A microwave test fixture for measuring four-terminal passive components from DC to 10 GHz

The test fixture is an important element of accurate component measurement.

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In the past, most capacitor test methods were standardized for two-terminal passive component technology. To meet user demands for low inductance designs, passive component manufacturers have developed new, internal electrode arrangements as well as external termination configurations in passive components. One of these newly-developed configurations is a surface mount (SMT), four-terminal capacitor. The new passive designs exhibit broadband performance from kHz to GHz frequencies. Still, these advancements in component designs have themselves created challenges for accurate component characterization.

Our goal was to show the benefits of these advancements in a new passive design. Beginning with the early methods for testing a new four-terminal capacitor (Figure 1), our examination will progress to the development of a new microwave test fixture and a discussion of future test methods for multi-port devices.

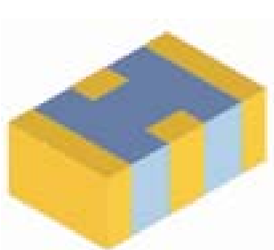

Figure 1. Four-terminal DUT.

FOUR TERMINAL DUT

Most of the discussion will focus on a capacitor called X2Y®[1] and a feedthru capacitor because the microwave test fixture described later was designed to measure these devices. A network of three standard two-terminal capacitors will serve as a comparison.

A quick overview of a feedthru capacitor and the X2Y capacitor show they are similar in external design. Both have four terminations at the same location on the exterior of the component body. Internally, both devices have a stack of parallel electrode plates that extend to both sides of the narrow aspect of the component body, where they are terminated. The feedthru capacitor has a second stack of parallel electrode plates that extend to both sides of the long aspect of the component body where they terminate. Here, the X2Y differs from the feedthru, having instead two stacks of parallel plates electrically isolated from each other and terminated separately on either end of the long aspect of the component body (Figure 2). The X2Y is a bypass device, while the feedthru capacitor is designed to carry the line current as its name implies.

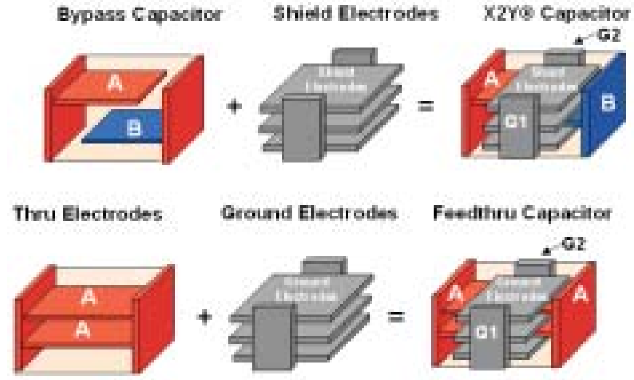

Figure 2. Internal electrode comparisons.

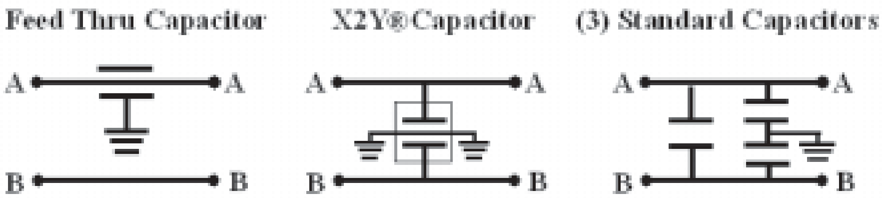

Figure 3. DUT Schematics.

Another significant difference between the two devices is their use in a circuit. A feedthru capacitor is an unbalanced single-ended device operating in common mode. The X2Y capacitor is a balanced device[2] with two approximately equal halves that can operate in both common and differential mode and is therefore often compared to an equivalent circuit of three discrete capacitors configured in an "X" and two "Y" capacitor network (Figure 3).

A product application was the first test method employed to demonstrate the benefits of the new device.

TEST METHOD 1: APPLICATION TESTING

Small DC motors used in automobiles were chosen because the automotive industry is imposing strict emissions requirements on these electrically noisy devices. A motor with the component installed would become the device-under-test (DUT), and a radiated emissions test was performed in a GTEM (gigahertz transverse-electromagnetic) chamber to obtain "before and after results" for the whole system. GTEM cells show good correlation to open-area test sites (OATS) for frequencies from 150 kHz to 1 GHz.[3]

The process began with baseline measurements of the radiated emissions from a DC motor with the standard filter components. The standard filter components were then removed from the motor and a prototype motor was mocked-up with a single X2Y component. The motor was then re-measured in the chamber to record the difference in radiated emissions. Once testers were satisfied with the prototype performance in the GTEM chamber, the motor was sent to a certified test chamber for measurement to customer specifications. In this manner, correlation points to the various test specifications were soon established in the GTEM cell.

