

Secondary electron yield characterization of high porosity surfaces for multipactor-free microwave components

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ABSTRACT

We present secondary electron yield (SEY) characterization of high porosity surfaces for multipactor-free microwave components. We first calculate the SEYs of through porosity surfaces using Monte Carlo simulations. We demonstrate that these high porosity surfaces can be treated as homogeneous materials with low effective SEYs. We prove that a significant SEY reduction is attainable by high porosities, and above a certain porosity level, the entire effective SEY of the surface falls below unity, offering a multipactor free capability. We import the resultant SEYs into our semi-analytic approach to obtain multipactor susceptibility charts corresponding to different surface porosities. We predict the reduction of the multipactor-susceptible zone as the porosity increases and a total multipactor suppression with 0.66 through porosity level. The theoretical results were validated with multipactor experiments, and relatively good agreement was observed. Finally, we propose an alternative blind porosity approach that can offer the same multipactor suppression capabilities. The approach discussed herein can be adopted to design high-power multipactor-free microwave components.

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I. INTRODUCTION

Multipactor is generally known for its undesired effects in radio frequency (RF) components under hard vacuum, e.g., in communications satellites.¹ Such destructive effects include increased noise level and disruption of normal RF power transmission. In its developed stages, multipactor might cause total reflection of the RF power, breakdown, and damage of RF components. Repairing or replacing a damaged or destroyed payload of a satellite in orbit is prohibitively expensive, so it is desirable to avoid multipactor within vacuum RF components.

Multipactor is an electron-RF field resonance phenomenon that occurs in vacuum RF components.^{1–3} Free electrons can be generated by cosmic rays, ultraviolet (UV), field, and thermal effects close to RF components of a satellite's payload. When accelerated by a time-harmonic electric field, these electrons can collide with the surfaces of the RF

components. If the impact energy of these electrons is within a range that results in greater than unity secondary electron yield (SEY), then these particles can release more than one secondary electron. Under certain resonance conditions, these secondary electrons will experience the same dynamics and release even more secondaries over the subsequent collisions. This multiplicative increase in electrons over successive surface impacts can result in an avalanche growth of electrons, called multipactor, which can cause breakdown in the RF components.

Multipactor mitigation methods essentially deal with disrupting one or more of the above-mentioned conditions needed for the multipactor to evolve.^{4–16} One can interrupt the multipaction by disturbing the harmonic features of the applied electric field, e.g., by using different modulation schemes.^{4,5,17} Semenov *et al.* demonstrated that the Quadrature Phase Shift Keying (QPSK) modulation will not be an efficient multipactor suppression approach unless the switching rate of

the signal is very fast, which is impractical.^{4,18} Another approach is to reduce or suppress secondary electron emission of the surface when impacted by high-energy electrons. For example, there are many published studies on low SEY materials.^{6–8} Dielectric coating can also block the direct incidence on metallic surfaces, thus significantly reducing the SEY.⁹ Another approach that achieves the same effect as low SEY materials is surface alteration.^{10–16,19} This can stop or slow down the electron growth by trapping, removing the electrons, or deflecting their normal trajectories. Examples include creating grooves,¹² nonperiodic roughness such as metallic fuzz⁷ or surface pores.^{10,16} Blind porosity and its effects on SEY reduction have been studied in the literature.^{10,16} We have recently investigated the impacts of through porosity on multipactor suppression.²⁰ We showed that as the porosity increases, the multipactor growth diminishes. However, this raises a question as to whether these high porosity surfaces can be treated as a homogeneous low SEY material.

In this paper, we first characterize the SEYs of surfaces with periodic through holes, using Monte Carlo (MC) simulations. We calculate SEYs for several representative porosities. The resultant SEYs are imported into a semi-analytic approach to determine their corresponding multipactor susceptibility charts for a parallel plate transmission line. We finally validate our analytic approaches with multipactor experiments across a broadband frequency range. We demonstrate that as the porosity of a surface increases, its effective SEY decreases similar to that of a homogeneous low SEY surface. We also show that beyond a certain porosity level, the entire effective SEY falls below unity; thus, this sample can represent a multipactor-free surface.

II. PREDICTION OF SEY FOR THROUGH HOLE POROUS SURFACES

Figure 1 presents two different layouts: rectangular [Fig. 1(a)] and interleaved [Fig. 1(b)] porosity arrangements. The rectangular arrangement simply includes pores positioned in rows and columns. The porosity (ρ) of the surface, which is defined as the ratio of the pore surface area to the total surface area, is calculated as

$$\rho = \frac{\pi(d/2)^2}{(d+G)^2}, \quad (1)$$

where d and G are pore diameter and gap distance, respectively. To achieve different porosity levels, we choose the pore diameter ($d = 0.8$ mm) and reduce the gap distance (G) by increasing the number of pores per given area. However, for high porosities, the narrow inter-pore wall thickness is difficult to fabricate using commercially available approaches. Therefore, we present the interleaved porosity [Fig. 1(b)] as an alternative approach. This arrangement consists of two interleaved arrays of large and small pores with diameters D and d , respectively, with a gap distance G between two adjacent large pores. The porosity (ρ) of the interleaved arrangement is calculated as

$$\rho = \frac{\pi(D/2)^2 + \pi(d/2)^2}{(D+G)^2}. \quad (2)$$

Using the interleaved arrangement, one can achieve high porosities with relatively wider inter-pore wall thickness, thus, easier fabrication. In the following, we calculate the SEYs for both arrangements.

