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Article

Microwave Corona Breakdown Suppression of Microstrip Coupled-line Filter using Lacquer Coating

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Abstract: Due to its potential harm to space payload, microwave corona breakdown of microstrip circuits has attracted much attention. This work describes an efficient way to suppress corona breakdown. Since corona breakdown threshold is determined by the highest electric field intensity at the surface of microstrip circuits, lacquer coating with thickness of tens of microns is sprayed on the top of microstrip circuits. The applied dielectric coating is used to move the discharge location away from circuit's surface which is equivalent to reduce the highest electric field intensity on the interface of solid/air of the circuit and thus results into higher breakdown threshold. Two designs of classic coupled-line band-pass filter were used for verification. Corona experimental results at 2.5 GHz show that, in the interested low pressure range (100 to 4500 Pa), 5.3 dB improvement of microwave corona breakdown threshold can be achieved for a filter with narrowest gap of 0.2 mm while its electrical performances like insertion loss, Q-factor are still acceptable. A threshold improvement prediction method is also presented and validated.

Keywords: coupled-line filter; dielectric coating; microstrip circuits; microwave corona breakdown suppression

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1. Introduction

With the rapid development of space communication systems, study of microwave corona breakdown, also known as gas breakdown or low-pressure discharge, has received considerable attention. When RF/Microwave components working in a low-pressure environment, generally refers to 10^{-3}~10^{5} Pa [1], a number of initially charged particles in the gas may accelerate under the established electric field. If they can obtain sufficient kinetic energy to collide with neutral particles or excitation of secondary electron emission on the surface of the component, then it may result into an avalanche increase in the number of charged particles [2]. In this case, the originally insulating gas may form plasma and affect transmission of RF/microwave signals. Thus, from this point of view, corona is an undesired effect. However, this discharge phenomenon is sometimes desirable such as realization of a microwave phase shifter [3].

Although microwave corona breakdown has been researched for decades, most studies published focused on cavity resonators or waveguide components [4–6]. Due to the increasing use of solid-state microwave components, corona breakdown of microstrip circuits is becoming interested by space community. Recently, studies on corona effect of microstrip circuits, including microstrip-to-coaxial transition, are reported which mainly focus on interpretation and modeling/simulation of corona effect [7–9], [10]. Like another power handling problem, multipactor, one of the most important aspects of corona research is how to suppress corona effect. Due to the similarity between multipactor and corona, they sometimes can be suppressed by using similar techniques such as electrical structure design/optimization [11,12], dielectric filling [13,14] as well as surface treatments [15]. For example, measurement results in [11] show that by introducing rounded-end resonators, hairpin microstrip bandpass filter's corona threshold can be improved by 2.1 dB. By placing a dielectric brick of thickness around 1.5 mm [13] over the open-circuit terminations of hairpin-type resonators, simulation results show a corona threshold improvement around 7 dB and in [16], measurement results show that a peak power handling capability enhancement of 3.1 dB at high pressures was achieved with very small influence on quality factor and insertion loss. In this work, we propose a corona suppression strategy by depositing a thin dielectric film, namely, commercially available clear protective lacquer which is widely used in print-circuit-board (PCB) industry, with thickness around tens of microns on the top of microstrip circuits. Compared with existed methods like [11,13,16], our method shows potential advantages such as lower weight, higher improvement of breakdown threshold. As a demonstration, we use one kind of classic microstrip filter, namely, coupled-line bandpass filters as device under test (DUT). Microstrip technology has been widely used for the realization of filters, owing to its simple structure, low fabrication cost and easy integration with lumped circuits [17].

In section II, basic idea of the proposed corona suppression method and experimental details are described. In section III, the obtained results are presented and discussed.

2. Methods

2.1. Principle of the Proposed Corona Suppression Method

The basic idea of the proposed corona suppression method is shown in Figure 1. It is widely known that corona breakdown is tend to occur in air or low pressure with highest electric field. So, physically speaking, if the highest electric field can be reduced, then it can be expected that corona breakdown threshold will be improved. For a coupled-line filter, since the strongest electric field exists around the coupling gap, corona breakdown usually also occurs around this gap as shown in Figure 1(a). As schematically shown in Figure 1(b), with conformal dielectric coating, the discharge location will move upward since the gas-solid interface moved upward. Considering the fact that, for microstrip circuits, electric field intensity decreases sharply along z axis, it can be expected that, with dielectric coating, corona threshold can be improved. What's more, one would expect that improvement of corona breakdown should be more obvious for thicker dielectric coating. However, as will be mentioned below, dielectric coating also affects microstrip circuit's electrical performance such as filter's center frequency, insertion loss and unloaded Q-factor. This is because the dielectric coating changes the effective permittivity of microstrip circuits. So, there is a trade-off between corona threshold improvement and electrical performance degradation [16].