Radiated Emissions Data

In a previous paper,[4] a single X2Y component was shown to replace up to seven filter components being used in DC motors to meet EMC requirements (Figure 4).

The test results quantified the effect on the DUT but not the performance of the device itself. Important information was learned from this process that helped guide future testing:

- The filter devices replaced by this single component were designed for both differential and common mode filter performance. Ideally, a testing method to measure DUT performance in both modes would eventually be developed.
- Independent testing by motor OEMs with the component inside showed effective filtering to 3 GHz. Clearly, a test isolating the effect of the device alone would be challenging because of its broadband performance.

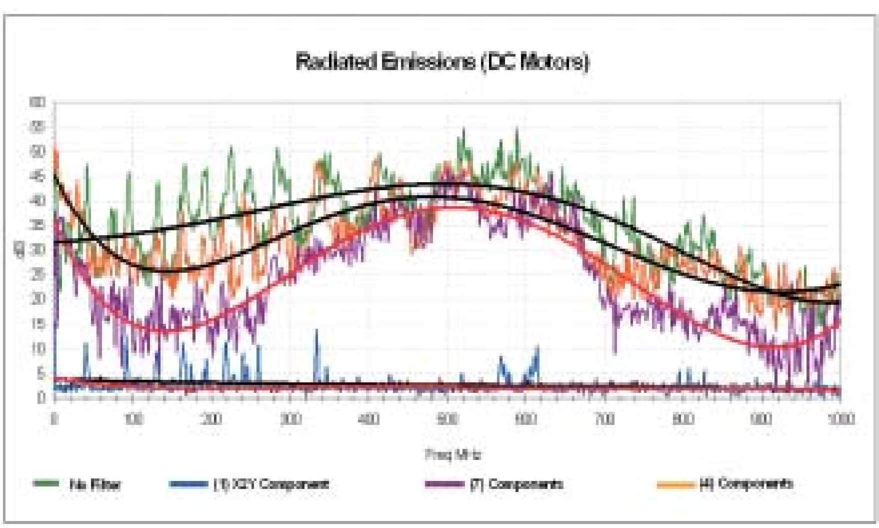

Figure 4. Radiated emissions for small DC motors, filter comparisons.

TEST METHOD 2: DUAL-LINE TESTING

The next test method employed a self-made test jig configured for dual-line testing (Figure 5). This arrangement was chosen to simulate the most common application of the DUT. The test system included a spectrum analyzer, power divider, test jig, and a current probe to measure the common mode noise attenuation on a transmission line (Figure 6). The tracking generator inside the spectrum analyzer was used as the noise source.

Figure 5. Dual-line test jig.

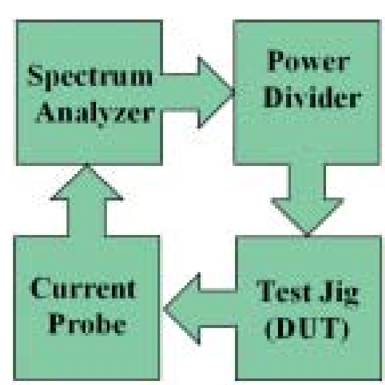

Figure 6. Test system block diagram.