We adopt Vaughan's empirical formula^{6,21} to estimate the SEY from a flat surface (δ_f),

$$\frac{\delta_f(\xi)}{\delta_{\max}(\xi)} = (we^{1-w})^k \quad \text{for } w \leq 3.6, \quad (3)$$

$$\frac{\delta_f(\xi)}{\delta_{\max}(\xi)} = \frac{1.125}{w^{0.35}} \quad \text{for } w > 3.6, \quad (4)$$

where $w = \frac{E_i}{E_{\max}}$ (E is the impact energy of primary electrons), $k = 0.56$ for $w < 1$, $k = 0.25$ for $1 \leq w \leq 3.6$. The parameters are adjusted in calculating the yield, for impact at an angle ξ with respect to the normal, according to the following equations:^{6,21}

$$E_{\max} = E_{\max 0} \left(1 + \frac{k_{sE} \xi^2}{2\pi} \right), \quad (5)$$

$$\delta_{\max} = \delta_{\max 0} \left(1 + \frac{k_{s\delta} \xi^2}{2\pi} \right), \quad (6)$$

where k_{sE} and $k_{s\delta}$ represent surface smoothness factors ($k_{sE} = k_{s\delta} = 1$ used in this study). For a quantitative investigation, and in preparation

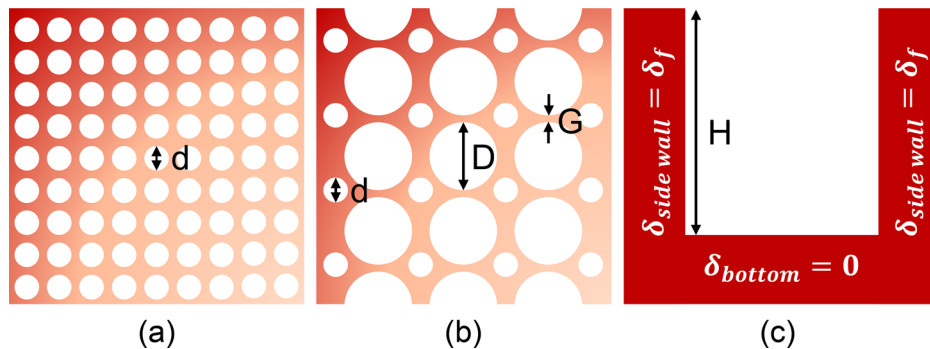


FIG. 1. Schematics of two proposed porosity arrangements. (a) The top view of the rectangular porosity arrangement. The layout consists of an array of pores with the same diameter d arranged in a rectangular grid. (b) The top view of the interleaved porosity arrangement. The layout consists of two interleaved arrays of large and small pores with diameters D and d , respectively. G is the wall thickness between two adjacent large pores. (c) The two-dimensional rectangular well (pore) geometry assumed in the MC simulation. H is the depth of the well corresponding to the thickness of the surface with through-pores. We set the SEY from the bottom surface, $\delta_{\text{bottom}} = 0$, to model the through-pore geometry of the experiment while the SEY from the side walls ($\delta_{\text{side wall}}$) is set equal to the SEY from the flat surface (δ_f).

for experimental validation measurements, we choose the SEY properties of annealed copper. Therefore, we set $\delta_{\max 0}$ (the maximum SEY for normal incidence) and $E_{\max 0}$ (the corresponding impact energy of primary electrons) to 2.1 and 150 eV, respectively, from the catalogue of the Vaughan's SEY model parameters in CST.²¹

To estimate the SEY of the pores (δ_p), we adopt the Monte Carlo (MC) simulation model described in Refs. 8 and 22 with slight modifications. The MC simulation scheme employs Vaughan's model of SEY^{8,21} that accounts for true secondary electrons as well as low-energy inelastically scattered (rediffused) electrons through an empirical fitting to a wide range of experimental data. However, high-energy elastically backscattered electrons (appearing at the tail of the SEY curve) that contribute to about 1% of the total SEY²³ can often be missed in experiments (as discussed in Ref. 8) and, therefore, might not be accurately accounted for in Vaughan's model. In our configuration, the few elastically backscattered electrons are expected to have little influence on the multipactor breakdown threshold. Their influence on multipactor in other configurations (for example, see Ref. 24 with a parallel magnetic field) can be of interest for future research.

