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Quantifying Parasitic Induced by No-Clean Solder Paste Residue at RF Frequencies

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Abstract

Residue left behind from no-clean assembly is a visually obvious artifact of the manufacturing process that can cause concern to those with RF circuit assemblies. This paper describes a test vehicle and test procedure, independent of product design and function, that allows for a quick and relatively simple examination of the electrical effects of residue frequencies up to 7.15 GHz and the determination of the capacitive parasitic associated with it.

Two test vehicles were compared, each comprising a bi-directional coupler. Flux medium was extracted from no-clean paste using centrifuge, applied to the center of the bi-directional coupler and reflowed. It was found empirically that for null frequencies in the range of 7 GHz, one of these bi-directional couplers was more sensitive than the other to parasitic induced by residue. This finding was in accordance with linear circuit simulations performed on the electrical model equivalents of the couplers that were also developed during this project.

The flux residues from extracted flux medium of five pastes were examined. The flux residue that induced the most amount of parasitic could be modeled as a capacitor of 25 fF +/- 15 fF.

Any change in parasitic as a result of aging of the extracted flux medium to an equivalent of one-year floor life was determined to be negligible.

Introduction

No-clean flux residue—which appears as a white translucent solid substance – remains on the surface of a printed circuit assembly after the no-clean paste is reflowed. Flux residue between microstrips has been shown to induce parasitic capacitive coupling, which changes transmission characteristics, between these signal paths.[1]

Using a microstrip directional coupler as a test circuit, a method for measuring stray capacitance due to flux residue at frequencies up to 4.8 GHz has already been demonstrated to industry. Coupling shifts have been shown to be large enough to measure experimentally, even for stray capacitance on the order of 10 fF[2]

This paper investigates coupling effects due to residue up to a frequency of 7.15 GHz, compares two test vehicles for their sensitivity to electrical changes due to residue, and explores the effect of aging on residue-induced parasitic. When exposed to temperature and humidity, both the flux remaining on the assembly after activation and the by-product of the fluxing process have been found to produce increasing amounts of residue with time.[3]

Test Vehicle Design

The test vehicle was designed on Rogers 4350 substrate with an electroless Ni/immersion Au finish. The 2-layer test vehicle board with 30 mil core and ½ oz copper on the surfaces was not expected to undergo significant variation as a result of exposure to assembly processing

Two bi-directional couplers, “coupler A” and “coupler B”, each with 50 ohm characteristic impedance and 6mil gap, were evaluated and compared. An SMA connector was used in conjunction with a snap-on connector interface system in order to reduce the amount of manual effort required to attach and detach the cables to the network analyzer. Two 50-ohm terminators were connected to the otherwise open ends of the couplers while under test.

The test vehicle included a solid ground plane on the bottom surface, and a partial ground plane on the top surface. In order to provide minimal inductance between the ground plane and the ground pins of the connector, the ground plane on the top surface did not include thermal relief to the connector pins.

An ½” thick solid brass plate was attached to the bottom side of the coupon to allow for increased stability, although anecdotal evidence suggests that these may not have been necessary. A picture of test coupon “coupler A” with the connectors, terminators, snap-on interface and brass plate attached is shown in Figure 1.

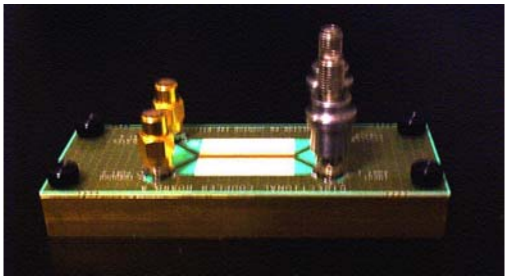


Figure 1 – Test Vehicle " Coupler A"

Because the coupling was measured in transmission, the measurement was not expected to be sensitive to stray capacitance outside of the coupler.[2] Indeed, simulations performed early in the design of experiment predicted a strong effect of capacitive coupling between the two lines of the bi-directional coupler and a weak effect due to coupling to ground due to residue present at or under the connector. Therefore, the effect of any variation in capacitive coupling at the connector from sample to sample was not expected to mask the effect of residue at the center of the couplers.

The connectors were attached using standard reflow processes and washed after connector assembly. After all the boards were washed, testing for ionic contamination was performed at the site of the bi-directional coupler in the area local to the intended residue deposit on a random sample of five test coupons.

Electrical Test of "Clean" Test Vehicles

A flow chart of the experimental plan is shown in Figure 2.

Before no-clean flux material was applied, measurements were made of the frequency response of the bi-directional couplers. The highest null of the frequency response was chosen as the variable to be measured. For Coupler A and Coupler B, this frequency was called NullA, and NullB, respectively. Nulls were chosen over lobes because of their sharp, more singularly identifiable location. Frequency was preferred over amplitude for two reasons: First, amplitude was more sensitive than frequency to shift in calibration. Also, as shown in Table 1, the standard deviation of the amplitudes were a greater proportion of the measured value than were the standard deviations of the frequencies.

