, electron-blocking dielectric has been loaded into the circulator design for performance improvement.

II. SIMULATION METHOD

As shown in Fig. 1, the simulation method of multipactor in ferrite circulators involves five main steps,

---

This work was supported by the key project of National Natural Science Fund (Grant No. 11705142, No. 61701394 and No. U15372 11).

I. Initiation of electrons and field distributions. The frequency f_0 and power P of the input EM field is set. The component is discretized into small grids. And the time domain is discretized into time steps. Initial electrons are distributed randomly in the grids with initial energy of several electron volts.

II. EM field simulation. In each time step (Δt), EM field components on each grid are calculated using the finite-difference time-domain(FDTD) method.

III. Electron trajectory tracking. Since the field calculation is stale, initial particles are loaded. Electron trajectories are tracked using the PIC solver.

IV. SEE calculation. The SEE model is used for calculation of electron collision and emission on the material surface. SEE data of silver were given in the our previous paper[13-14]. SEE date of ferrite materials used in the circulators have been measured and given later in this paper.

V. Multipactor threshold analysis. Collision and emission data of secondary electrons are collected and the onset power of multipactor is predicted.

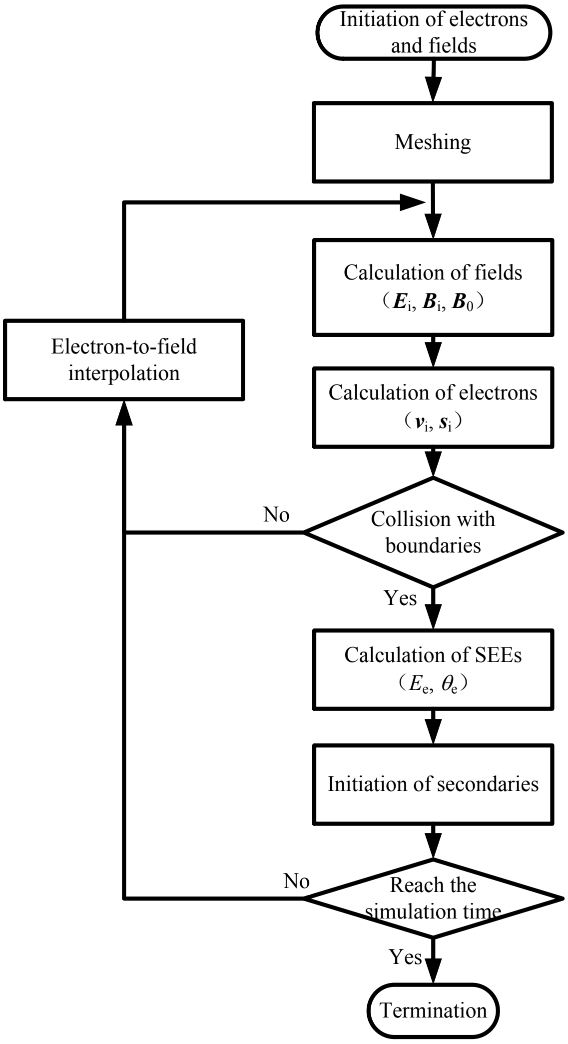

Fig. 1 Schematic program of multipactor simulation method

III. SEE MODEL FITTED BY MEASURED DATA

In multipactor simulation, SEE models proposed previously by Vaughan[15,16] and Furman[12,17] have been utilized and fitted by the measured data. When electrons impact with the device surface, the collision information are collected and fed into the SEE model, and the emission information of secondary electrons, including number, angle and energy, can be calculated.

As shown in Fig. 2, SEYs of the ferrite samples were measured using the collection current method in a newly established Ultra-High-Vacuum (UHV) chamber. The base pressure in the UHV chamber is 10^{-7} Pa. The SEY is not measured directly, but calculated by $\delta=I_c/I_t$, where I_c represents the secondary electron current, which is emitted from the sample and collected from the collector, and I_t represents the total current collected from the test platform.