In our MC simulation scheme, 3D cylindrical through-pores are represented as two-dimensional (2D) rectangular wells with SEY from the bottom surface, $\delta_{\text{bottom}} = 0$ [Fig. 1(c)]. To model the through pores, we slightly modify the MC simulation scheme employed in Refs. 8 and 22 by setting the SEY from the bottom surface, $\delta_{\text{bottom}} = 0$ [Fig. 1(c)].

We adopt the following emission energy (E_0) and angle (ϕ) distributions for the emitted secondary electrons:^{8,22,25}

$$f(E_0) = \frac{E_0}{E_{0m}^2} e^{-\left(\frac{E_0}{E_{0m}}\right)}, \quad (7)$$

$$g(\phi) = \frac{1}{2} \sin(\phi), \quad 0 < \phi < \pi, \quad (8)$$

where E_{0m} is the peak of the distribution of emission energies, on the order of the work function. By taking into account all the generations

of secondary electrons inside a well, our MC results have been found to be in very good agreement with previous experimental data.^{8,22} Once we obtain the SEY from the flat surface (δ_f) and the pores (δ_p), the effective SEY of the porous surface can be obtained as^{8,10,22,26}

$$\delta_{\text{surf}} = \delta_p \rho + \delta_f (1 - \rho). \quad (9)$$

Figure 2 shows the predicted SEY curves for through-holes surfaces with some representative porosities for both rectangular and interleaved layouts. As discussed previously, δ_f is obtained from the Vaughan's model of SEY and δ_p is obtained from our MC simulation with through-pores. We observe similar SEY levels for the same porosity level of two arrangements. From Figs. 2(a)–2(g), we also observe that as the porosity increases, the effective SEY of the porous surface decreases.²² For the porosity of $\rho = 0.66$ [Figs. 2(d) and 2(g)], the SEY curves for different incident angles are below the $\delta = 1$ level. Therefore, complete suppression of multipactor is expected for through-hole porosity with either porosity arrangement.

III. SEMI-ANALYTIC PREDICTION OF MULTIPACTOR SUSCEPTIBILITY CHARTS FOR POROUS SURFACES

We recently introduced a semi-analytic approach to rapidly identify the multipactor susceptible zone for parallel plate structures²⁷ subject to a single-tone time-harmonic RF electric field. We briefly review our approach for the first-order multipactor and also discuss the modifications that we applied to the model in order to increase its accuracy specifically in predicting multipactor zones for low SEY materials. The reader is referred to Ref. 27 for additional details. Consistent with the most literature on multipactor susceptibility, we present the multipactor susceptibility chart as the region between the lower and upper threshold boundaries in RF voltage (V) vs the product of frequency (F) and gap distance (d). The calculated SEY information gets used in the calculation of whether we expect multipactor onset at a given combination of V , F , and d . Using the Lorentz force equation, we calculated the trajectory and the instantaneous velocity of an electron as it

