MLC Discoidal Capacitors for EMI-RFI Filters Employing Non-Overlapping Electrodes Yield Substantial Performance Improvements.

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Abstract

Multilayer ceramic discoidal capacitors used in EMI/RFI filter feedthroughs have traditionally been designed with overlapping electrodes. The problem arises when there is a need to increase the voltage rating by an order of magnitude from, 100VDC to 1000VDC, while maintaining similar capacitance. This is especially challenging when the discoidal capacitor's overall size is small, approximately .080", and the capacitance requirement is relatively large, approximately 1500pF. Due to volume constraints of the device, the traditional method of increasing dielectric thickness in order to increase voltage rating would yield a part with marginal reliability.

In this application, the solution is to employ non-overlapping electrodes. The electrodes can be arranged in a way that takes advantage of the fringe effect capacitance that is produced at the edges of the electrodes. This electrode arrangement resembles a small washer sitting entirely inside the hole of a larger washer and not touching the larger washer. When the sets of washers are stacked and interleafed with layers of dielectric, they effectively form a small cylinder inside a larger cylinder. Since the electrodes are non-overlapping, the voltage rating of the capacitor is no longer determined by the dielectric thickness; instead it is determined by the gap, g, between the outside of the small cylinder and the inside of the large cylinder. The active area of the capacitor is thus determined by the outer surface area of the small cylinder, 2πrh, where, h, is the height of the cylinder. The traditional equation for capacitance kA/d is replaced by k2πrh/g.

The non-overlapping electrode (NOE) construction results in a variety of performance improvements over the traditional design. Improvements include increased capacitance density, increased voltage rating as a result of higher voltage breakdown, and substantially improved insertion loss performance. Other improvements are higher Q and lower ESR.

Introduction

Traditional MLC discoidal capacitors used in EMI/RFI filter feedthroughs are designed with overlapping electrodes. This is the typical construction for surface mount MLCC's. The problem arises when there is a need to increase the voltage rating by an order of magnitude from 100VDC to 1000VDC while retaining the same capacitance and package size. This is especially challenging when the discoidal capacitor's overall size is relatively small and the capacitance requirement is relatively large, given the voltage requirement.

Design parameters are .080" diameter, 1500pF X7R with rated working voltage of 1000VDC. For high reliability applications, it is desirable to have the breakdown voltage be at least several times the rated voltage. That would put the desired breakdown on the order of 4000-5000 volts. X7R dielectrics typically exhibit voltage breakdown on the order of 1000VDC per mil of dielectric thickness. This necessitates dielectric layers that are at minimum 4-5 mils thick.

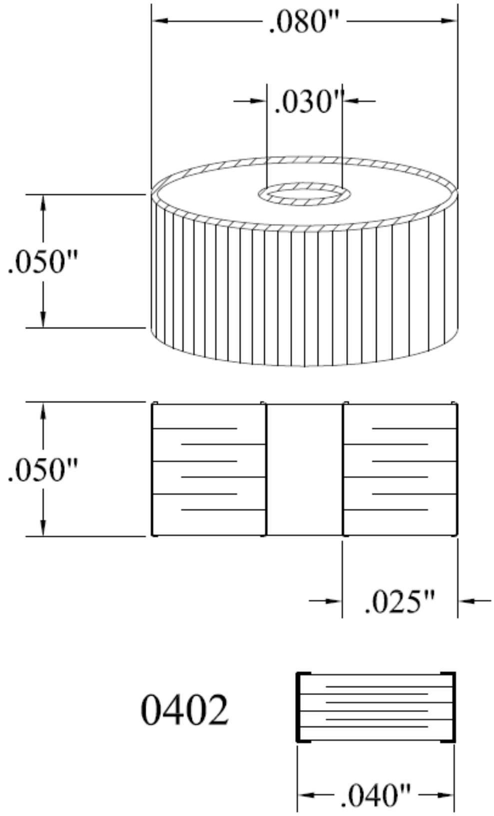

Figure 1. The discoidal cap has effectively two thirds the length of an 0402 MLCC

Figure 1 outlines the overall volume constraint in this application. The distance from the ID to the OD is .025", whereas the length of the typical 0402 MLCC is .040". This length comparison demonstrates the challenge of meeting the 1000V rating in a part that is effectively only two thirds the length of an 0402 MLCC. Given the volumetric limitation, the traditional overlapping electrode construction would at best yield a capacitor with marginal reliability.