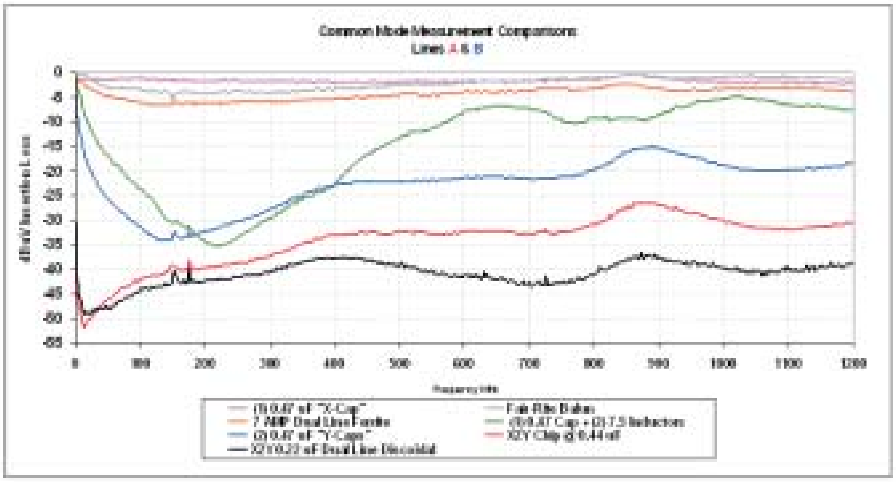

Figure 7. Comparisons of dual line filters.

At the time the test results were published in ITEM 2000,[5] there were no known existing test standards for dynamic testing of a dual-line filter. Rather than using a printed circuit board, dual transmission lines were constructed from coax wire. The coax wire allowed for a current probe to be clamped around each transmission line separately or around both lines simultaneously. Common mode insertion loss from the single four-terminal component could be measured, and comparisons against various filter devices could also be made.

Dual-Line Test Data

Conclusion from Data – The data showed that a single X2Y four-terminal component significantly outperformed the various filters to which it was compared (Figure 7). However, the test system had some limitations to showing the full benefits of the component:

- A spectrum analyzer limits the calibration to a throughput baseline of the total system, a figure that often includes the parasitic effects of the power divider, test fixture, *etc.*
- Measurable bandwidth was only 1.2 GHz, far short of the DUT capability.
- Using a self-made jig rather than a printed circuit board test fixture prompted some engineers to ask if the test results would correlate to application on a board.

The resulting test data served to fuel the demand for component use, and we proceeded on to more testing. At this time, two fundamental changes were made. Future testing would be done on a printed circuit board, and we would use a vector network analyzer (VNA) in place of the spectrum analyzer. We were fortunate at the time that one of our manufacturing licensees[6] had already begun testing components on a printed circuit board, and we were provided with six boards to jumpstart our own testing.

TEST METHOD 3: PC BOARD TEST FIXTURE

Using a printed circuit board as a fixture for R&D testing provides flexibility when measuring non-standard components. Board material is relatively low cost and layout can address many different DUT form factors and connection scenarios.

A PC test board was configured with two parallel traces on the top layer and a ground plane on the bottom of a 0.042" thickness board. A center land pad was located between the two parallel traces to accommodate the two side ground terminations of the four-terminal DUT. The center land pad was joined to the bottom ground layer by multiple vias to produce a low inductance connection to the bottom ground plane.[7] All ports were terminated with 50 ohms, either through the two measurement ports of an HP 8753E VNA, or by 50-ohm resistor end caps on the unused SMA connectors that were soldered to the board (Figure 8). A through measurement was used as a baseline prior to each DUT measurement.

The DUT comparison consisted of a single X2Y component vs. (3) discrete components configured in an equivalent (1) “X” and (2) “Y” circuit. It should be noted that equivalent capacitance values were used for the test. Because of the structural differences in the test circuit connections, the (3) discrete capacitors represent 33% more capacitance than the X2Y when mounted as a circuit on the PC board.

Two through measurements were conducted for each DUT (Figure 9). The first was made by connecting two of the board SMA connectors on trace A and A^1 to Ports 1 and 2 of the VNA, respectively. Then a second measurement was taken with the A and B^1 SMA trace connectors attached to Ports 1 and 2 of the VNA ports, respectively. With these steps, direct comparisons of the single X2Y could be made with the equivalent circuit of three discrete capacitors.

Figure 8. Printed circuit board test fixtures, attached to vector network analyzer.

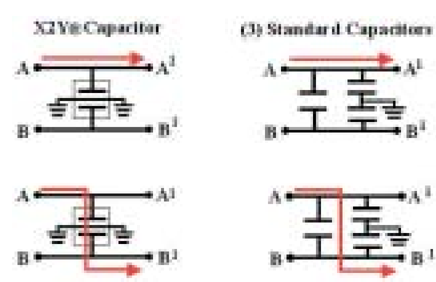

Figure 9. Depiction of measurement sequence.