Table 1 - Comparison of Frequency and Amplitude Measurements

Residue from paste…	Sample size	Ratio Std Dev:Mean	
		Frequency	Amplitude
None ("clean")	30	0.002	0.062
A	28	0.002	0.027
B	28	0.003	0.024
C	28	0.004	0.025
D	28	0.004	0.028
E	27	0.003	0.025

Frequency response was measured using a network analyzer. In order to facilitate testing, a snap-on interface was attached to the ends of the cables to allow for them to "snap" onto, rather than "screw onto", the coupon connectors. In order to minimize the distortion due to the snap-ons, the network analyzer was calibrated with the snap-ons attached. As a result, snap-ons were not a part of the device under test.

A photo of coupon A attached to a brass plate, with snap-ons and terminators is shown in Figure 1. For a random sample of 30 coupon A's, the mean value of NullA was 7.147 GHz, with a standard deviation of 0.014 GHz. For a random set of 15 clean, un-aged Coupler B coupons, the mean and standard deviation of NullB was 6.678 GHz and 0.008 GHz, respectively. These values for coupler A and coupler B are presented in Table 2 and Table 3, respectively.

Flux Residue

Five no-clean solder pastes were investigated and for the purpose of this paper are coded as Paste A through Paste E. All materials were consumed within their expiry date, which was taken to be the date on the manufacturer's label on each of the jars of paste.

The flux medium was centrifuged from the no-clean pastes and deposited with an automated dispenser onto the bi-directional couplers at the center of the bidirectional coupler between the traces. There was a difference in the viscosity of the extracted flux medium from the various no-clean paste products. Therefore the machine was re-calibrated before each new material was dispensed in order to achieve the most repeatable amounts. In all cases, the weight of material dispensed was on the order of one-half of a milligram. Based on calibration data, the weight of the material and its variation is given in Table 4.

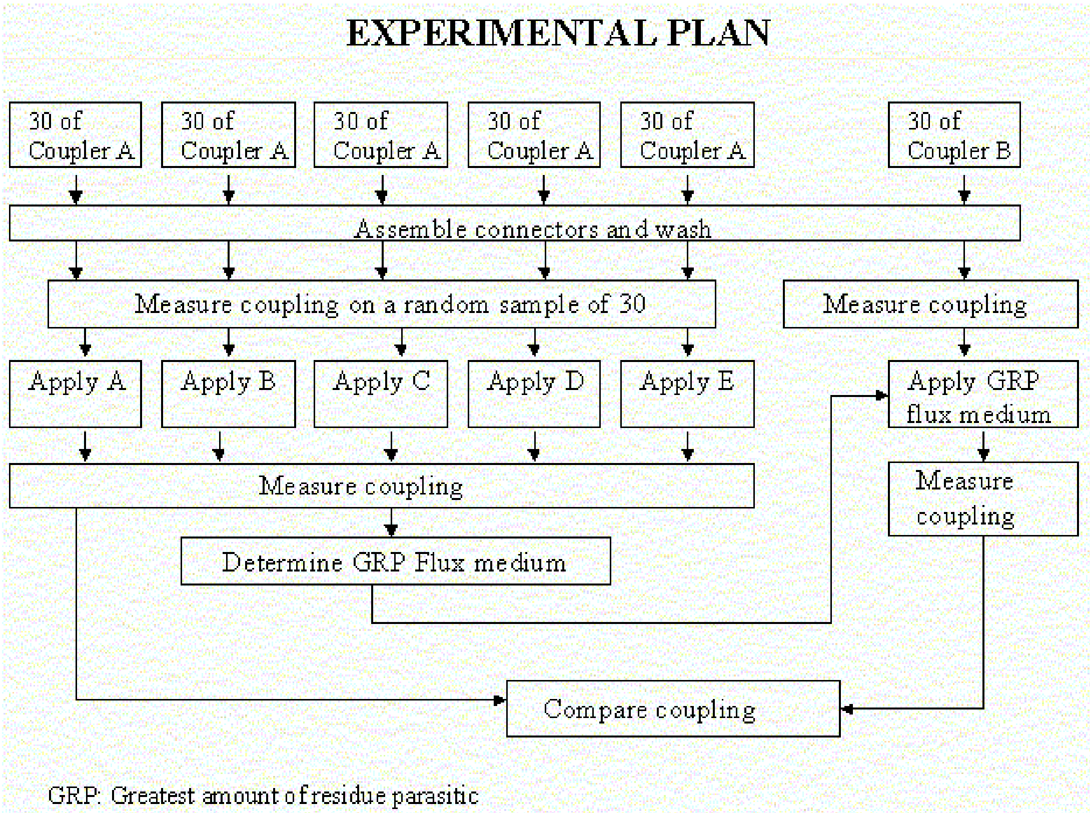


Figure 2 – Experimental Plan

Table 2 - Electrical results for "Clean" Coupon A and Coupon A with Residue Before and After Aging