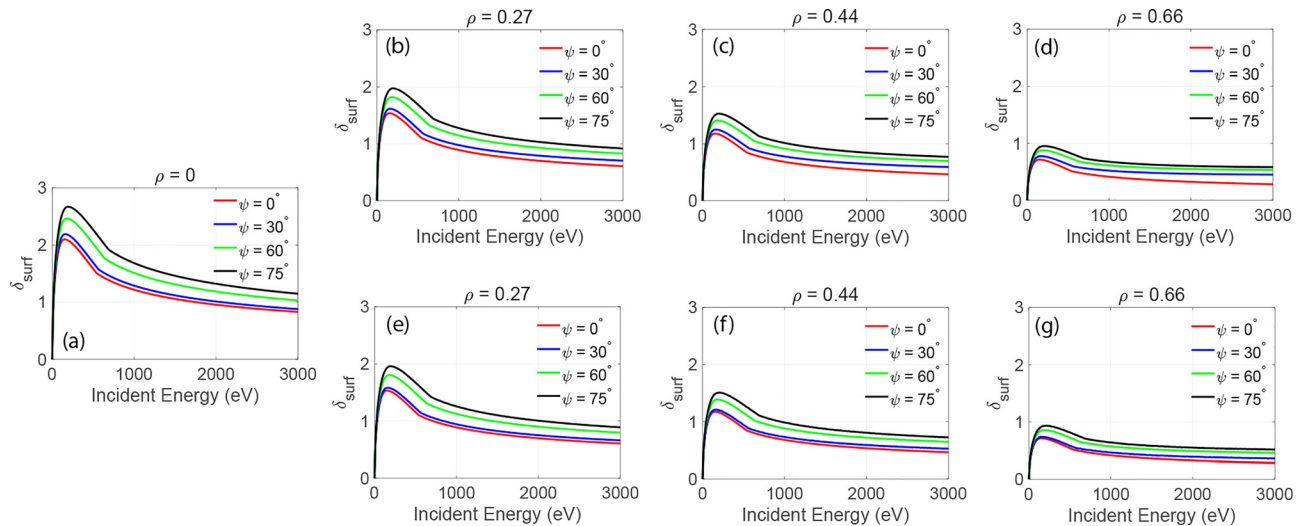


FIG. 2. Predicted secondary electron yield (SEY) curves of through-hole surface porosities for incident angles $\psi = 0^\circ, 30^\circ, 60^\circ, 75^\circ$, and (a) $\rho = 0$ (flat surface), rectangular surface porosities: (b)–(d), interleaved surface porosities: (e)–(g). SEY curves for other incident angles (e.g., $15^\circ, 45^\circ$) were also calculated but not shown on these figures to avoid overcrowding of them.

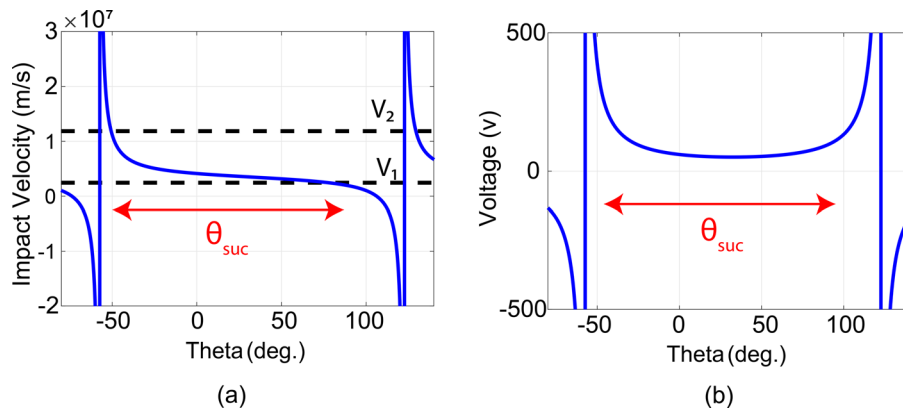


FIG. 3. (a) Impact velocity and (b) required gap voltage vs a period of emission phase (phase of RF voltage when a secondary electron is emitted) for half-cycle multipactor resonance with a 3 mm gap distance at 500 MHz. θ_{suc} represents the susceptible emission phase interval.

crosses the gap [Eqs. (2) and (3) in Ref. 27]. Moreover, we calculated the impact velocity of an electron and the required RF voltage that causes the electron to cross the gap in a half-cycle of the RF signal. Figure 3 displays the impact velocity of the electron and the required RF voltage vs a period of the electron's emission phase for a set of representative parameters, $F = 500$ MHz, $d = 3$ mm. Plots like Fig. 3(a) allow us to identify the susceptible emission phase interval (θ_{suc}) that is the range of emission phases that correspond to an electron resonantly crossing the gap in a half-cycle of the RF signal while gaining an impact velocity between the two values v_1 and v_2 , which correspond to SEY values greater than or equal to one. Transferring that range θ_{suc} to Fig. 3(b) allows us to identify the upper and lower RF voltages between which we can expect multipactor onset for a particular value of the Fd product. This procedure for predicting the multipactor susceptibility chart is relatively simple and quick to implement and reasonably accurate, as revealed in validation experiments reported in Ref. 27.

We have revised our semi-analytic approach to obtain a more accurate prediction of multipactor susceptible zones for low SEY materials. Our original model in Ref. 27 just included v_1 , and we assumed that v_2 is sufficiently large for regular materials that it does not impact the multipactor boundaries. However, as we deal with low SEY materials in this study, a relatively small v_2 is expected; hence, we added the impact velocity criteria corresponding to v_2 to our prediction model. Adding this condition enables including susceptible emission phases very close to the singularity point in Fig. 3(a) and those emission phases that lead to impact velocities larger than v_2 will be automatically excluded. Figure 4 compares the multipactor zones predicted by the original and modified models. As seen, the modified model predicts an extension of the multipactor zone in the low Fd region that was cut off by the original model due to excluded v_2 criteria. Moreover, we previously assumed a 10 eV emission energy for secondary electrons in our original model. Some studies predict lower emission energies for secondary electrons in the order of the work function of the material.^{28,29} Emission energies of ≈ 5 eV were reported in the literature.^{13,14,25} Therefore, we adopted the same 5 eV emission energy for secondary electrons in our revised prediction model and MC simulations.