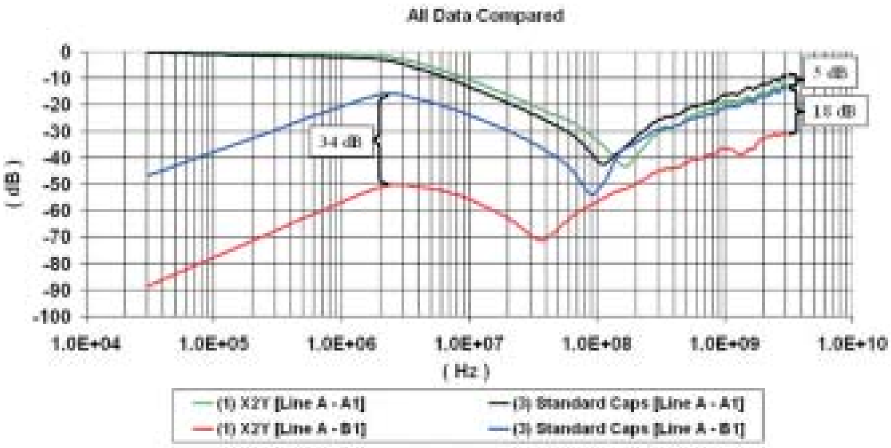

Figure 10. Comparison data, X2Y vs. discrete "X and 2Y" circuit.

PC Board Data

Conclusion from Data – The test on the PC board effectively highlighted the difference in the two circuits. There was a significant improvement in the differential performance of the X2Y capacitor as compared to the discrete circuit of three capacitors—consistent with the characteristics of a balanced device (Figure 10). There was simply not enough improvement in the X2Y's common mode performance to explain why so many standard devices could be removed when filtering the DC motors.

Clearly, further improvements in the test procedures were needed.

- A two port VNA was used for a board originally designed for a four port VNA.
- The PC board design had not been optimized. Testing by others on a coplanar substrate showed much better attenuation (less inductance) with a larger 1812 (0.180" x 0.120") size component past the self-resonant frequency.[8]
- The trace layout limited test components to 1206 or 1210 sizes. We needed to test both larger and smaller component sizes, a process which would require many more boards. Repeated soldering and unsoldering of components risked destroying the board integrity.

NEW CHALLENGES

Many segments in the electronics industry using capacitors rely heavily on CAD tools to model complex circuit boards prior to going to initial board build out. As part of that process, "S-Parameter" data for individual components are used to develop a simulation model of a device. S-Parameters are used to characterize high frequency circuits and are considered the "shared language between simulation and measurement."[9] To broaden our component usage in other industry segments, we would have to speak "their language."

A vector network analyzer with an S-Parameter option kit is used to measure signals reflected from, or transmitted through a DUT. The VNA has the internal instrumentation to source the signal as well as the sensitive receivers needed to detect the port response, collected in the form of signal magnitude and phase.[10] The test fixture is an important element of accurate component measurement but excluding the effects of the fixture from the final data is crucial. We needed to find a company with expertise in test fixture design and an effective pre-packaged test system.

TEST METHOD 4: ICM TEST FIXTURE

The search led to Inter-Continental Microwave (ICM).[11] ICM offers total measurement solution kits for many types of passive devices. One of their standard products is a surface mount chip component test fixture for measuring surface mount chip capacitors (single or multi-layered), inductors or resistors.

The fixture in combination with a VNA can be used to measure S-Parameters, Q, and Resonant Frequency characteristics of a DUT. A calibration kit is provided with each test fixture, which allows the tester to de-embed the component data using TRL/LRM or TOSL calibration standards.[9] This process excludes the effect of the test fixture from the DUT measurements.

Besides accurate calibration, other features overcame the limitations encountered in earlier testing:

- Solderless contacting, which allows repeatable, non-destructive testing with one board.
- Separate midsections for measuring different sized components (*e.g.*, 25 (0603), 40 (0805), and 80 (1206) mil gaps and larger). The midsections can be interchanged without disrupting the calibration.
- Match of materials chosen for the end application via input and output launches on microstrips.
- DC to 10 GHz performance capability.

At the time we approached Inter-Continental Microwave about a fixture for the X2Y component, the company had been in development of a test fixture specifically for feedthru capacitors. One of ICM's products is a series-thru test fixture for two-terminal capacitors. To make the new four-terminal fixture required a modification of their standard series-thru fixture (Figure 11). One main modification consisted of replacing "spacers," which are used to separate the microstrip launches (depend-

Figure 11. ICM four terminal surface mount test fixture.[12]

ing on the component size measured) with "midsections."