Residue from paste…	Mean	Std Dev	Sample size	t-test against "clean"	t-test against "unaged"
None ("clean")	7.147	0.014	30	Not applicable	Not applicable
A	7.122	0.016	28	<u>6.415 *</u>	Not applicable
B	7.096	0.023	28	<u>10.254 *</u>	Not applicable
C	7.085	0.031	28	<u>9.929 *</u>	Not applicable
D	7.086	0.030	28	<u>9.976 *</u>	Not applicable
E	7.097	0.023	27	<u>10.083 *</u>	Not applicable
A aged	7.114	0.016	15	<u>7.101 *</u>	1.516
B aged	7.086	0.014	6	<u>9.637 *</u>	0.944
C aged	7.082	0.022	15	<u>12.023 *</u>	0.3
D aged	7.083	0.030	15	<u>9.835 *</u>	0.287
E aged	7.082	0.023	15	<u>11.539 *</u>	2.029

*** Underlined values for t-tests that indicate populations are different**

Table 3 - Electrical Results for "Clean" Coupon B and Coupon B with Residue Before and After Aging

Residue from paste…	Mean	Std Dev	Sample size	t-test against "clean"
None ("clean")	6.678	0.008	15	Not applicable
C	6.669	0.021	15	1.621
C aged	6.668	0.019	15	1.843

Table 4 – Electrical Effects of Residue and Weight of Dispensed Flux Medium

	Weight Dispensed		Rank order of…	
Residue from Paste…	Mean (mg)	St Dev (mg)	Weight	Electrical effect of residue
A	0.47	0.07	2	5
B	0.41	0.12	5	3
C	0.45	0.052	4	1
D	0.46	0.09	3	2
E	0.52	0.055	1	4

After the flux medium was dispensed, samples were reflowed according to a combination of Celestica guidelines and the suppliers' suggested profile for each no-clean solder paste. Manufacturing process parameters can vary the characteristics of the flux residues created[4]. The variables of significance are length of preheat and preheat temperature. These need to be set such that the flux has enough time above activation temperature to activate and dissipate without subsequent oxidization of the solderable surfaces before the formation of solder joints. At the flux activation temperature, flux breaks up any oxides on the metallic surfaces. At temperatures that are too high, severe corrosion will occur. At temperatures that are too low, any remaining flux will not evaporate. The resulting profiles adhered to the suppliers' recommendations within the preheat/flux activation stage.

Effect of Residue on Coupler A

Measurements were made of the frequency response of the bi-directional coupler A after no-clean flux material was applied. The results are given in Table 2. All of the samples demonstrated a statistically significant difference at the 95% confidence level, as indicated by the t-test results. Note that the sample sizes in some case were less than the initial 30; this is because some connectors broke off due to the stiffness of the network analyzer test port cables.

The no-clean flux material from Paste C caused the greatest shift in average frequency for NullA compared to "clean" coupler A's. For this reason, Paste C was identified as the one creating the greatest amount of residue parasitic (the "GRP paste"). The difference between the average of the 28 samples with the extracted flux from Paste C and the average of the 30 "clean" samples was 62 MHz.

As shown in Table 4, the weight of dispensed flux medium was on the order of one-half of a milligram for all of the pastes. However, due to differences in viscosity between flux mediums of different paste products, there was some variation in dispensed weight from one paste's flux medium to another. However, as Table 4 indicates, differences in dispensed weight between the products cannot explain the change in parasitic induced by the residue. The residue of paste C created the most amount of electrical parasitic but was neither the highest nor the lowest weight of dispensed flux medium.

Electrical simulation was performed using AWR's Microwave Office. The model of the bi-directional coupler A is shown in Figure 3. The effect of the connectors, which are part of the device under test, were modeled in the feed subcircuit. The residue was modeled as a capacitor between the two parallel lines of the bi-directional coupler. The simulation model was sensitive to changes in the capacitive coupling that were on the order of femtoFarads.

The measured response was compared to the simulated results in order to identify how much parasitic capacitance was added as a result of the residue. The value of this capacitance was determined by modifying the value of the shunt capacitor until the placement of the null frequency of interest was at the same location in the simulated and measured results.