Using the effective SEY values calculated with the procedure described in Sec. II, we can calculate multipactor susceptibility charts for our microstripline structure with the semi-analytic procedure

outlined in this section. Our microstripline multipactor test structure has a 3 mm gap and operates from 0.1 to 1.2 GHz.²⁷ For simplicity, we assume same emission velocity for all secondary electrons after impact.²⁷ Also, in this study, we focus only on the first-order multipactor, corresponding to electrons crossing 3-mm gap over a half-cycle of the RF signal. This is because we are primarily interested in the relative effect on multipactor suppression of porous surfaces compared to the reference case of a nonporous surface. Therefore, we make the assumption that the relative reduction of the first-order multipactor susceptibility will similarly manifest in a reduction of higher order multipactor resonance scenarios. We use the average of predicted SEYs for normal and 15 incident angles [$\delta_{ave} = \frac{\delta_{surf}(\psi=0^\circ) + \delta_{surf}(\psi=15^\circ)}{2}$] for each porosity as most of the electrons involved in multipactor tend to have a close-to-normal incidence. This fact can be analytically verified using the Lorentz force equation and also can be observed by tracking the trajectory of the electrons in particle-in-cell (PIC) simulations of CST Microwave Studio. Figure 5 shows the multipactor susceptibility charts corresponding to each porosity level for our microstripline test cell. As the porosity increases, the effective SEY of the surface decreases, thus shrinking the multipactor zone. With 0.66

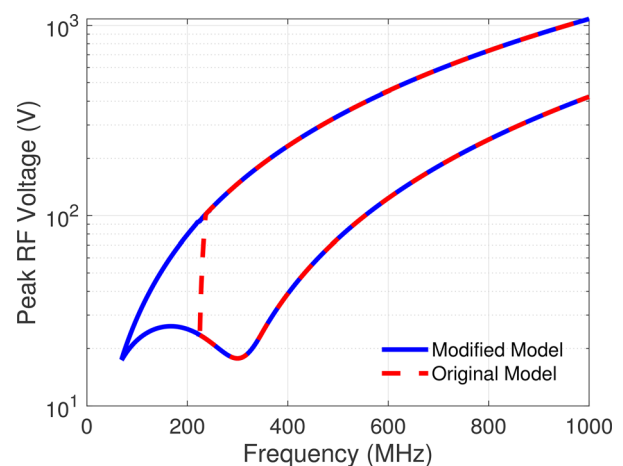


FIG. 4. Comparison of multipactor susceptibility charts predicted by the modified and original semi-analytic approaches for a solid microstripline ($\rho = 0$) with 3-mm gap distance. We assumed 5 eV for emission energy of secondary electrons.

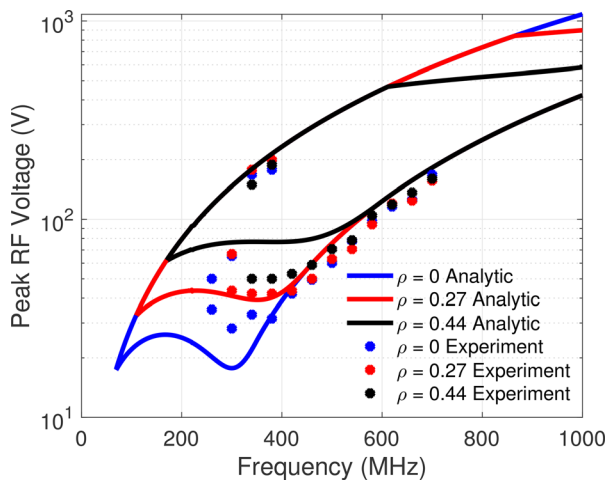


FIG. 5. Multipactor susceptible zones corresponding to 3-mm gap for different through-hole porosities. Solid lines show the predicted susceptibility charts using the semi-analytic model of Ref. 27. Note that with $\rho = 0.66$, the model predicts total suppression of the multipactor zone; thus, nothing is shown for this porosity. The dots represent the experimental multipactor results. Again, we observed no multipactor event with $\rho = 0.66$ through-hole porosity.

porosity, the entire SEY curve falls below one; thereby, the multipactor region totally disappears.

IV. MULTIPACTOR TEST APPARATUS AND EXPERIMENTAL VALIDATIONS

We developed a comprehensive experimental apparatus to study the multipactor under controlled conditions.³⁰ This system allows high-power multipactor tests with parallel plate structures over a broadband frequency range from DC to 1.2 GHz. Figure 6 represents a cut-away view of our symmetric configuration, including the vacuum

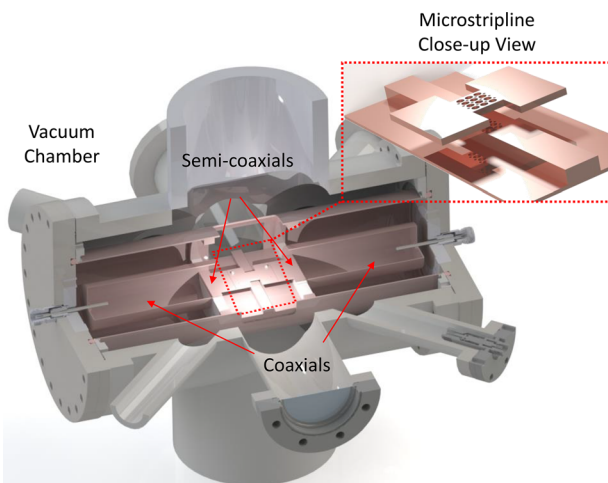


FIG. 6. A cut-away drawing of the vacuum chamber with transmission line segments enclosed. The inset shows a zoomed-in view of the microstripline section where multipactor occurs and is studied. Single-sided porosity is implemented in the upper strip of the narrow gap microstripline section.