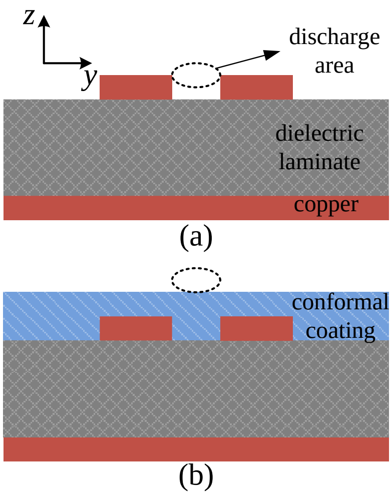

Figure 1. Schematic of corona suppression: (a) without dielectric coating; (b) with dielectric coating.

As a preliminary step, using CST, we conducted some simulations to observe the dependence of corona threshold on thickness of dielectric coating. The electromagnetic model is shown in Figure 2. In detail, Figure 2(a) is a filter without dielectric coating and Figure 2(b) shows the same filter but with dielectric coating. In our simulations, the thickness of the microstrip line conductor is 35 microns while the thickness of dielectric coating ranges from 0 to 45 microns. Corona threshold simulation results are shown in the Table 1 (simulated pressure is 100 Pa). It can be seen that, as expected, the threshold increases with increasing thickness of the dielectric coating. Since there are many publications dealing with the mechanism, calculation and simulation of microwave corona, potential readers interested on theoretical aspects of corona may refer to related literature. Some of them are list as references in this work.

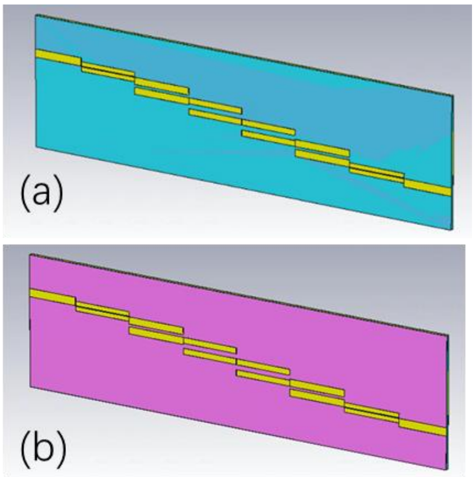

Figure 2. Electromagnetic model used for corona simulation: (a) without dielectric coating; (b) with dielectric coating.

Table 1. Results of corona threshold simulation.

coating thickness (μm)	0	25	35	45
corona threshold(W)	15.8	18.9	24	74.9

It should be noted that, theoretically speaking, the S-parameters are likely to be affected by the covered dielectric film, especially for thick film with large permittivity. On the other side, one can expect that thicker films will present higher threshold. So, there is a trade-off between threshold improvement and S-parameter degradation. Good trade-off may be achieved by using films with low permittivity, partially coating or one can take the loading effect of the dielectric film into consideration at the designing stage of the circuits.

2.2. Description of the Devices Under Test (DUT)

A couple of five order coupled line band-pass filters [18] were designed and fabricated as DUTs. The used high-frequency dielectric laminate has thickness of 1 mm and the thickness of copper foil is 35 μm. A photo of one of the used filters is shown in Figure 3. These filters were fabricated in our own lab using a process similar to the photolithography process widely used in semiconductor industry. For demonstration, two designs are presented: one with a narrowest coupling gap of 0.2 mm (ε_r is 3) and the other 0.3 mm (ε_r is 3.5). S-parameters are measured using Rohde&Schwarz's ZND vector network analyzer (VNA) and the obtained results are shown in Figure 4. The VNA was calibrated using a standard through-open-short-match calibration kit. After dielectric coating, the filters still have reasonable S-parameters. For example, the frequency shift caused by the coating is around 20 and 25 MHz for the 0.2 and 0.3 mm filter, respectively. The unloaded Q-factor of the 0.2 mm filter after coating is 36 which is almost the same with the case before coating, namely, 35. As regard to insertion loss, for the 0.3 mm filter, its insertion loss increased from 1.8 to 3.1 dB after coating

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while, for the 0.2 mm filter, the insertion loss decreased about 0.5 dB. It should be noted that we didn't taking dielectric coating into account in the filter design stage. In fact, as depicted in [11,13,16], it is possible to make all the filters have almost the same S-parameters by slightly tuning their design parameters. The spurious resonance at 2.3 GHz for the filter with 0.3 mm coupling gap is caused by unoptimized filter design. It is possible to get a better design if further optimization is adopted.

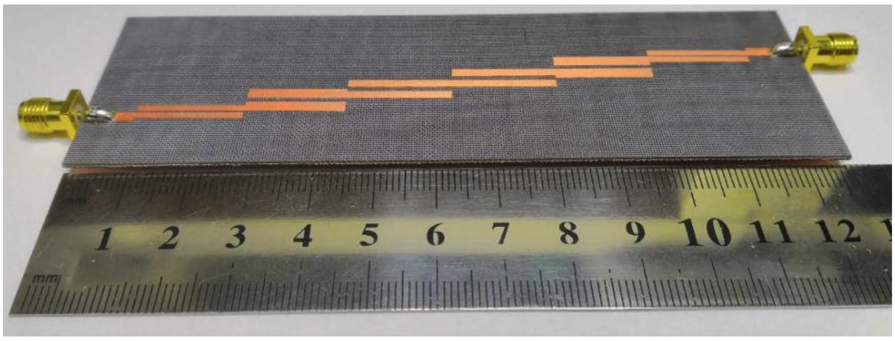

Figure 3. Photo of the fabricated filter.