Since it is desirable to have the voltage breakdown be in the range of 4000-5000 volts, the probable breakdown paths must be considered. Figure 2 shows the three most probable breakdown paths. Path 1 is between opposite electrodes and is typically on the order of 1000 volts per mil. Path 2 is between an electrode and the opposite end terminal. The breakdown strength of path 2 is typically on the order of 200 volts per mil. Considering the desired 4000-5000V breakdown, path 2 would need to be approximately 20-25 mils. This length is unachievable since the effective length of the discoidal is 25 mils, as shown in figure 1. The third path is surface breakdown between opposite end terminals. Surface breakdown is generally ignored in this study since surfaces of the capacitor can easily be coated with a high breakdown material such as dielectric fluid, glass, or epoxy.

In order to increase voltage breakdown it would be necessary to lengthen both breakdown paths 1 and 2. With traditional construction, as paths 1 and 2 are lengthened, the electrode overlapping area decreases, which yields less capacitance. By contrast, the NOE structure drastically changes the breakdown paths. Path 1 is no longer relevant since it is between electrodes of the same potential. The path between opposite electrodes, labeled 1*, is significantly longer than path 1 from the traditional structure. Path 2 in the NOE structure is also significantly longer than the comparable path in the traditional structure. From the breakdown path consideration, NOE construction should yield much higher voltage breakdown than traditional construction

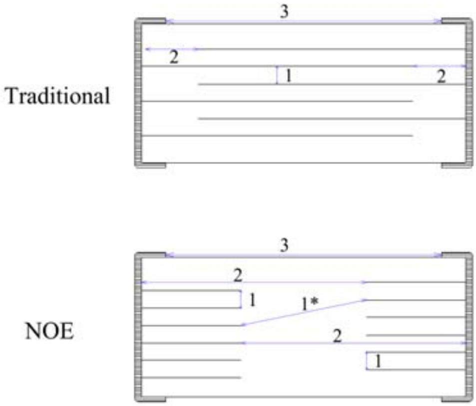

Figure 2. Probable voltage breakdown paths for traditional and NOE construction

Figure 3 illustrates the overall differences between overlapping and NOE construction. Externally, the

NOE cap is identical to the traditional discoidal. Internally, the non-overlapping electrodes resemble a stack of small washers sitting concentrically inside a stack of larger washers. Although not immediately obvious, another feature of the NOE construction is that there are many more electrodes than traditional construction with comparable dielectric thickness. This feature is illustrated in the cross-sectional side view in figure 3 and will be important when Q and ESR results are discussed