The midsection provides dimensional separation like the spacer it replaces and also becomes part of the circuit ground reference when clamped into the fixture main frame. The midsections also include electrical contact points with the side termination bands of the four-terminal DUT during measurement (Figure 12). The addition of the ground midsections to the series-thru test fixture produces shunt data for this type of DUT because of their internal construction.

ICM FIXTURE DATA

The DUT is clamped into the fixture by pulling down a handle, thus creating repeatable down pressure on the component body with a plastic pushpin inside the arm of the fixture. A second brass pushpin applies pressure to a spring-loaded contact on the midsection (shown in purple on Figure 13) to make contact with the side termination of the four-terminal DUT during measurement. The plots in Figure 14 are a reflection (s11) and thru (s21) of a feedthru capacitor. The s21 represents the insertion loss of the DUT.

The plots in Figure 15 show the reflection (s11) and thru

Figure 12. ICM midsection with side contacts.

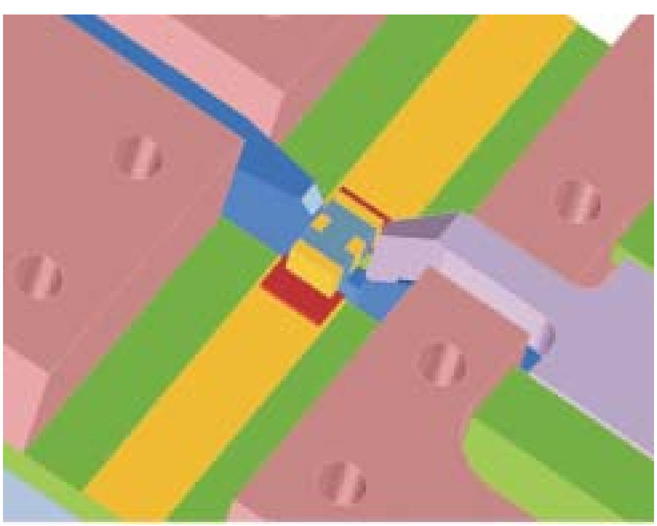

Figure 13. Midsection in fixture for DUT measurement.

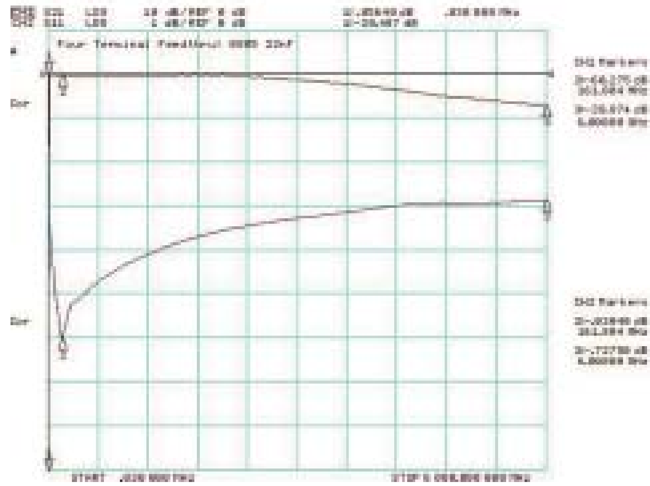

Figure 14. Feedthru capacitor measurement (s11, s21).

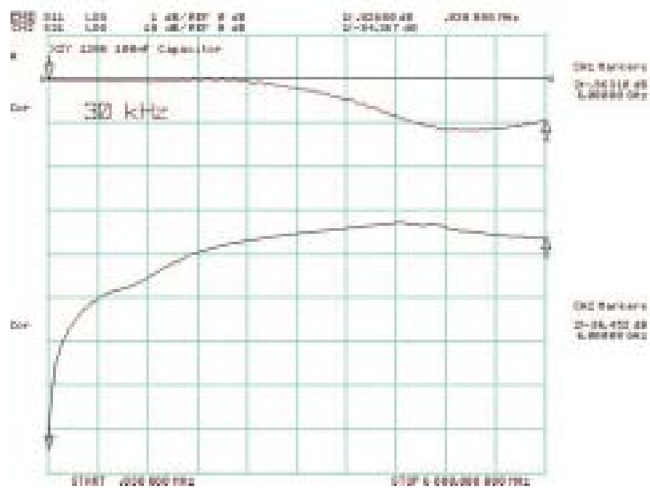

Figure 15. X2Y capacitor measurement (s11, s21).