The measured SEY curves of different ferrite materials upon vertical incidence, which are composed of different elements and components, such as Lithium and Garnet, are given in Fig. 3.

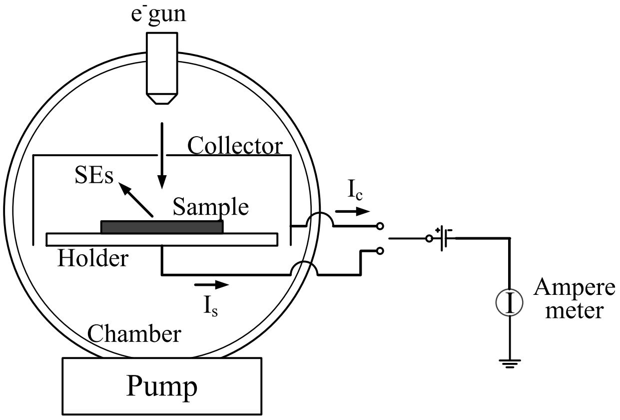

Fig. 2. Schematic of the Secondary Electron Yield (SEY) measurement platform

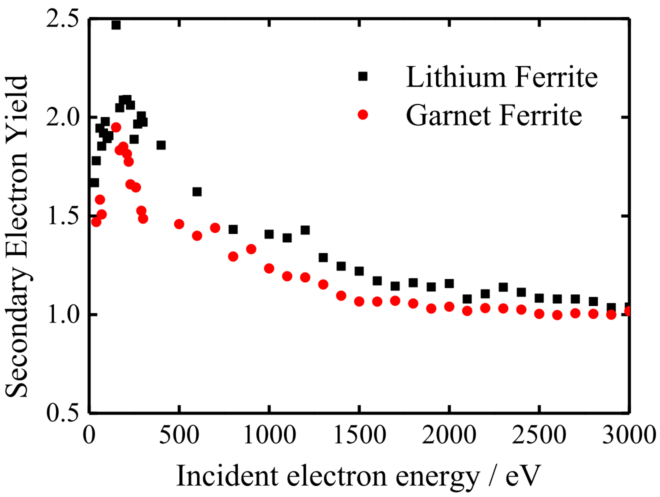

Fig. 3. SEY curves of Lithium ferrite and Garnet ferrite

IV. SIMULATION RESULTS AND DISCUSSION

As shown in Fig.4, a X-band Garnet-ferrite circulator has been designed and simulated for high-power application.

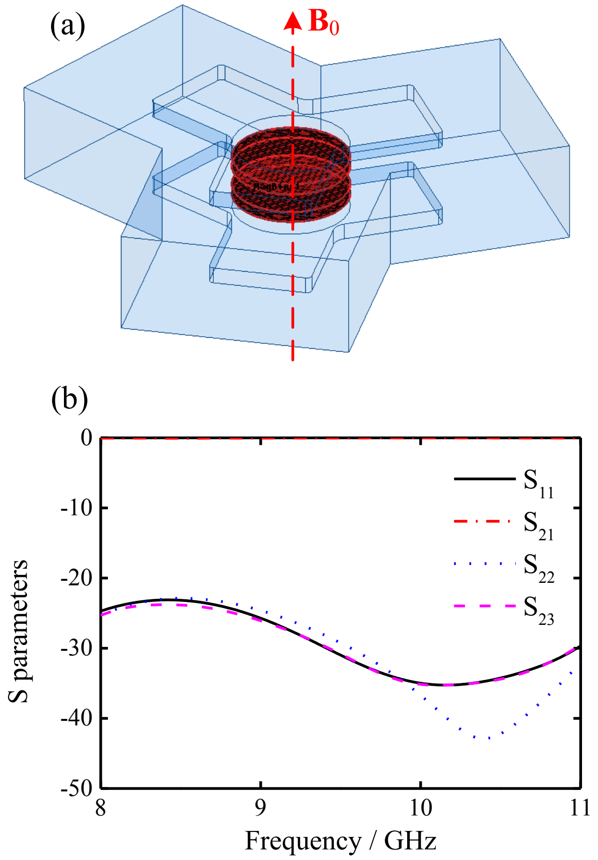

Fig.4 A X-band Garnet-ferrite circulator, (a) 3D model, (b) S parameters.