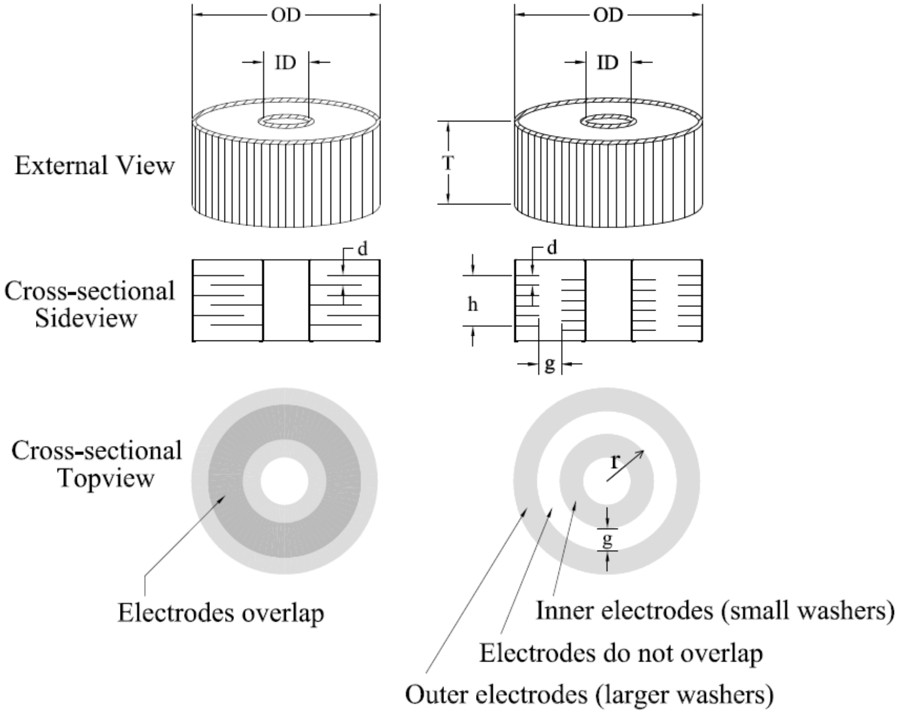

Figure 3. Comparison of internal construction. Breakdown paths are significantly lengthened in order to improve voltage breakdown performance.

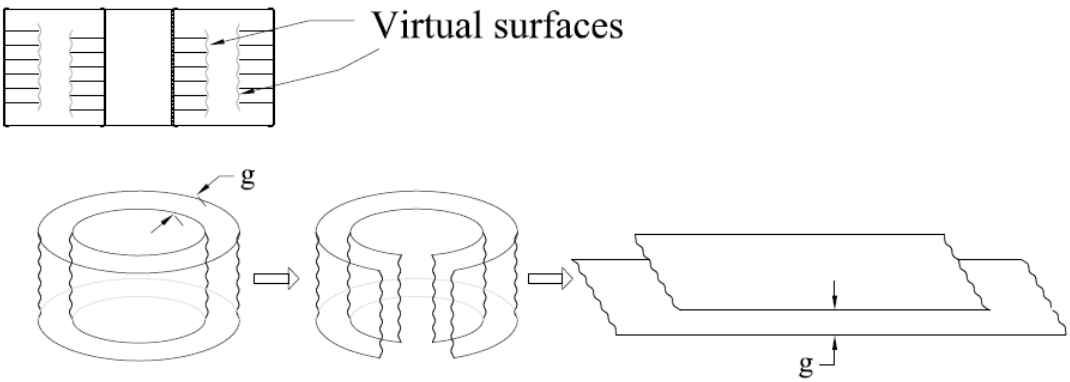

Figure 4. Virtual surfaces form the active area of the capacitor. The surfaces resemble an ideal capacitor.

At first glance it would appear that NOEs would yield no capacitance. However, as shown in figure 4 the two concentric sets of electrodes have the effect of forming virtual surfaces which are active area of the capacitor. This will be referred to as the fringe effect. The active area of the capacitor is thus determined by the outer surface area of the small cylinder, 2πrh, where, h, is the height of the cylinder. The traditional equation for capacitance, kA/d, is replaced by k2πrh/g, where, g, is the gap between the two cylinders. If the two cylinders are cut and laid flat, the result is two parallel plates separated by a layer of dielectric. This essentially forms an ideal capacitor, and this consideration will be important when insertion loss data is discussed.

Experimental Procedures

The procedures comprised building parts, testing electrical performance, and comparing the performance of non-overlapping parts against traditional parts. Over thirty thousand parts were tested in this study. The tests included measurements for capacitance, dissipation factor (DF), insulation resistance (IR), dielectric withstanding (DWV), DC voltage breakdown, equivalent series resistance (ESR), and S21 parameter insertion loss. Reliability tests included 168 hour burn-in at 125C and 1000 hour life at 125C. The tests were performed according to Mil and EIA standards when applicable.