Figure 16. X2Y capacitor, balance measurement (s11, s22).

(s21) of the X2Y device. The s21 shows the insertion loss and also represents either crosstalk attenuation or differential decoupling for this DUT.

Although the fixture is designed for single-ended measurements, taking s11 and s22 measurements can show the two halves of a balanced capacitor (Figure 16). This data further confirmed the static capacitance measurements we had made on components, including typical capacitance tolerances of 1 to 3% on the two internal Y caps of the device.

We had requests to measure the common-mode performance of the component so that the pass function could be identified for filter applications. This identification required changing the midsections and rotating the component 90 degrees to make two more thru (s21) measurements. We could then see the attenuation of two-Y caps to ground or a single-Ycap to ground. A typical performance plot of X2Y in this fixture will show three responses (Figure 17).

We were fortunate in that three fixtures measured X2Y components at different locations with similar VNA equipment while the S-parameter data correlated among the different locations. We had an opportunity to check for measurement repeatability with our own fixture when asked to re-measure the 3-dB roll off points of the same component. Two TRL calibration procedures were conducted approximately two days apart (VNA setting, points/1600, IF Bandwidth/100Hz, frequency span/30 kHz to 100 MHz). The test results showed a high degree of repeatability considering the mechanical factors involved with a measurement (Figure 18).

FUTURE TEST METHODS

The current ICM test fixture is designed for single ended measurements. The four terminal X2Y is a balanced device that can operate in multiple modes. Multi-port testing of balanced devices is progressing rapidly. New test fixtures and vector network analyzers[13] are emerging to fill the need for accurate device characterization.

One example of such a test fixture might consist of a four-piece system that when assembled would provide the test bed for the DUT. The sequence of pictures in Figure 19 shows the placement of the DUT with the bottom picture showing two sections pulled apart (probe attachment not shown). This system is designed to make calibration with a 4-port network analyzer possible because each port can be connected to any other port for the thru-calibration. With this fixture, all DUT port responses could be measured when stimulated with a common or differential mode signal.

CONCLUSION

A series of test methods were used in an effort to characterize a new four terminal capacitor design. Each new method created the need for further testing. The trial-and-error experience from early testing helped define and lead us to a new microwave test fixture.

We met our immediate goal of producing accurate repeatable S-Parameter data on the X2Y component. A new

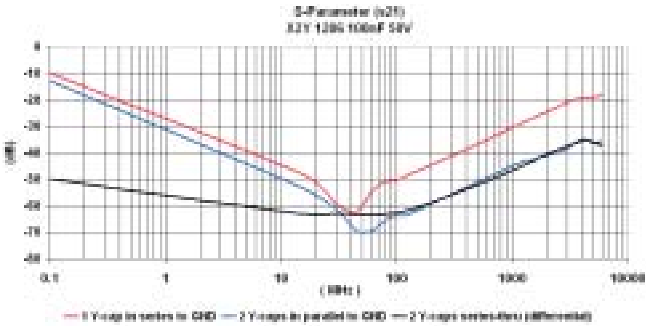

Figure 17. X2Y capacitor, balance measurement (s11, s22).