For "clean" coupler coupon A (i.e. without residue), the placement of NullA in empirical tests matched that in the simulated results when the simulation model included no capacitance at the center of the bi-directional coupler. A capacitor of 25 fF was successfully used to model the mean parasitic arising from the flux residue of Paste C; using a 25 fF +/- 15 fF capacitive coupling in the model, the same amount of shift was observed in the simulation as was observed by the measurements of flux residue of paste C on coupler A. The measured results from a "clean" coupler A, those from a coupler A with flux residue of Paste C, and the simulated results for coupler A with coupling from 0-100 fF are depicted in Figure 4 (a), (b) and (c), respectively.

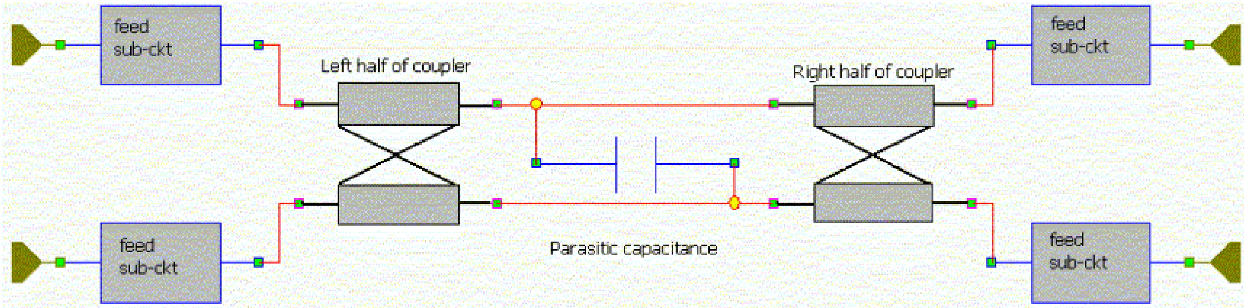


Figure 3 – Electrical Model of Bi-Directional Coupler A

Effect of Residue on Coupler B
The previous steps were repeated with coupler B using the material that resulted in the most amount of parasitic from the experiment with coupon A, namely the flux medium of Paste C. Fifteen (15) samples of coupon B was determined to be a sufficient number to test to 95% confidence level due to low variability in sample values.

Figure 5 (a), (b) and (c), respectively, shows the measured results from a "clean" coupler B, those from a coupler B with flux residue of Paste C, and the simulated results for coupler B with coupling from 0-100 fF. Table 3 lists the electrical results for NullB of coupon B. There was no statistically significant difference found at the P=0.95 confidence level, as demonstrated by the t-test results. Subsequent simulation results were consistent with this finding. The position of NullB was very stable and did not vary significantly with change to this parasitic, even when this was increased to 100 fF. Therefore, coupler B is not considered to be an effective test vehicle for determining parasitic in the 7GHz range.

Effect of Aging
Next, the coupons were aged to JEDEC Level2, which simulates a floor life of 1 year at <=30degrees C/60%RH. This involved soaking the coupons for 168 hours at 85 degrees C/60% RH [J-STD-020].

They were subsequently re-tested and no significant difference was found between the aged and un-aged sets of samples for either coupon. The results for Coupon A and Coupon B, and their t-test results, are given in Table2 and Table 3, respectively. The values of t which are underlined are those which are above the threshold and therefore estimate no significance between the populations compared.

Some of the aged samples of coupler A with residue from paste B were visually very different after aging, as depicted in Figure 6. Only 6 out of the 15 samples looked similar to coupons that were aged that had different no-clean paste residues on them. Only the 6 "typical good" looking ones were measured at the time of this study. Subsequent measurements indicate that there was no difference in results between "typical good" and the ones that were visually different.