Capacitance and DF were measured at room temperature, 1kHz, 1VACRMS. IR was measured at 1000VDC, and DWV was tested at 1500VDC minimum. DC voltage breakdown was performed by slowly increasing the voltage, approximately 100V per second, until failure occurred. Both burn-in and life test were performed at 125C with 1000VDC applied. Capacitance, DF, IR, and DWV were performed before and after burn-in and life test to determine failure rates. ESR was measured between 10kHz and 10MHz using an HP 4194A impedance analyzer. Insertion loss measurements were performed by Modelithics from 250MHz to 3.5GHz using an Anritsu vector network analyzer model 37347C. Figures 5 and 6 show, respectively, the test and test fixture schematics. Both figures were furnished by Modelithics

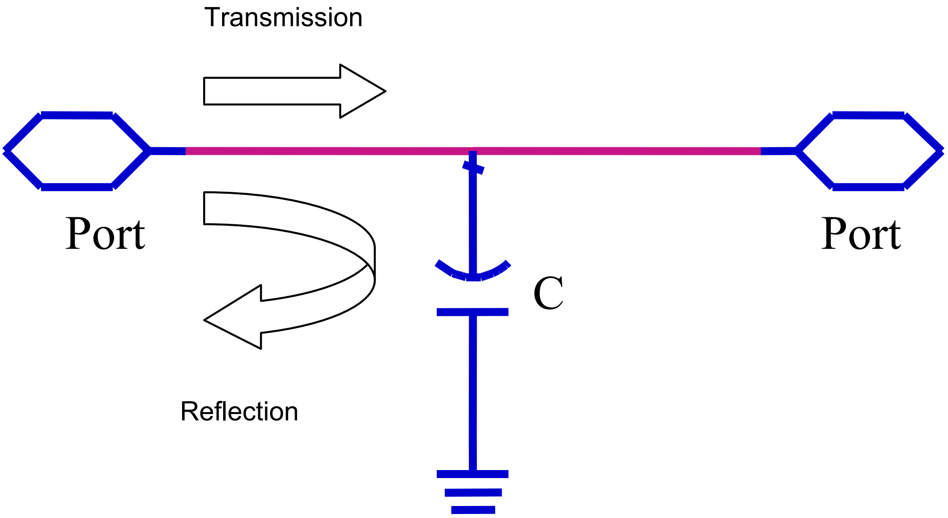

Figure 5. Schematic of S21 insertion loss measurement.

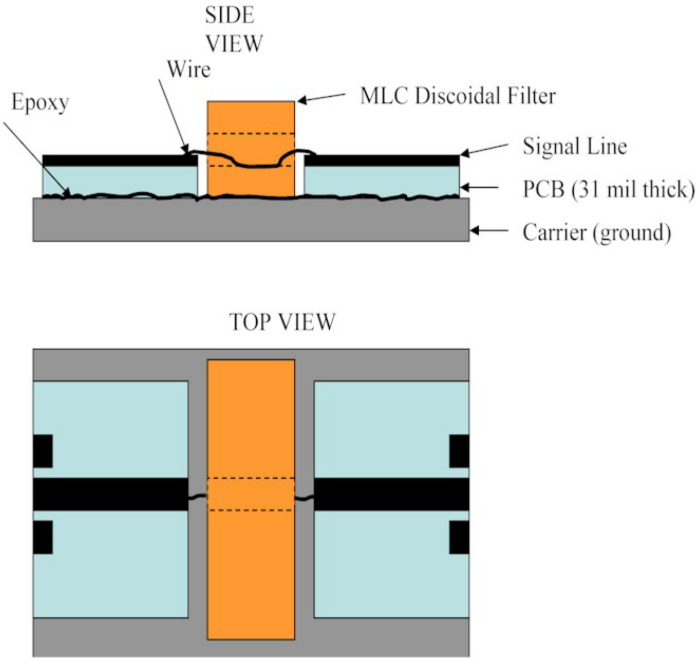

Figure 6. Schematic of insertion loss measurement fixture

Table 1. Summary of test results.