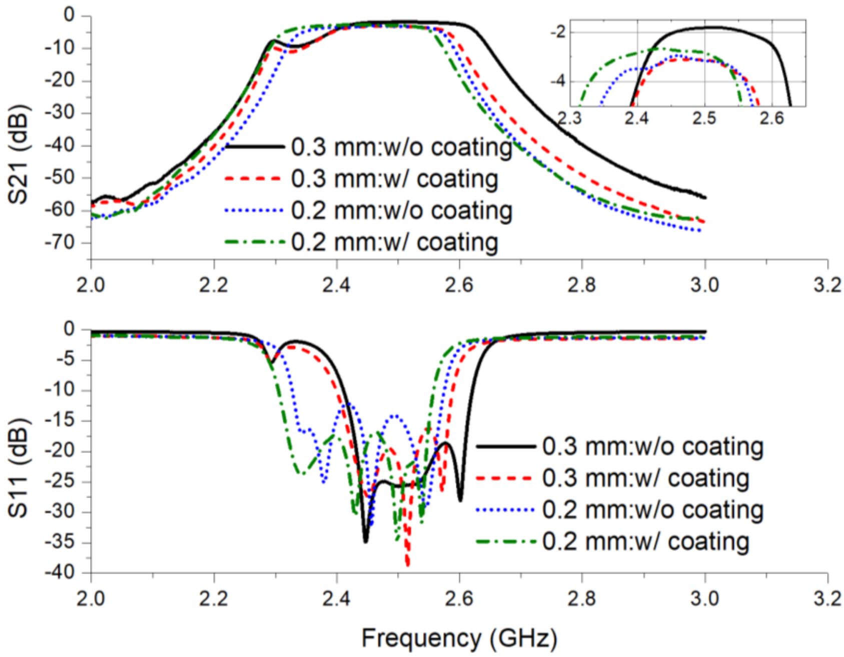

Figure 4. Measured S-parameters with and without dielectric coating.

Conformal dielectric coating (commercially available clear protective lacquer which is widely used in print-circuit-board (PCB) industry) was sprayed on the top of the fabricated filters. By observing the cross section using stereoscopic microscope (SMZ 745T), it was found that the coating is a little non-uniform and the observed thickness ranges from ~20 to ~50 microns with an average value of ~35 microns, as shown in Figure 5. Through simulations, as described later, the relative dielectric constant of the used lacquer is estimated as around 2. It should be noted that, in order to obtain an estimation of the coating's thickness, we used a glass substrate as deposition sample due to its flat surface. For the PCB, its rough surface makes the thickness observation inaccurate.

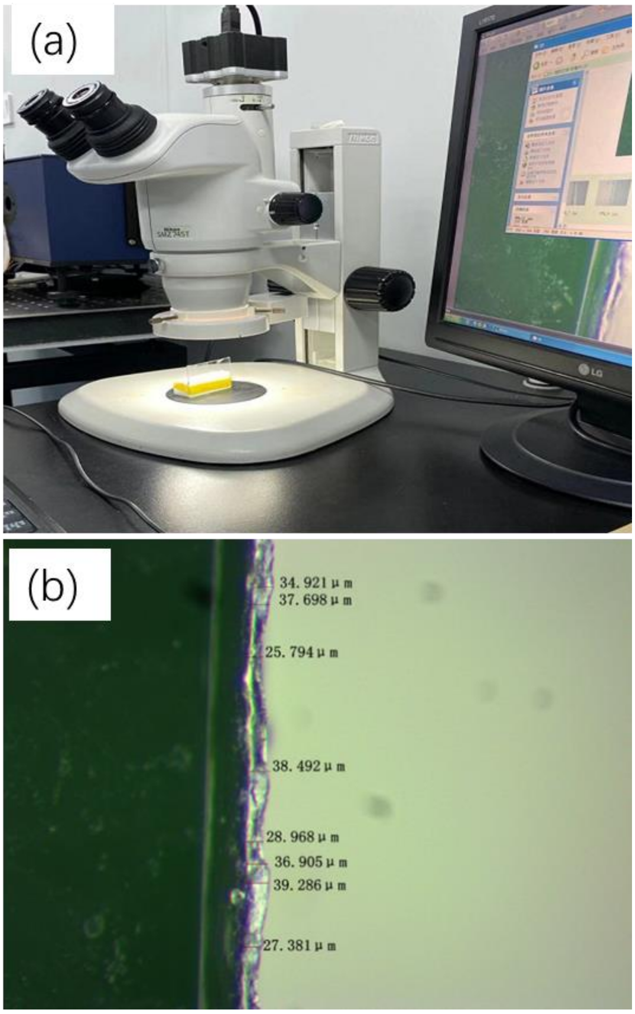

Figure 5. (a)Microscope used for coating’s thickness test. (b) Photo of the coating observed by the microscope.

