Plasma limiter for protecting against high power microwave

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Breakdown parameters of plasma limiter are calculated to find new measure to protect electronic systems against high power microwave (HPM). Limiter filled with Xe of 1 torr can be charged by incident HPM in approximate 14 ns, providing protection to electronic systems.

Keywords: Electronic systems, High power microwave, Plasma limiter

Introduction
High power microwave (HPM), which threatens radar and other electronic systems1-3, necessitates protective devices to protect against high power and pulses with very short rise times. Conventional protective devices, such as gas discharge tubes4 and solid-state limiters, do not protect against HPM. In order to provide protection against high power and fast rise time pulses, plasma limiter (PL) was proposed5-6. However, feasibility of PL for protecting against HPM was not investigated. This paper presents option of breakdown parameters and feasibility of PL for protecting against HPM based on HPM characteristic.

Plasma Limiter (PL)
Before charging of PL, microwaves propagate through waveguide (Fig. 1a). Once microwave reaches PL, a discharge occurs and plasma forms. Ionized gas in plasma, reflecting incident energy, prevents microwave propagation into sensitive receiver electronics (Fig. 1c).

Gas Breakdown Equations
Breakdown electric field E_B for low-pressure (0.01 torr=1 torr, 1 torr=133.32 Pa) and high-pressure (10 torr=1000 torr) cases are as follows5:

\[ E_{Bl} = \sqrt{\frac{m\phi_i}{3\,e\,\sigma\,P\,\Lambda}} \] …(1a)

\[ E_{BH} = \sqrt{\frac{2\phi_i m\nu_m}{\nu_m M e}} \] …(1b)

where m, mass of electron; \( \phi_i \), ionization potential; f, frequency of microwave; \( \sigma \), characteristic diffusion length; P, gas pressure; \( \sigma \), collisional cross section; T, gas temperature; k, Boltzmann constant; e, electron charge; M, mass of atom; and \( \nu_m \), collision frequency.

For noble gas, \( \nu_m = \alpha P \); \( \alpha \), mean coefficient (Table 1).

Breakdown time \( t \) is given by5

\[ t = \Delta \tau_{min} \ln \left( \frac{n_e}{n_{e0}} \right) = \Delta \tau_{min} \ln \left( \frac{\gamma n}{n_{e0}} \right) \] …(2)

\[ \Delta \tau_{min} = \frac{m(V_m^2 + \nu_m^2)\phi_i}{e^2 E^2\nu_m} \] …(3)

where \( n \), gas density; \( n_{e0} \), density of seed electrons; \( n_e \), plasma density; and \( \gamma \), ionization degree.

Breakdown Calculation
PL is placed in a rectangular waveguide (a, 72.14 mm; b, 34.04 mm) forming plasma (thickness \( d \), 50 mm) for protecting against HPM. Characteristic diffusion length
(0.834 cm) of plasma in PL is calculated using 
\[ \frac{1}{\lambda^2} = \pi^2 \left( \frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{d^2} \right) \]. \( E_{BL} \) decreases with increase in pressure (Fig. 2a), and Xe has lowest breakdown field \( E_{BH} \approx 70.78 \text{ V/m at 1 torr} \), whereas \( E_{BL} \) increases for increasing pressure (Fig. 2b), and Ne has lowest breakdown field \( E_{BH} \approx 2.06 \times 10^3 \text{ V/m at 10 torr; } 2.06 \times 10^5 \text{ V/m at 1000 torr} \). \( E_{BH} \) is higher than \( E_{BL} \). Also, \( E_{BL} \) increases slightly with frequency increase (Fig. 3). Breakdown time with increasing pressure (Fig. 4), decreases under low-pressure case (<1 torr), whereas increases under high-pressure case (>1 torr). Breakdown times of Xe and CO\(_2\) are lower than that of other gases.

Results and Discussion

A) Breakdown Field

Gas Pressure

Power reflected from a sharp vacuum-plasma interface increase with increasing plasma density\(^7\), and plasma density increase with increasing gas pressure. Therefore, gas with high pressure would induce good protective performance. However, \( E_{BH} \) is far higher than \( E_{BH} \) (Fig. 2); Xe in low-pressure case has lowest breakdown field (70.78 V/m), which is lower than that of Ne in high-pressure case (2.06\( \times \)10\(^3\) V/m). Thus, gas pressure in PL will be chosen in the range of low pressure, by also considering that gas discharge plasmas are not easy to sustain when gas pressure is too high.

Frequency Response

Field frequency does not affect \( E_{BH} \) [Eq. (1b)]. Thus PL filled with gas of high-pressure will response to HPM
over full frequency band. $E_{BL}$ increases slightly as frequency increases (Fig. 3). Thus, PL filled with gas of low-pressure has good frequency.

Feasibility of Plasma Limiter

For HPM (microwave power, 10 GW; pulse duration, 100 ns; frequency, 1 GHz; parabolic antenna area, 100 m²; and aperture efficiency, 50%), electric field intensity (V/cm) over different distances (km) is as follows, respectively: 4600, 0.1; 460, 1; 90, 5; 46, 10; and 14, 32. Microwaves, when transmitted in air, are attenuated due to absorption and scattering by air and vapor. Therefore, HPM maintains their power just up to tens of km. Electric field intensity (1400 V/m at 32 km) is stronger than breakdown field of Xe at 1 torr (70.78 V/m). Thus, PL can be charged for protecting against HPM through this rough estimation.

B) Breakdown Time

Gas Type and Gas Pressure

Gas discharge plasmas are not easy to sustain when gas pressure is too high. Therefore, gas pressure in PL is chosen in low-pressure range. CO₂ and Xe have almost same breakdown time in low-pressure case, and their breakdown times are shorter than other gases (Fig. 4). However, polyatomic molecules are not stable in plasmas, so noble gases are usually used in gas discharge plasma.

Protective Feasibility of Plasma Limiter

When pressure is 1 torr and gas temperature is 300 K, gas density is $0.35 \times 10^{23}$ m⁻³ by solving the state equation of gas. Plasma density $n_e$ is $0.35 \times 10^{19}$ m⁻³ at ionization degree of 0.0001. Then, frequency of plasma ($f_p = 9\sqrt{n_e}$) is approximate 17 GHz. At present, frequency of HPM is over a range of 500 MHz to 10 GHz. Plasma reflects all incident HPM with frequency less than plasma frequency. Therefore, PL can prevent HPM propagating into sensitive receiver electronics.

Density of Seed Electrons

Seed electron density is increased to shorten breakdown time of PL. Coating radioactive isotope in PL would meet this requirement. For incident HPM (frequency, 1 GHz; electric field intensity, $9 \times 10^3$ V/m; Xe gas pressure, 1 torr; density of seed electrons, $10^{16}$ m⁻³) breakdown time is 14 ns (ionization degree, 0.0001).

Conclusions

Breakdown field and breakdown time of plasma limiter is calculated. Plasma limiter filled with Xe (1 torr) can be charged by incident HPM in 14 ns, reflecting HPM (frequency, < 17 GHz) to prevent propagation into sensitive receiver electronics.

References

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