	Traditional Overlapping Electrode Design	Non-Overlapping Electrode Design
Capacitance 25C, 1kHz, 1VACRMS	1200-1800 pF	1200-1800 pF
Dissipation Factor 25C, 1kHz, 1VACRMS	<1% typical	<1% typical
Insulation Resistance at 1000VDC	>100 GOhms	>100 GOhms
Dielectric Withstanding at 1500VDC min.	High Fallout	<1% fallout
DC Voltage Breakdown (VDC)	1000-2000	5000-8000
Burn-in at 1000VDC, 125C, 168 hours (>30,000 parts tested)	Not reliable	<0.5% fallout
Life test at 1000VDC, 125C, 1000 hours (>100 parts tested)	Not reliable	All passed
Monophasic Pulse 2400VDC (2 sec, 25amps peak, 25 pcs)	Did not test	All passed
Equivalent Series Resistance	See Figure 7	See Figure 7
Q	See Figure 8	See Figure 8
Insertion Loss, S21	See Figure 9	See Figure 9

Results and Discussion

Table 1 summarizes the comparison between traditional discoidals and non-overlapping electrode discoidals. Both construction methods produce parts with acceptable capacitance, dissipation factor, and insulation resistance. The NOE caps vastly outperform the traditional caps in the areas of dielectric withstanding, voltage breakdown, burn-in, and life test. The traditional design exhibits an unacceptably high fallout rate, so the design was deemed 'not reliable' of surviving burn-in, and life. This is evident in the voltage breakdown test. The traditional caps break down between 1000-2000 volts. Many parts would fail DWV (1500V) prior to burn-in or life test. In contrast, the NOE caps break down between 5000-8000 volts. The improved breakdown is due to longer breakdown paths as shown in figure 2. High dielectric strength translated directly into exceptional performance with burn-in and life test. In addition, monophasic pulse testing was performed, and the NOE design was shown to withstand more than 1000 monophasic pulses at 2400VDC. The pulses were at 2 second intervals with greater than 25 amps of peak current.

Figures 7-9 compares ESR, Q, and S21 parameter insertion loss. The NOE caps exhibit significantly higher Q and lower ESR. Improved ESR and Q are most likely attributable to the NOE construction having many more electrodes than the traditional caps, as shown in figure 3. For insertion loss, figure 9, the NOE caps significantly outperform the traditional caps between 1 and 3.5GHz. In this frequency range, NOE caps exhibit approximately 10dB greater attenuation. This equates to an order of magnitude improved filtering performance. Improved filtering can likely be attributed to the NOE structure resembling an ideal capacitor, as shown in figure 4

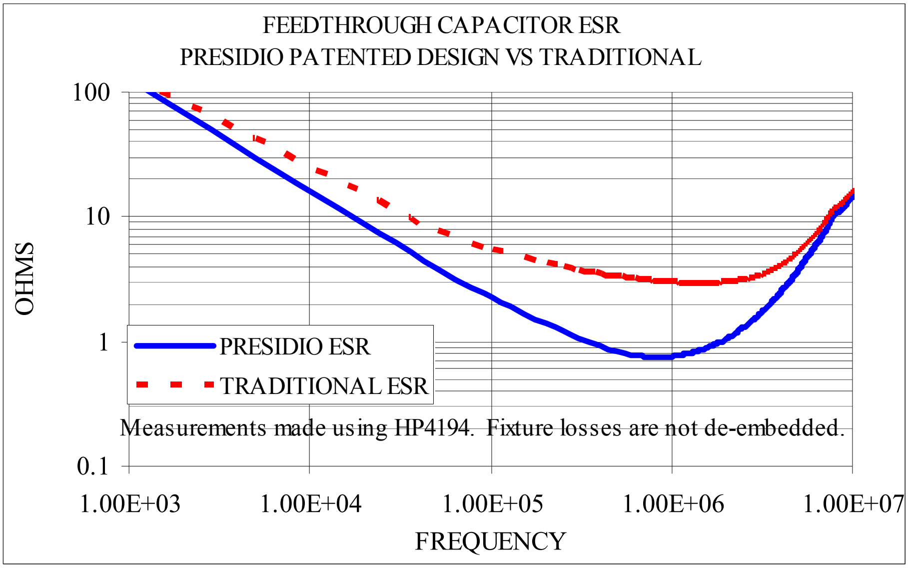

Figure 7. Comparison of ESR.