chamber and the multi-step, impedance-matching transitions between coax to microstripline and back to coax transmission lines. The microstripline section, enlarged in the inset of Fig. 6, includes transitions in the strip width and the ground-to-microstrip gap distance to achieve a narrow gap in the center while maintaining an excellent RF impedance match. The narrow gap microstripline section is the designated multipactor region, and the electrons are expected to grow over the ridge. The upper conductor of the microstripline is replaceable, providing the capability to locally manipulate the multipactor region for different experiments without needing to replace the entire transmission line. Such experiments include variable gap dimensions and various surface treatments. Using such versatility, we created porosity in the upper strip of the narrow microstripline section shown in the close-up view of Fig. 6. We selected single-sided porosity because drilling through holes in the thick copper of the microstripline's ground plane is prohibitively difficult to fabricate. We fabricated four different samples of the upper conductor of the microstripline with 0, 0.27, 0.44, and 0.66 porosities shown in Fig. 7. As seen, we used a rectangular arrangement for 0.27 and 0.44 porosities and an interleaved arrangement for the 0.66 porosity. These are *as-received* samples, and no cleaning procedure was applied on them.³¹ We conducted passive RF transmission measurements (cold tests) and multipactor experiments (hot tests) with all samples, keeping the rest of the configurations and conditions identical. Figure 8 depicts the cold test results, showing the reflection and transmission coefficients of the entire transmission line with different porosities. These results demonstrate that the proposed porosity levels do not noticeably disturb the RF properties of the microstripline. This is because the RF current mostly flows near the edges of the upper strip where we left a 1-mm border between the edge of the upper strip and the first row of the pores.²⁰ After each cold test confirming that the porosity negligibly impacted the RF fields, we identified the multipactor susceptible zone by conducting multipactor onset tests at multiple frequencies with 40 MHz spacing following the specific procedure detailed in Ref. 30. We selected a pulsed RF signal with a 2 μ s pulse width and a 20 μ s cycle time (10% duty cycle). To verify the lower multipactor threshold (minimum RF voltage multipactor threshold), the peak power was set to a low amplitude and gradually increased in 0.1 dBm input RF power steps until a multipactor event was detected. For the upper multipactor threshold, we did the reverse. The results of our multipactor tests for the lower and upper thresholds of the multipactor zone are plotted in Fig. 5 and compared with the susceptibility charts predicted by the semi-analytic approach. As seen in Fig. 5, we observe a similar trend in the experimental and prediction results, i.e., the multipactor zone diminishes as the porosity increases. We observed no multipactor event with 0.66 porosity, consistent with our prediction. We also observe discrepancies between experimental measurements and predicted multipactor onset thresholds at lower frequencies, which we attribute to simplifying model assumptions and differences between the assumed surface conditions in the model and the actual surface conditions in the experiment. For example, the model uses the simplifying assumption of a single-valued emission velocity for the secondary electrons, whereas in fact the emission velocities of secondary electrons constitute a distribution function. Also, we did not include the space charge effects that apparently impact the lower susceptibility boundary in the low-frequency region.¹⁷ Meanwhile, there are expected to be difficult-to-characterize differences between the assumed SEY properties of the model's surface