The waveguide cavity and the double-ferrite substrate structure have been adopted for the electrical performance design. Furthermore, an electron-blocking dielectric has been added between the two ferrite substrates for multipactor suppression. Then, multipactor simulations have been performed on them for high-power design. The average SEY curve is used for the prediction of multipactor threshold. When the input power is not sufficient to support electron accelerating and resonant multipacting, the average SEY will decrease quickly. As long as the input power is increasing to the threshold level, electrons get enough energy to knock out secondaries consistently and multipactor occurs. Then, the power that leads to the average SEY maintains a certain equilibrium value is predicted to be the breakdown threshold of multipactor.

As shown in Fig. 5, the average yield amounts of secondary electrons emitted from the circulator surface have been recorded when applying different input powers.

For the traditionally design circulator without electron-blocking dielectric(Fig. 5(a)), the breakdown threshold power was predicted to be 1000W. When the input power is 950W, electrons dissipate quickly and the average SEY discreases quickly. When the input power is increased to 1050W, the average SEY increases exponentially. Then, electrons in the component will avalanche and multipactor occurs. Thus, multipactor threshold power of the traditional design is predicted to be 1000W. And the prediction error is ±50W and simulation accuracy is 5%.

For the circulators with electron-blocking dielectric, multipactor threshold is increased to about 9700W. The prediction criteria is also based on the simulated average SEY.

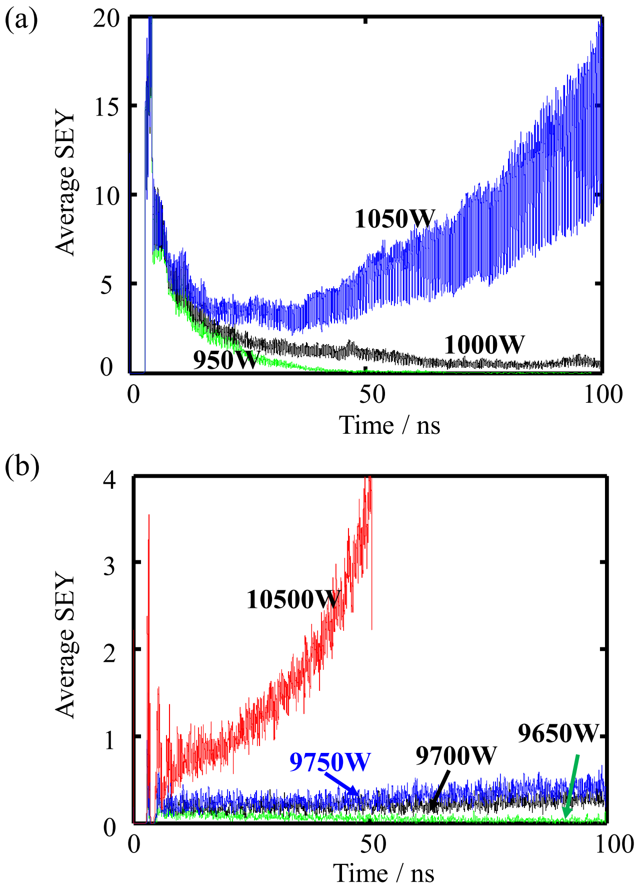

Fig.5 Average SEY in the circulator during multipactor simulation, (a) without electron-blocking dielectric, (b) with electron-blocking dielectric.