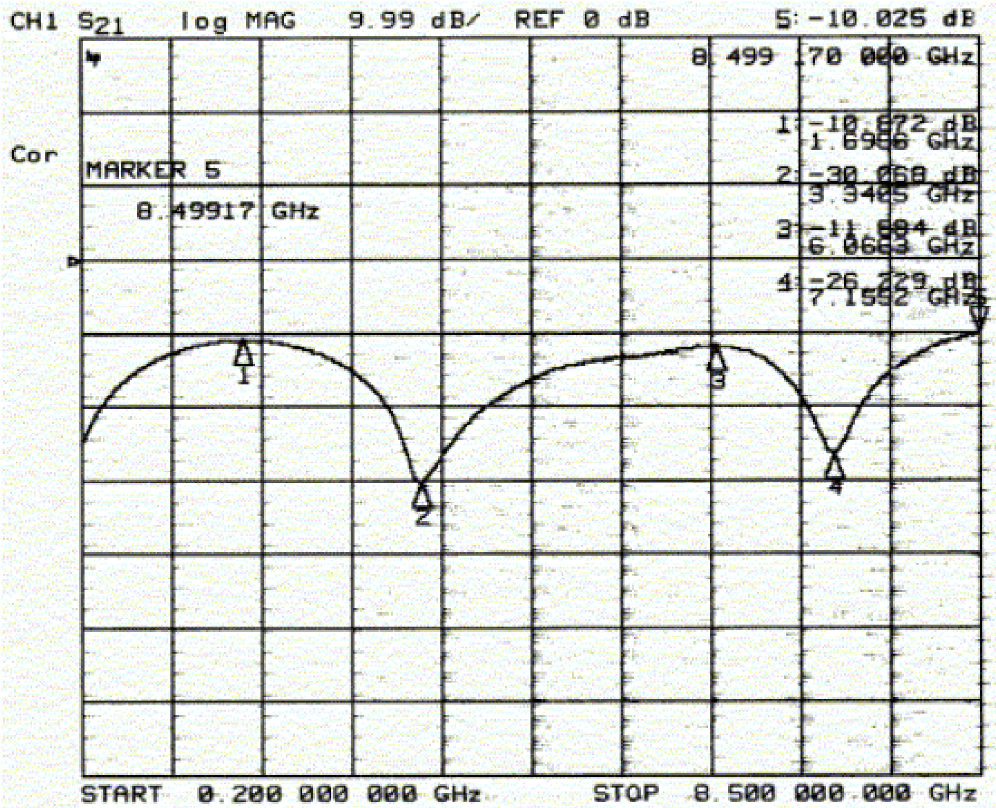
Alternate Method of Achieving Flux Residue
Another method of achieving flux residue was attempted but was abandoned in favor of the dispense method. Following the alternate method, paste was to be manually squeegeed onto coupon A at the site depicted in Figure 7 using a 4 mil thick, laser-cut stencil with appropriate apertures.

To most accurately model the residue feature as a lumped element at the center of the bi-directional coupler, the feature needed to be as small as possible compared to the coupler length. In particular, the ratio of the length of the residue deposit to a 1/4-wavelength of the maximum frequency of interest needed to be less than one, and as small as possible.For this study, 7.15 GHz was the highest frequency of interest. During the flux activation stage (i.e. reflow), the solder wetted to the trace and spread out from the location it was deposited to cover a length of 4 mm, which corresponds to approximately 1/6-wavelength. By contrast, the maximum length of the residue from dispensed flux medium was 3.3 mm, which corresponds to about 1/7-wavelength, and which would be acceptable for frequencies around 20% higher than the 4mm feature. The preferred method was the one that yielded the smallest feature length.

Also, the addition of solder on the coupler could increase the parasitic capacitance masking the capacitive effect of the residue, and could change transmission characteristics at the site.

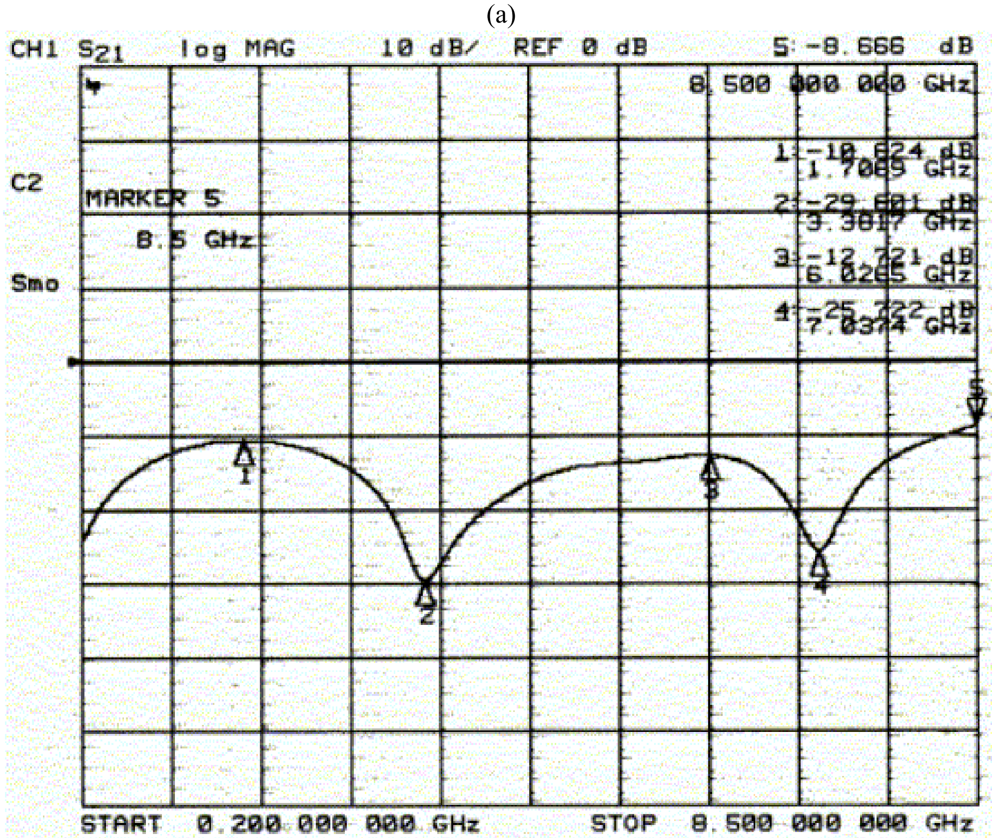
Another disadvantage of the stenciled method was that seepage of flux from the solder was relatively uncontrolled compared to that using the dispense method and so more variation (i.e. less consistency) in the quantity of flux residue between the gap would be expected.