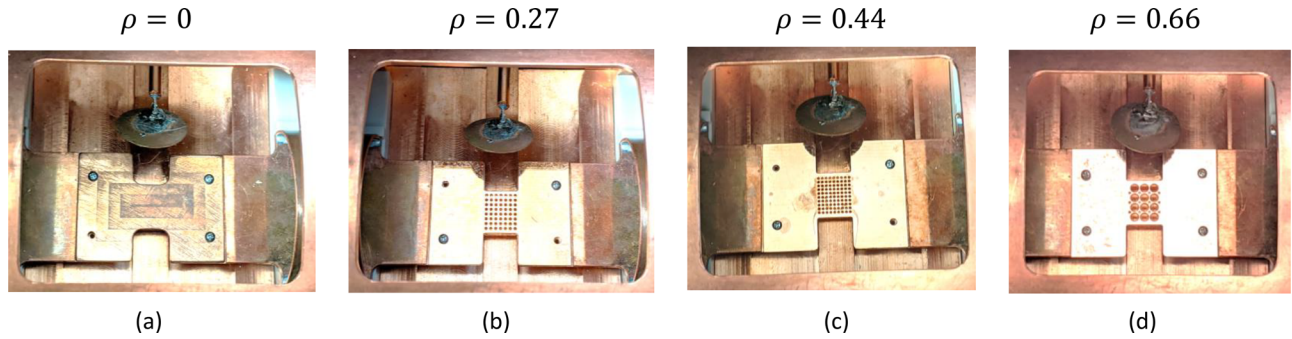


FIG. 7. The top view of the fabricated microstripline sections with different through-hole porosities, including (a) solid surface, (b) $\rho = 0.27$, (c) $\rho = 0.44$, and (d) $\rho = 0.66$. Note that we used a rectangular porosity arrangement for $\rho = 0.27$ and $\rho = 0.44$ porosities and an interleaved arrangement for $\rho = 0.66$ porosity.

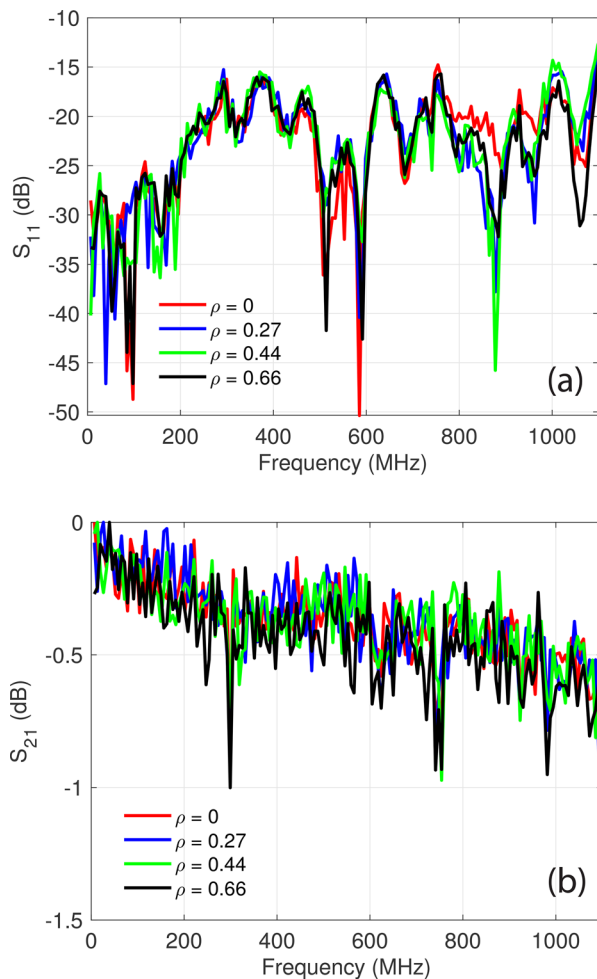


FIG. 8. The cold test results including (a) the reflection coefficients and (b) the transmission coefficients of the entire transmission line with different porosities.

and the SEY of the experimental surfaces³² (e.g., due to adsorbates). Nevertheless, the experimental results and the predictions agree on both the trend and the complete suppression of multipactor for a porosity of 0.66. These experiments and model calculations have

identified a surface that provides full multipactor suppression while negligibly perturbing the RF properties.

V. BLIND POROSITY SURFACES WITH FULL MULTIPACTOR SUPPRESSION CAPABILITY

Instead of using a surface consisting of through-pores, multipactor suppression is also predicted to occur with a surface with finite-depth or *blind* pores. The aspect ratio of a finite-depth pore is defined as $A_R = H/D$, where H and D are the depth and the diameter of the pore, respectively. Iqbal *et al.* previously showed²² that as $A_R = H/D$ increases, the effective surface SEY decreases and approaches the asymptotic minimum value, $\delta_{surf, effective}^{min} = \sigma\rho + \delta_f(1 - \rho)$ as $A_R \rightarrow \infty$, where σ represents the backscattering coefficient from the bottom surface of the well.¹⁰ For through-pores, we have $\sigma = 0$ (since $\delta_p = 0$ if we assume normal incidence). Therefore, the asymptotic minimum value of the maximum effective SEY of a surface with through-pores for normal incidence of primary electrons can be obtained as

$$\delta_{surf, effective}^{min} = \delta_f(1 - \rho), \quad (10)$$

which is the effective SEY of a surface with through-pores for normal incidence of primary electrons [i.e., using $\delta_p = 0$ in Eq. (9)].