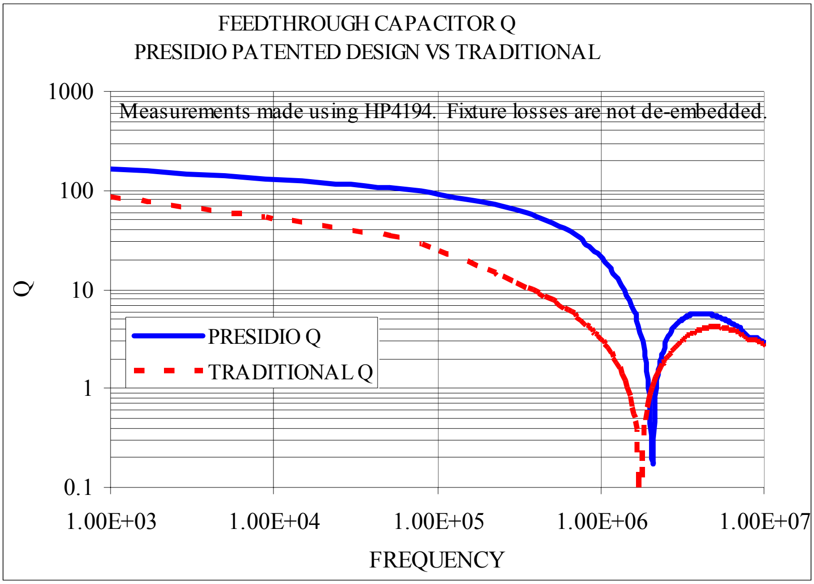

Figure 8. Comparison of Q.

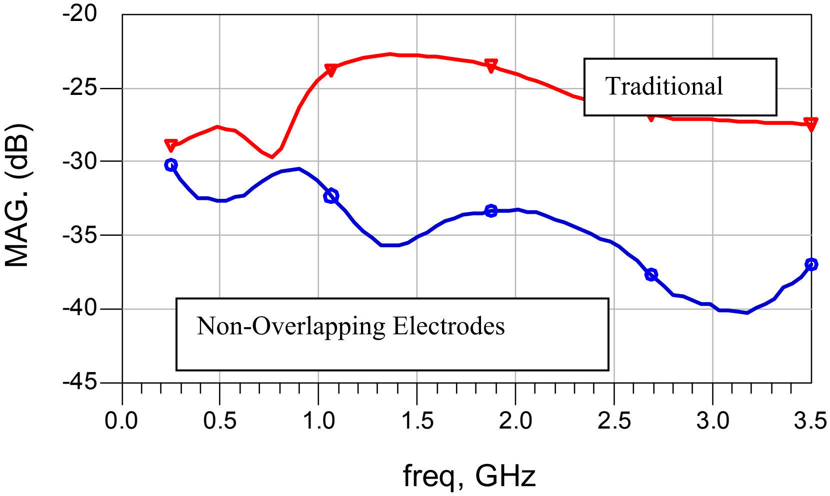

Figure 9. Comparison S21 insertion loss. Measurements made by Modelithics Inc.

Conclusions

In an effort to produce EMI-RFI discoidal filters that would be capable of performing in an ultra high reliability application, MLC discoidals with non-overlapping electrode structure were developed. Both traditional and NOE constructions are capable of producing parts with acceptable capacitance, dissipation factor, and insulation resistance. This is where the similarities end. NOE construction exhibited vastly superior performance than traditional construction in terms of DC voltage breakdown, reliability, Q, ESR, and insertion loss. The NOE structure significantly alters internal breakdown paths resulting in approximately four times higher voltage breakdown. Improved voltage breakdown translated directly into superb reliability performance. Two other features of NOE construction also resulted in vastly improved performance. Q is significantly higher, and ESR is significantly lower. These improvements can be attributed to the NOE design having many more electrodes than the traditional design. S21 insertion loss was improved by an order of magnitude between 1 and 3.5 GHz. Insertion loss improvement is likely due to the NOE structure resembling an ideal capacitor.

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