For these reasons, the dispensed method was preferred over the using the stencil that was available.



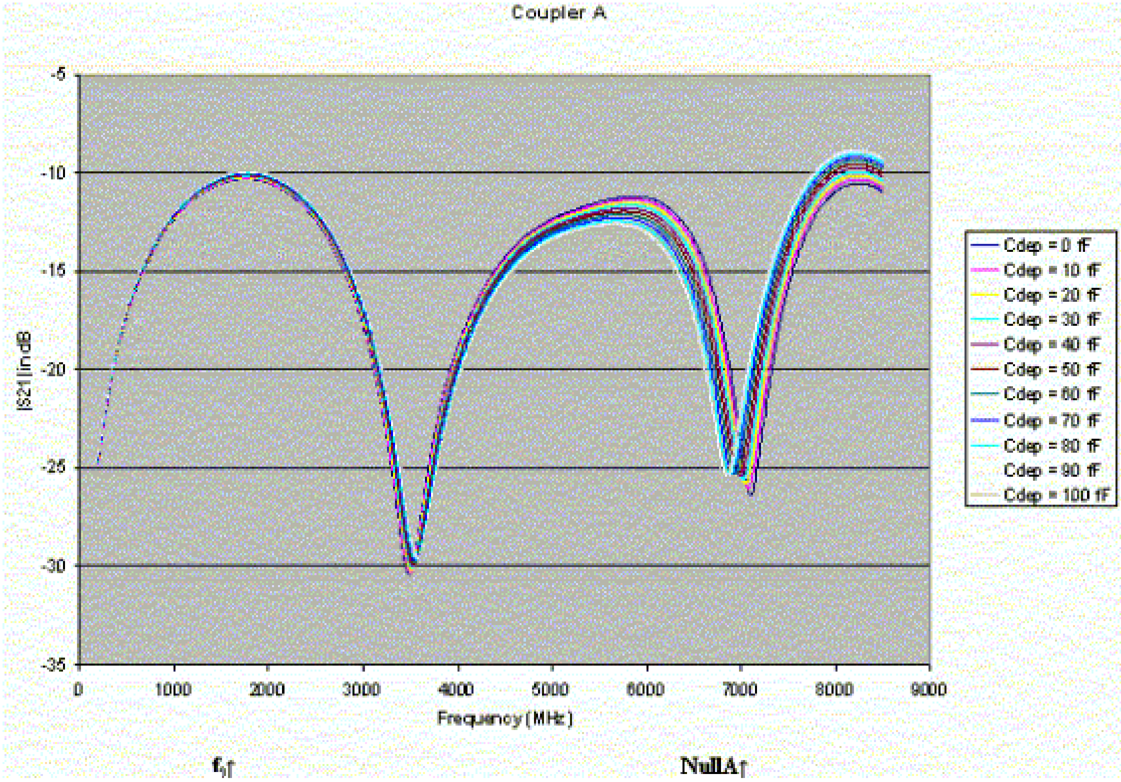
CH1 S21 log MAG 9.99 dB/ REF 0 dB
5: -10.025 dB
Cor
MARKER 5
8.49917 GHz
START 0.200 000 000 GHz
STOP 8.500 000 000 GHz

(a)