In usual case, as observed in [16], a dielectric coating results into higher insertion loss. However, as shown in the inset of Figure 4, our measurement results of the 0.2 mm gap filter shows that the insertion loss is a little lower after dielectric coating. This may be attributed to better matching after coating. To conform this point, we ran some electromagnetic simulations. A similar five order coupled-line filter was used for these simulations. First of all, one filter without dielectric coating was simulated as benchmark. Then, dielectric coating with thickness of 35 μm was placed on top of the benchmark filter. As the relative dielectric constant ε_r of lacquer is not known, we used two values of ε_r. Namely, the second and third filter was coated with ε_r equal to 2 and 3, respectively. For simplicity, the loss tangent of the coating was set as zero. The narrowest gap of all of the three filters is 0.2 mm which is the same with the above experiments. Obtained simulation results are as Figure 6.

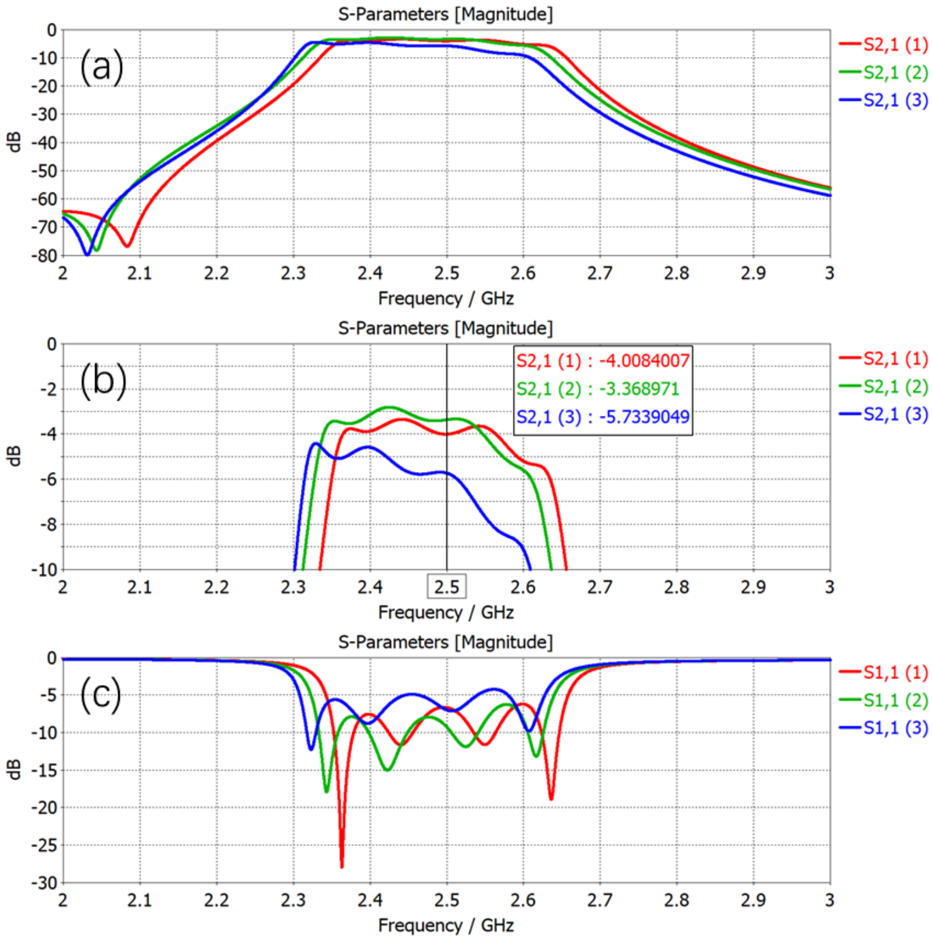

Figure 6. Electromagnetic simulation results showing dielectric coating's effect on S-parameters. (a) S_{21}; (b) S_{21} showing details around the center frequency; (c) S_{11}. Label (1), (2), (3) represents the following filters: benchmark filter, filter coated with a layer of 35 μm and $\varepsilon_r = 2$, filter coated with a layer of 35 μm and $\varepsilon_r = 3$.

It can be seen from Figure 6, as regard to frequency shift, one can see that a 35 microns coating with $\varepsilon_r = 3$ induced a ~40 MHz (about 2%) frequency shift while a 35 microns coating with $\varepsilon_r = 2$ induced a ~20 MHz (about 1%) frequency shift. In our experiments, the observed frequency shift is ~20 MHz. So, we estimate that the relative dielectric constant of the used lacquer is about 2. As regard to insertion loss, one can see that a 35 microns coating with $\varepsilon_r = 3$ induced increased insertion loss, increased about 1.7 dB at 2.5 GHz while a 35 microns coating with $\varepsilon_r = 2$ induced decreased insertion loss, decreased about 0.6 dB at 2.5 GHz. Our measurements show that the insertion loss decreased about 0.5 dB which is similar to simulations.