V. CONCLUSION

A simulation evaluation and threshold prediction method is proposed in this paper for multipactor analysis in high-power circulators. The real SEE properties on the ferrite material have been measured and utilized for the SEE model fitting in multipactor simulation. To further improve multipactor breakdown power in the component, the electron-blocking dielectric is added between the two ferrite substrates. Simulation results show that the threshold power of multipactor is increased by more than 900%, from 1000W to more than 9000W, in a X-band circulator.

REFERENCES

[1] N. Rozario and H. Lenzing, “Investigation of Telstar 4 Spacecraft Ku-Band and C-Band Antenna Component for Multipactor Breakdown,” IEEE Transactions on Microwave Theory and Techniques, 42, 558-564 (1994).

[2] J. Rasch, D. Anderson, J. F. Johanson, M. Lisak, J. Puech, E. Rakova and V. E. Semenov, “Microwave Multipactor Breakdown Between Two Cylinders”, IEEE Trans. Plasma Sci., 38, 1997-2005(2010).

[3] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J. P. Rousseau, F. Burgy, and V. Malka, Nature 431, 541 (2004).

[4] R. Kishek and Y. Y. Lau, Phys. Rev. Lett. **80**, 193 (1998).

[5] C. Chang, M. Zhu, J. Verboncoeur, S. Li, J. L. Xie, K. Yan, T. D. Luo and X. X. Zhu, “Enhanced window breakdown dynamics in a nanosecond microwave tail pulse”, Appl. Phys. Lett., **104**, 253504(2014).

[6] C. Chang,G. Z. Liu, C. X. Tang, C. H. Chen, S. Qiu and J. Y. Fang, “Review of recent theories and experiments for improving high-power microwave window breakdown thresholds,” Phys. Plasmas, **18**, 055702 (2011).

[7] J. You, H. Wang, J. Zhang, S. Tan, and T. Cui, "Accurate Numerical Analysis of Nonlinearities Caused by Multipactor in Microwave Devices", IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 24, NO. 11, pp. 730-732, 2014.

[8] ESA-ESTEC. Space Engineering: Multipacting Design and Test. ESA Publication Division the Netherlands ECSS-20-01A, 2003.

[9] A. Woode, Petit J. Multipactor diagnostic investigations at the European Space Agency. Space Technology & Science. 1990.

[10] D. C. Joy, “A Database on Electron-Solid Interactions”, Scanning, vol.17, pp.270-275, Dec. 1995.

[11] Vicente C, Mattes M, Wolk D, et al. Multipactor breakdown prediction in rectangular waveguide based components. International Microwave Symposium Digest. 2005.

[12] Y. Li, W. Z. Cui, H. G. Wang. Simulation investigation of multipactor in metal components for space application with an improved secondary emission model. Physics of Plasmas, 2015, 22(5):1172-2126.

[13] Y. Li, W. Z. Cui, H. T Zhang., et al. MSAT: A Novel Multipactor Simulation and Analysis Tool. 2018 International conference on microwave and millimeter wave technology, 2018, Chengdu, China.

[14] Y. Li, W. Z. Cui, Y. N. He, et al. Enhanced dynamics simulation and threshold analysis of multipaction in the ferrite microwave component. Phys. Plasmas, 2017, 24: 023505

[15] J. R. M. Vaughan, “Secondary emission formulas,” IEEE Trans. Electron Devices, vol.40, no.40, pp. 830, Apr. 1993. DOI: 10.1109/16.202798

[16] Y. Li, W. Z. Cui, N. Zhang, X. B. Wang, H. G. Wang, Y. D. Li and J. F. Zhang, Three-dimensional simulation method of multipactor in microwave components for high-power space application. Chin. Phys. B, Vol. 23, No. 4, pp.048402, 2014.

[17] M. A. Furman, M.T. F. Pivi, “Probabilistic model for the simulation of secondary electron emission”, Physical review special topics-accelerators and beams, Vol. 5, pp.124404, 2002