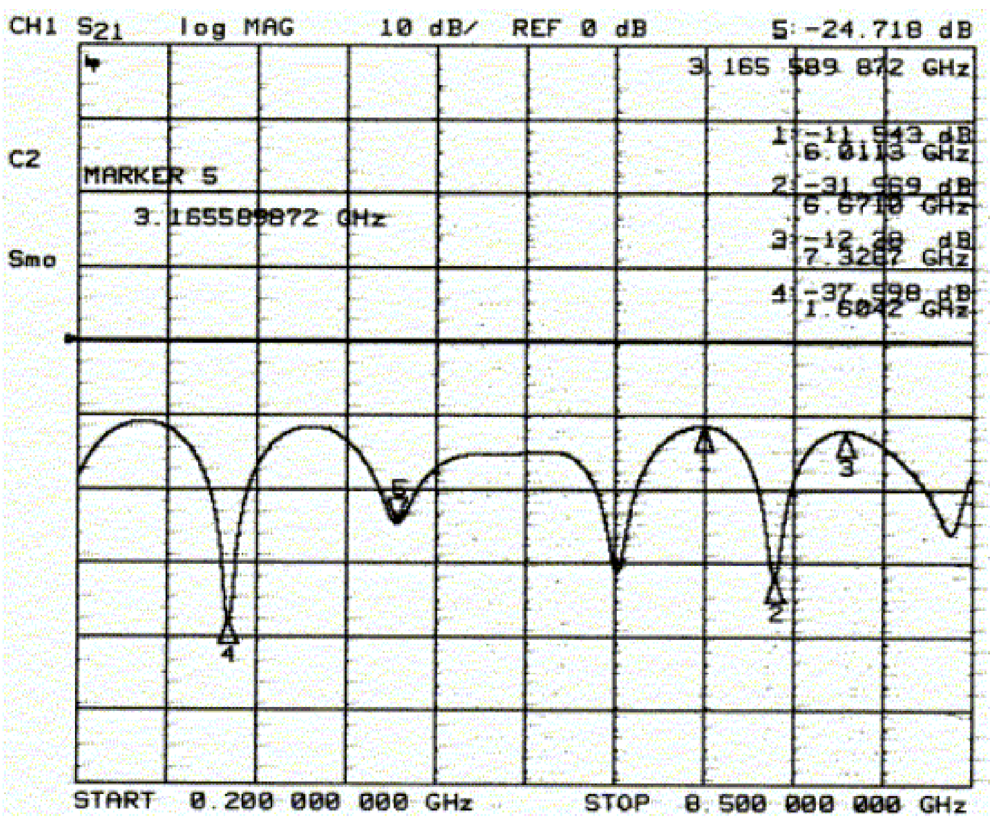
CH1 S21 log MAG 10 dB/ REF 0 dB
5: -8.666 dB
8.500 000 000 GHz
C2
MARKER 5
8.5 GHz
Smo
START 0.200 000 000 GHz
STOP 8.500 000 000 GHz

(b)

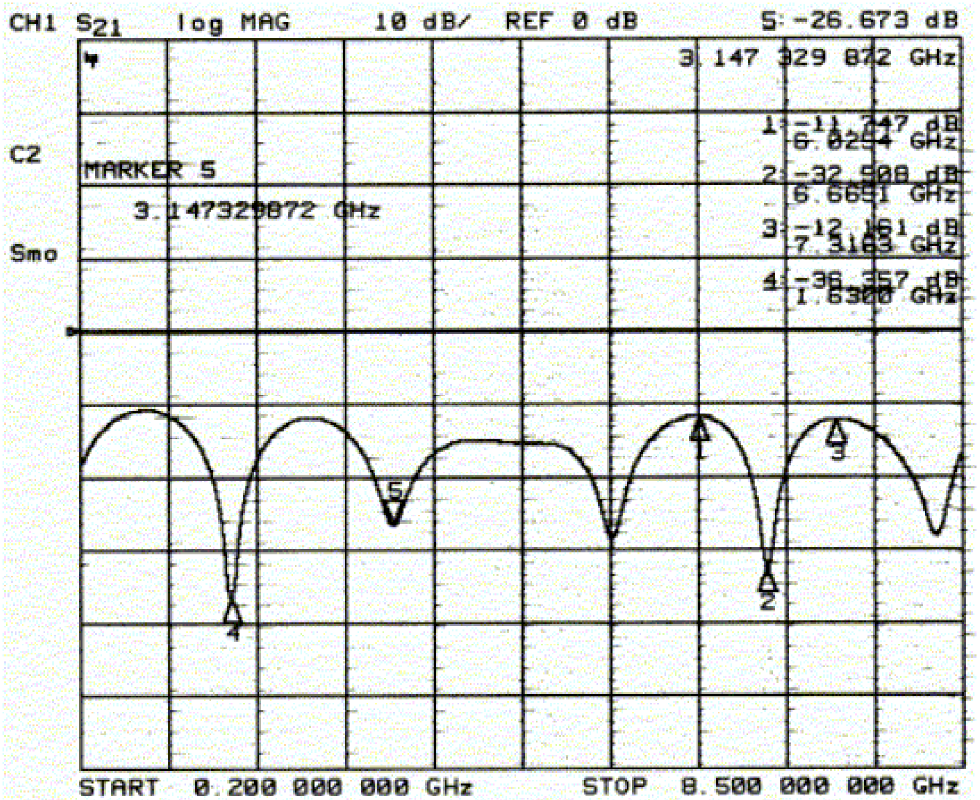


(c)