We also ran some simulations to observe the dependence of filter's performance on coating's loss tangent. In this group of simulations, the following three cases are considered: first, the curves denoted with (8) represent coating with $\tan\delta = 0.01$; second, the curves denoted with (11) represent coating with $\tan\delta = 0.1$; third, the curve denoted (14) represent coating with $\tan\delta=0.5$. For all of the three cases, the coating's thickness is 35 microns and $\varepsilon_r = 2$. The obtained results are shown as Figure 7. One can see that as the loss tangent of the coating increases, the insertion loss increases too. What's more, this parameter also influences the return loss. It should be noted that the coating's thickness is uniform in simulation while it may be nonuniform to some degree in our experiments since it is sprayed manually. This nonuniformity may have some effect on comparison between simulation and measurement.

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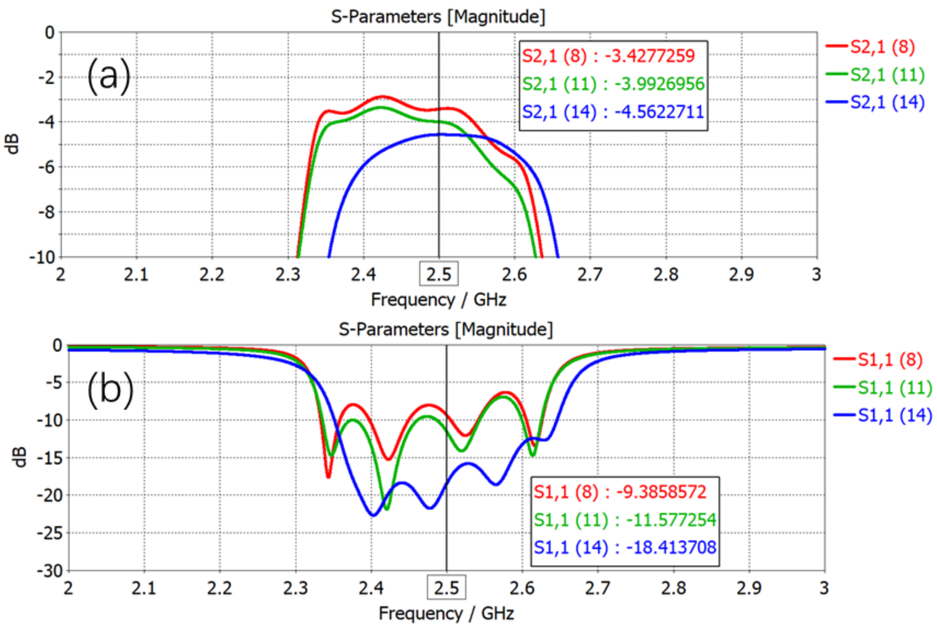

Figure 7. Electromagnetic simulation results showing dielectric coating's effect on S-parameters. (a) S_{21}; (b) S_{11}. Coating's thickness is 35 microns and $\varepsilon_r = 2$. Label (8), (11), (14) represents the following loss tangent settings: tanδ = 0.01, tanδ = 0.1, tanδ = 0.5.

We also ran some simulations to show that it is possible to consider the coating's effect at the early design stage of the filter for the purpose of minimize electrical performance degradation. The main purpose of this group of simulations is to show the possibility of minimizing frequency shift by tuned design. The curve denoted as (1) represents benchmark design of filter without coating. The curve denoted as (8) represents benchmark design of filter with coating (35 microns thickness, $\varepsilon_r = 2$, tanδ = 0.01). The curve denoted as (16) represents tuned design of filter without coating. The curve denoted as (17) represents tuned design of filter with coating (35 microns thickness, $\varepsilon_r = 2$, tanδ=0.01). The obtained simulation results are shown as Figure 8. The benchmark design without coating was obtained with center frequency of 2.5 GHz. After coating, its center frequency shifts to the left (about 20 MHz). The tuned design without coating was obtained with center frequency of 2.53 GHz. After coating, its center frequency also shifts to the left (about 10 MHz). Here, we just show the possibility of minimizing frequency shift by using a higher center frequency in the design stage. Iteration of parameter adjustment may be necessary to get a predefined center frequency. Anyway, this case study shows that the frequency shift problem can be relaxed using a slight higher center frequency at the design stage of the filter.