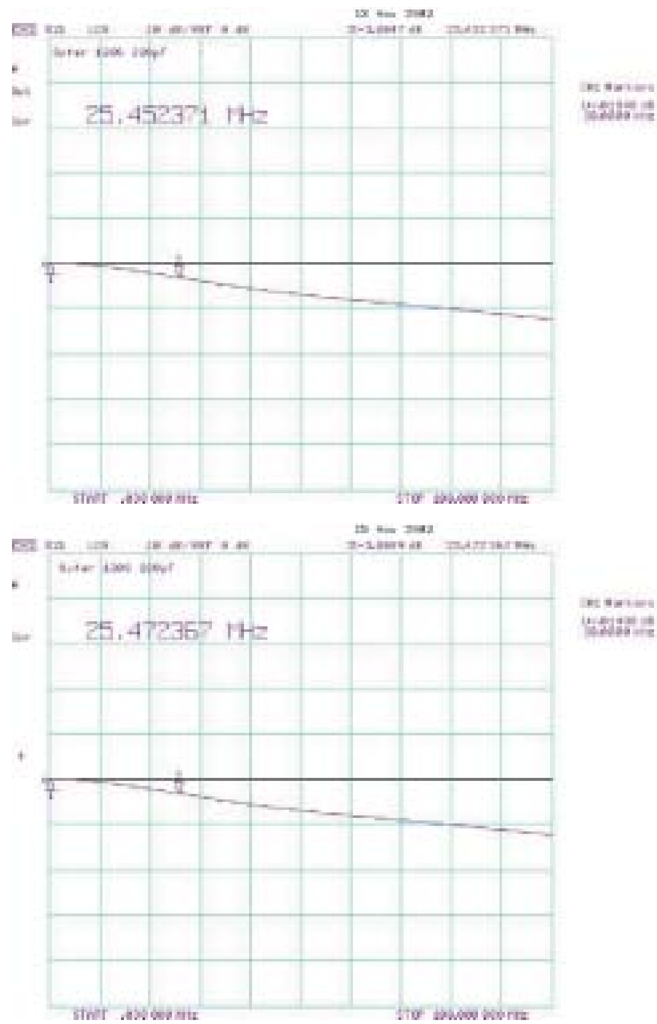

Figure 18. Repeatability data.

SPICE model has been developed[14] based on the S-Parameter data generated in the ICM fixture. Design progress will not end here; we are already looking forward to future fixture designs now in development as we strive for full and accurate component characterization.

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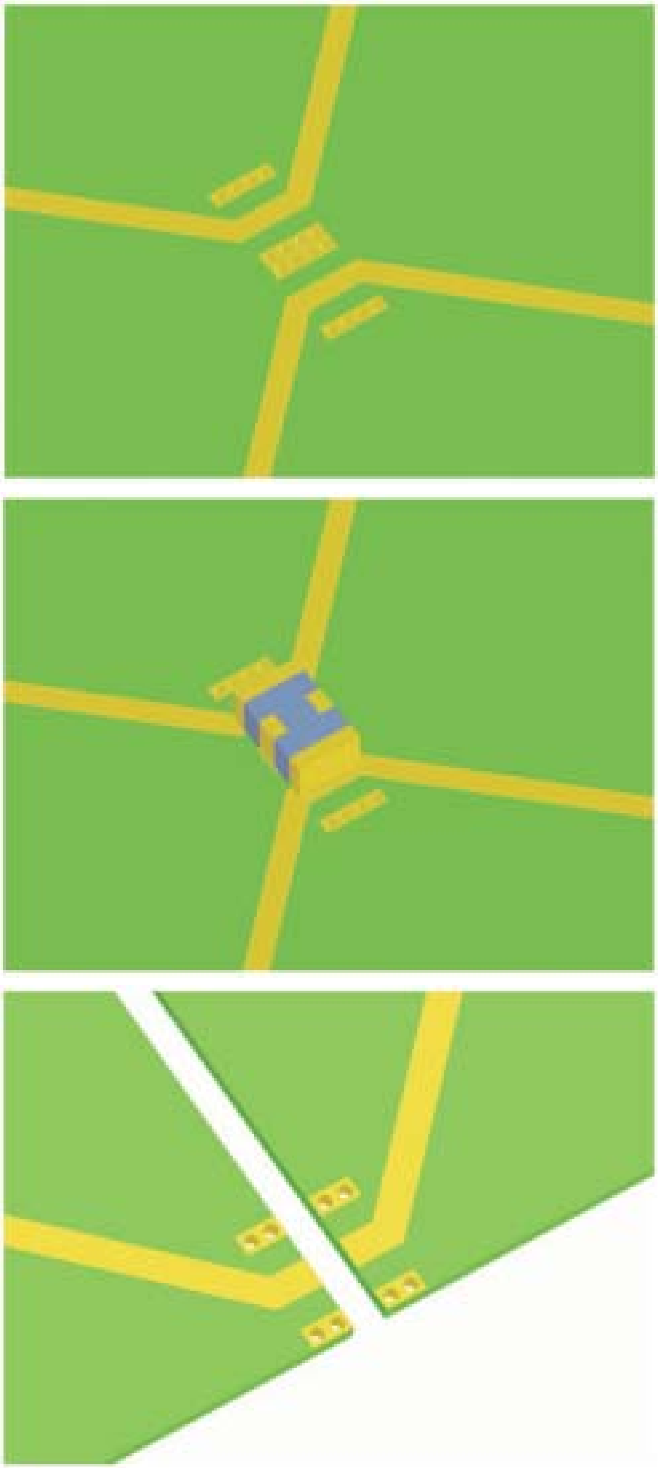

Figure 19. Future test fixture design.

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