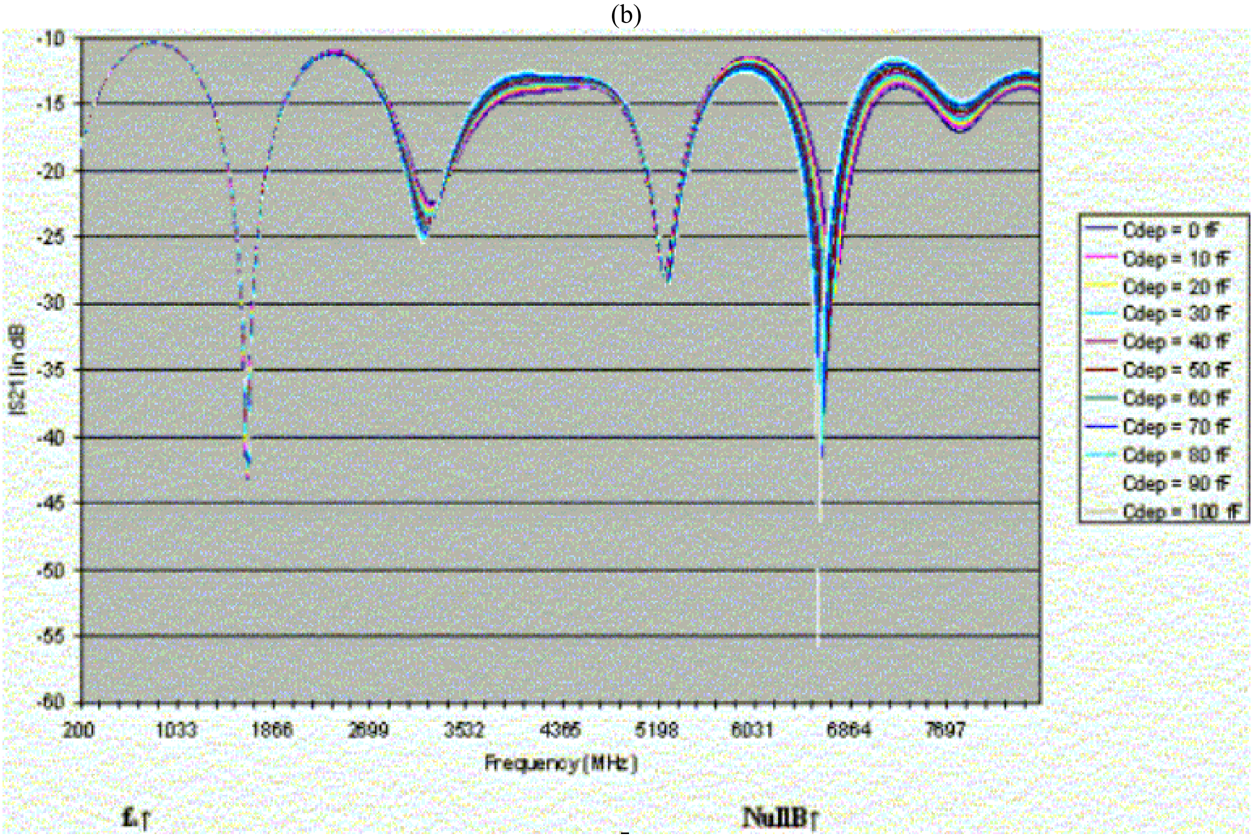
Figure 4 – Coupler (a) clean" (b) with Residue from Paste (c) Simulated Output



(a)



(b)



(c)

Figure 5 – Coupler B: (a) "Clean", (b) with Residue from Paste C, and (c) Simulated Output

Figure 6 – Darker Areas on the Traces Around the Central Dispensed Dot Occurs During Aging

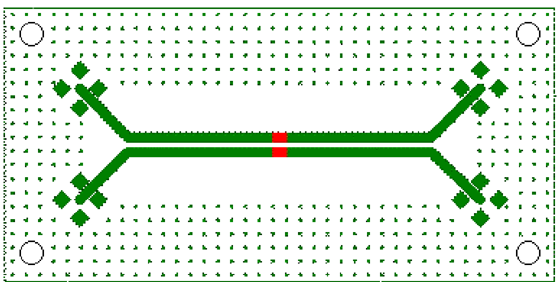


Figure 7 – Location of Stenciled Paste (Not Preferred Method)

Conclusion and Future Work

The authors have presented a simulation model for a bi-directional coupler with residue present that has been used for the work described herein to 7.15 GHz. The length of the bi-directional coupler model can modified in order to design other couplers would be sensitive to target frequencies of interest, such as those that are typically found on RF assemblies. This is planned for future work.

When performing this test, it is advantageous to make the null frequency be the variable of interest as opposed to lobe frequency or amplitude, because the former is a more sharply defined feature with comparatively low measurement error.

The procedure herein can be used to determine a value of capacitance that can be used during the design stage to test circuit robustness. Future work could be done developing models to predict the effect of increasing the gap between the traces of the bi-directional coupler, and of increasing the length over which the residue is present.

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