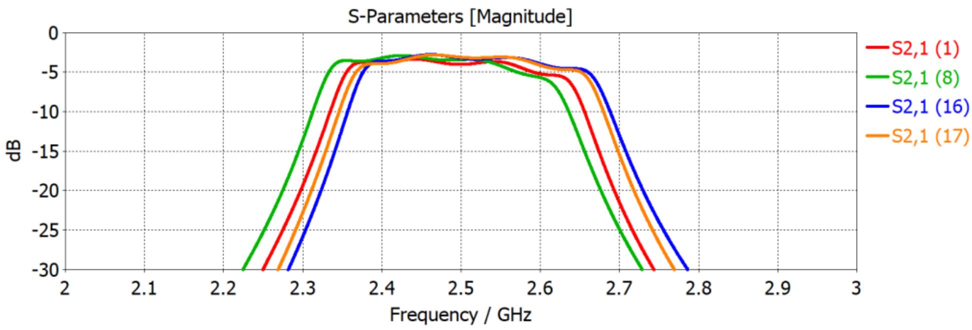

Figure 8. Electromagnetic simulation results showing possibility of minimizing frequency shift by using a slight higher center frequency at the design stage of the filter. The curve denoted as (1) represents benchmark design of filter without coating. The curve denoted as (8) represents benchmark design of filter with coating (35 microns thickness, $\varepsilon_r = 2$, tanδ = 0.01). The curve denoted as (16)

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represents tuned design of filter without coating. The curve denoted as (17) represents tuned design of filter with coating (35 microns thickness, $\varepsilon_r = 2$, tanδ=0.01).

2.3. Measurement System of Microwave Corona Breakdown

A schematic view and photo of the microwave corona breakdown measurement system used in this work is shown in Figure 9. The signal generator together with the power amplifier outputs a continuous sine wave signal of 2.5 GHz. This signal is then fed into the DUT through a circulator and a directional coupler. The function of the circulator is protecting the power amplifier from strong reflected power. A high-power load is used to absorb the power passing through the DUT which is inside a vacuum chamber. The vacuum chamber can be maintained at a specific predefined vacuum level using a vacuum pump system. By tuning the amplitude and phase of the forward signal (from the coupler to the DUT), the amplitude of the combined signal (also called as nulling signal) of the forward and backward (from the DUT to the coupler) signal can be minimized. If corona breakdown occurs, due to the plasma formed by the discharge, the amplitude and/or phase of the backward signal will change accordingly. Then, the nulling signal will experience a significant amplitude increase (see Figure 11) and this is the main indicator of the onset of corona. Also, the observable emitted light during discharge can be used as another indicator (see inset of Figure 11; by analyzing this emitted light, more detailed information regarding the discharge can be obtained as described in [6]).

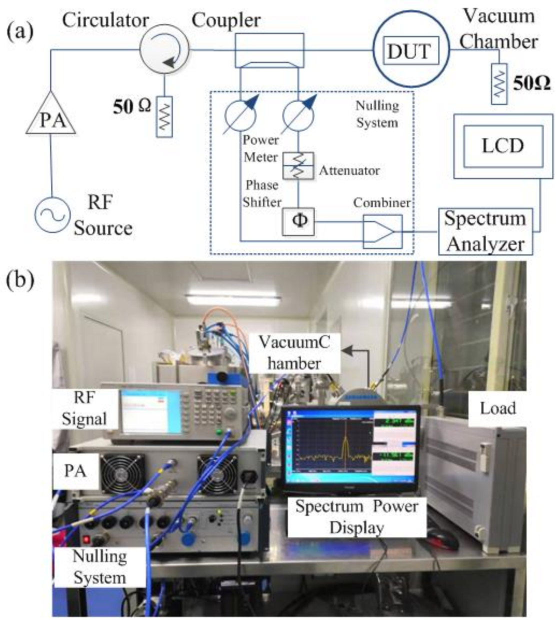

Figure 9. Corona breakdown threshold measurement system used in this work.

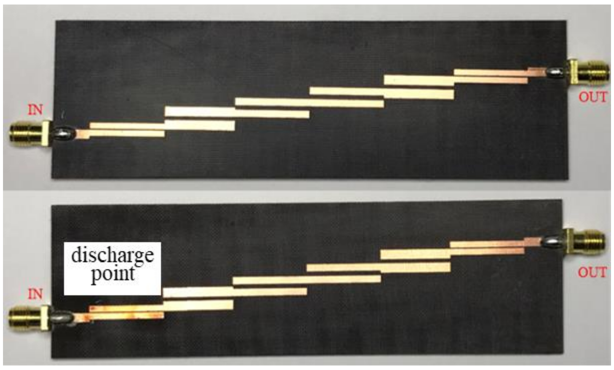

Figure 10. Photo of filter before (the up figure) and after (the bottom figure) corona breakdown.

Figure 10 and inset of Figure 11 show photos of DUT after corona breakdown and it can be seen that the discharge was occurred at the first (from left to right) narrowest gap which is close to the high-power input port. Although the filter has symmetry structure, due to insertion loss, the gap which is close to input port will have larger electric field and thus breakdown first. This observation agrees with [11].