Figure 9 shows that for normal incidence ($\psi = 0^\circ$), the asymptotic minimum values of the maximum effective surface SEY ($\delta_{surf, max}$) for porosities $\rho = 0.27, 0.44$, and 0.66 obtained from the MC simulation (solid lines) and from Eq. (10) (dotted lines) are in excellent agreement. Figures 9(b) and 9(c) show the $\delta_{surf, max}$ profiles with different porosities for incident angles $\psi = 45^\circ$ and 75° , respectively. We particularly note that in Figs. 9(a)–9(c), for $\rho = 0.66$ (red curves), the predicted maximum SEYs become less than unity ($\delta_{surf, max} < 1$) beyond a critical aspect ratio, $A_{R, critical}$. Therefore, ideally, a surface consisting of finite-depth pores having a porosity, $\rho = 0.66$, and an aspect ratio, $A_R > A_{R, critical}$, is expected to result in complete multipactor suppression for normal incidence of primary electrons, similar to the through-pore cases in Figs. 2(d) and 2(g). We observe that the value of $A_{R, critical}$ increases with the increase in the incident angle [Figs. 9(a)–9(c)] and $A_{R, critical} = 3, 3.73$, and 5.35 is observed for $\psi = 0^\circ, 45^\circ$, and 75° , respectively.

VI. CONCLUSION

We presented model predictions of secondary electron yields (SEYs) for both through-hole and blind-hole porous surfaces. The

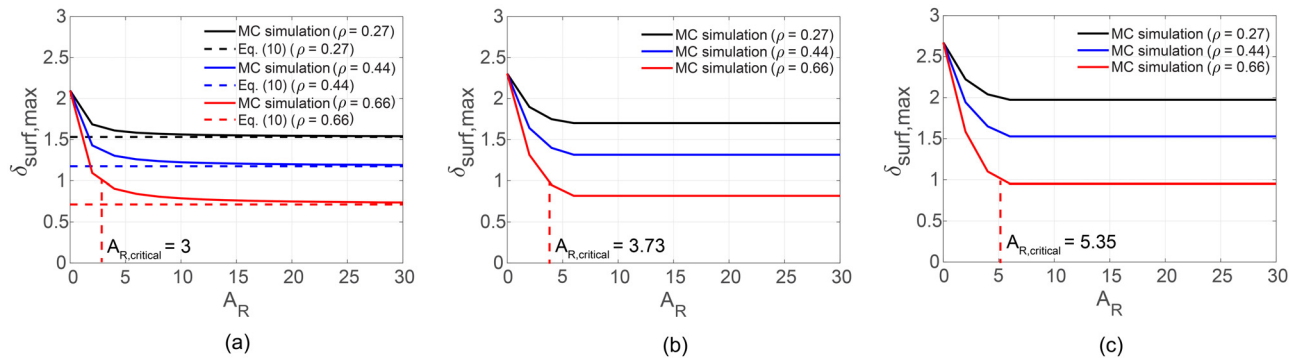


FIG. 9. Maximum effective SEY of blind-hole porous surface, $\delta_{surf,max}$, vs the aspect ratio of the blind pores, A_R , for porosities, $\rho = 0.27$ (black lines), 0.44 (blue lines), and 0.66 (red lines) and incident angles, (a) $\psi = 0^\circ$, (b) $\psi = 45^\circ$, and (c) $\psi = 75^\circ$. The horizontal dotted lines in (a) represent the asymptotic minimum values obtained from Eq. (10), and the solid lines are obtained from the MC simulations. In the MC simulations, the SEY model parameters for the flat region, the bottom surface, and the side walls of the well are assumed to be identical, i.e., $\delta_f = \delta_{bottom} = \delta_{side\ wall}$.

results predict that a sufficiently high through-hole porosity will completely suppress multipaction (e.g., ≥ 0.66 for copper). They also predict a similar effect should occur for blind holes with a height-to-diameter aspect ratio large enough to reduce the maximum effective surface SEY to less than unity. We verified these predictions of effective SEYs for through-hole porous surfaces by calculating multipactor susceptibility charts, which, in turn, were validated by experimental measurements over a broad frequency range. We demonstrated that as porosity increases, the multipactor zone shrinks, and beyond a certain porosity, it totally disappears. We finally validated our analytic approaches with multipactor experiments across a broadband frequency range. These experiments and simulations have identified surfaces that provide full multipactor suppression while negligibly perturbing the RF properties. These surfaces can be used in designing high-power multipactor free microwave components for applications involving evacuated high power microwave components such as in communications satellite payloads and high power microwave vacuum electronic devices. It is also notable that the porosity surface treatment provides the side benefit of light weighting the RF components.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Mirhamed Mirmozafari: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Software (equal); Validation (equal); Writing – original draft (equal); Writing – review and editing (equal).
Asif Iqbal: Conceptualization (equal); Data curation (equal); Software

(equal); Writing – original draft (equal); Writing – review and editing (equal).
Peng Zhang: Conceptualization (equal); Supervision (equal); Writing – original draft (equal); Writing – review and editing (equal).
Nader Behdad: Supervision (equal); Writing – review and editing (equal).
John Booske: Conceptualization (equal); Funding acquisition (equal); Supervision (equal); Writing – review and editing (equal).
John P. Verboncoeur: Funding acquisition (equal); Supervision (equal); Writing – review and editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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