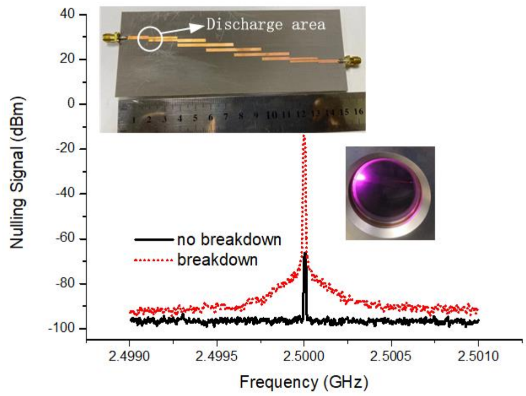

Figure 11. Nulling signal variation before and after corona breakdown. Insets are photo of DUT and emitted light observed at the window of vacuum system.

3. Results and Discussions

Microwave corona breakdown measurements were performed with various pressures ranging from 100 to 4500 Pa. A couple of filters with the same designs were measured and the obtained threshold power show good repeatability. So, averaged values are presented below. Totally, four groups of DUT are used for demonstration as shown in Table 1.

Table 2. Information on DUTs.

Group #	Narrowest gap (mm)	Coating
1	0.2	no
2	0.3	no
3	0.2	yes
4	0.3	yes

Measurement results are shown in Figures 12 and 13. The threshold power (in Watt) increased ~10% to 60% (average value is ~30%, corresponding to 1.1 dB) for 0.3 mm filters while increased ~190% to 270% for 0.2 mm filters (average value is ~240%, corresponding to 5.3 dB). Namely, by applied a dielectric film coating, microwave corona breakdown threshold can be improved by 0.4 to 2.0 dB for 0.3 mm gap filter and 4.6 to 5.7 dB for 0.2 mm gap filter. One reason for the lower improvement of corona threshold of the 0.3 mm gap filter is that the uncoated filter has larger bandwidth than its coated counterpart. It is known that widening the bandwidth increases the corona breakdown threshold. It should be noted that, to be rigorous, it would be necessary to compare the pairs of filters only when they have almost the same S-parameters.

In the measured pressure range, analytical threshold prediction formula is still lack. In [8], the threshold power can be analytically predicted only for high pressures. However, the authors show that numerical simulation could give reasonable predictions. Considering the focus of this work is corona breakdown suppression, for simplicity, we propose a threshold improvement evaluation method instead of predicting the absolute threshold power. Using this method, one can predict how much will the threshold be increased by dielectric coating. First of all, measurement data shown in Figures 12 and 13 can be fitted reasonably well with the following double exponential function (it may be called as a phenomenological model):

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$$P_{in} = a_1\, exp(a_2 p) + b_1\, exp(b_2 p) \quad (1)$$

Here, P_{in} is the maximum input power in watt and p is pressure in Pa. The obtained fitting coefficients are shown in Table 3.

Table 3. Fitting coefficients of equation (1) for filters without dielectric coating.

Group #	a1	a2	b1	b2
1	23.0421	-0.0074	8.5909	0.0002
2	142.252	-0.0085	20.8847	0.0002

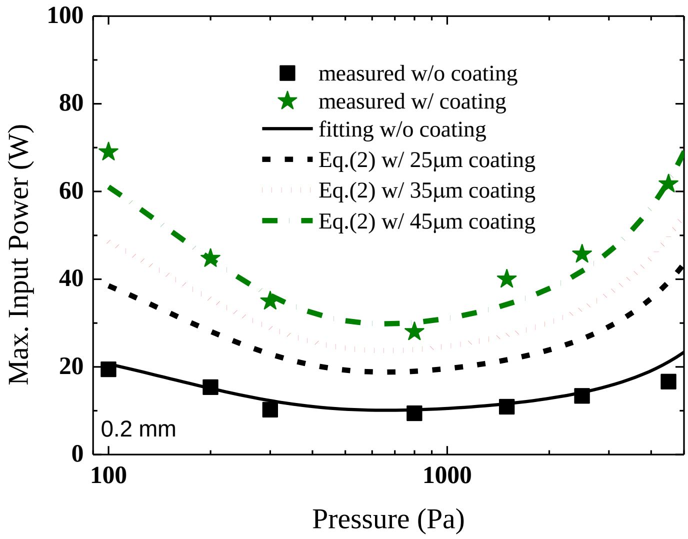

Figure 12. Results of corona threshold of filters with narrowest gap of 0.2 mm.

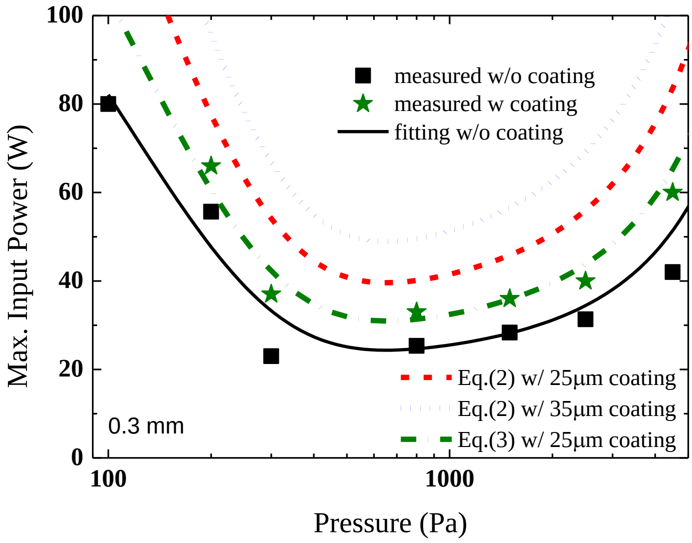

Figure 13. Results of corona threshold of filters with narrowest gap of 0.3 mm.

It is widely known that corona breakdown is strongly related with the intensity of electric field. So, the proposed threshold improvement prediction method is based on post-process of electric field which can be obtained from full-wave electromagnetic simulation. In detail, two potential methods may be used. The first method using the maximum E-field:

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$$P_{in,2} = P_{in,1}\left(E_{max,1}/E_{max,2}\right)^2 \quad (2)$$

Here, $E_{max,1}$ and $E_{max,2}$ is the maximum electric field at the narrowest gap without and with dielectric coating, respectively. $P_{in,1}$ and $P_{in,2}$ is the threshold power without and with dielectric coating, respectively. The second method using the average E-field:

$$P_{in,2} = P_{in,1}\left(E_{ave,1}/E_{ave,2}\right)^2 \quad (3)$$

Here, $E_{ave,1}$ and $E_{ave,2}$, is the averaged electric field at the narrowest gap without and with coating respectively.

As shown in Figures 12 and 13, the first method gives reasonable predictions for group 3 filters (0.2 mm gap) while the second method has better performance for group 4 filters (0.3 mm gap). For the former case, the best estimation of the film thickness is 45 microns and it is 25 microns for the latter case. These estimated thicknesses totally agree with observation from stereoscopic microscope. Compared with classic parallel-plate theory of corona breakdown (uniform electric field is usually supposed), microstrip circuits have obvious non-uniform electric field distribution. This non-uniformity is more obvious for narrow gap (group 3) than wide gap (group 4). So, for group 3 filters, the maximum electric field has better representation capability than the average electric field, and vice versa for group 4 filters. A typical electric field distribution from full-wave simulation is shown in Figure 14. It can be clearly seen that, after dielectric coating, electric field intensity is reduced. With the development of simulation tools, it is possible to predict corona threshold of microwave/RF planar circuits. It should be noted that, compared with [16], corona mitigation is more obvious here. Thus, one may infer that corona mitigation depends on the specific design of filter. In fact, even for the same type filter, such as the coupled-line filter, it is observed that corona suppression is related with filter's design. So, systematic research on relation between filter's topology and corona threshold improvement is necessary and of value for microwave engineers.

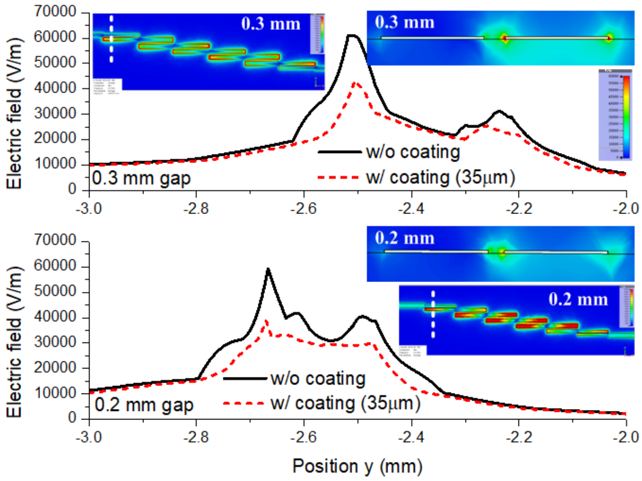

Figure 14. One dimensional and two-dimensional electric field distribution of the filters used in this work. The white dotted line shows the location of one-dimensional electric field.

4. Conclusions

Dielectric coating is proposed and verified as an efficient microwave corona breakdown suppression method for microstrip circuits. Two designs of classic coupled line band-pass filters are used for demonstration. After sprayed with conformal coating of lacquer with thickness ~35 microns, the threshold, in a pressure range from 100 to 4500 Pa, can be improved by 1.1 and 5.3 dB in average for a 0.3 mm and 0.2 mm coupling gap, respectively. An evaluation method is also presented to predict threshold improvement. It should be noted that the application of the proposed corona breakdown suppression method requires taking dielectric coating into account at the filter's design stage to achieve desired filtering performance after coating and one should also evaluate the dielectric coating's gas desorption performance as pointed out in [15] and the coating's long-term stability as mentioned in [16].

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Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy reasons.

Conflicts of Interest: The authors declare no conflicts of interest.

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