A SPICE model for a capacitive circuit from kHz–GHz

A new approach significantly reduces parasitics at high frequency.

JAMES MUCCIOLI AND DALE SANDERS
X2Y® Attenuators, LLC
Erie, PA

BART BOUMA
Yageo/Phycomp
Roermond, The Netherlands

THIS ARTICLE PRESENTS A NEW CONCEPT IN broadband filtering and decoupling. At high frequencies, traditional discrete components are significantly limited in performance by their parasitics, which are inherent in the design. For example, a standard capacitor is capacitive until reaching self-resonant frequency (SRF); beyond that point, it becomes inductive. The inductive parasitics degrade circuit performance and are undesirable in filtering and decoupling applications.

Capacitors with an innovative internal architecture dubbed X2Y® are a new approach that significantly reduces parasitics at high frequency. The behavior beyond SRF is coaxial—a factor which significantly lowers the inductance.

INTRODUCTION

To understand the source of the coaxial effect, an understanding of the component's physical structure is needed. A standard bypass capacitor consists of alternating electrode plates that are attached to opposing end terminations.[1] X2Y technology combines the standard bypass capacitor with a parallel reference electrode structure, similar to a Faraday cage. This structure isolates end terminals, A and B, and adds two new side terminations known as G1 and G2 (Figure 1).

Figure 1. X2Y component's structure is made up of a bypass capacitor in conjunction with reference electrode structure.

The parallel reference electrodes divide an unbalanced, single-ended capacitor into a symmetrically balanced capacitive circuit with two co-actively balanced potentials in each half of the structure. Typically, X2Y components have a tolerance of 1 to 3% or less (Figure 2). Testing has shown that balance is maintained over temperature and time (aging) because of the shared dielectric.

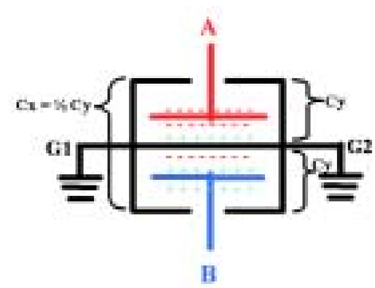

Figure 2. The reference electrodes create two tightly matched potentials.

To demonstrate symmetry and balance, a vector network analyzer (VNA) and a microwave test fixture are used to make s11 and s22 (reflection) measurements from 30

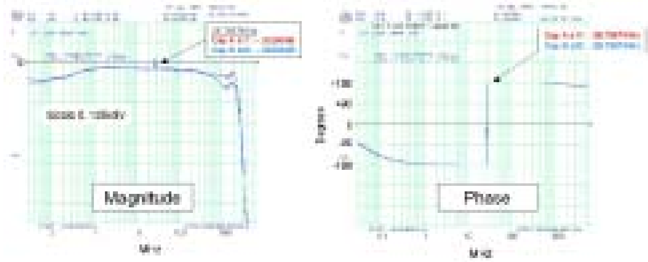

Figure 3. *s11 and s22 (reflection) measurements from 30 kHz to 6 GHz show X2Y is tightly balanced component.*

kHz to 6 GHz. Figure 3 shows the measured magnitude and phase plots.

The X2Y architecture can be compared to a dual rectangular coaxial structure that was studied and modeled by the National Institute of Standards and Technology (formerly the National Bureau of Standards).[2] The internal reference electrodes form a non-homogenous shield separating each active conductor (A and B). At high frequency, the unwanted noise chooses the path of least impedance, that is the reference electrodes. Since the reference electrodes are between opposite conductors and are attached in parallel, an image plane[3] effect occurs. Common-mode and differential-mode noise cancel within the component because of the balance and symmetry of the structure. Figure 4 illustrates the in-

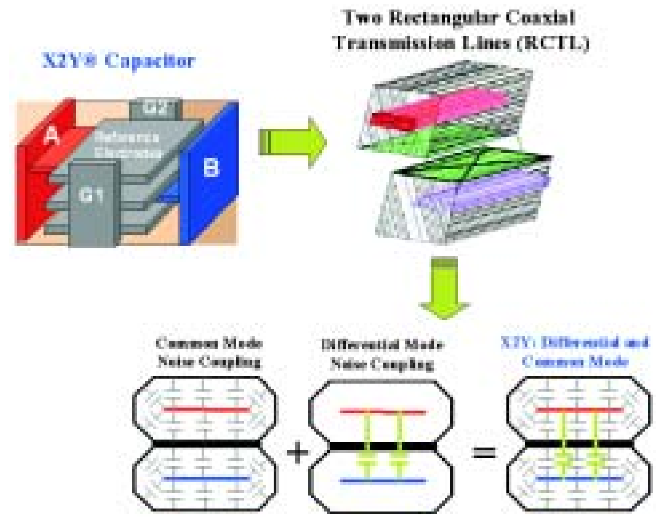

Figure 4. *X2Y can be thought of as a dual rectangular coaxial structure. Because of this structure, X2Y filters common-mode and differential-mode noise.*

ternal coupling of common-mode and differential-mode noise current that cancels.

INTERNAL ANALYTICAL MODEL

In addition to the transmission line effect and internal cancelling, another example illustrates the aptness of using the dual rectangular construct to explain the efficacy of this unique architecture. Consider the circuit and resulting current loop in Figure 5. As current flows in a closed loop, a magnetic field is created on the conductor and ground plane. The strength of the magnetic field is proportional to the rate of change of the current (di/dt). The higher the frequency, the stronger the field and the more easily it radiates.

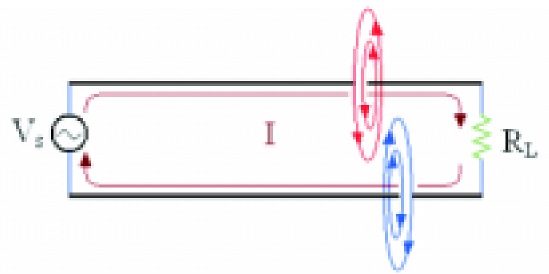

Figure 5. *Simple circuit showing magnetic fields created by current flow.*

Using the right-hand-rule, the direction of the magnetic fields on the conductor and the ground plane take opposite directions. Mutual inductance occurs when these fields overlap or couple onto each other.[4] Since the magnitudes of the fields are equal with opposite polarities, the magnetic fields cancel each other. Mutual inductance is directly proportional to the current loop area between the conductors. As the area is minimized, mutual inductance increases causing a greater amount of canceling. Figure 6 highlights the contrast between the unique X2Y architecture and the current loop of a standard capacitor.

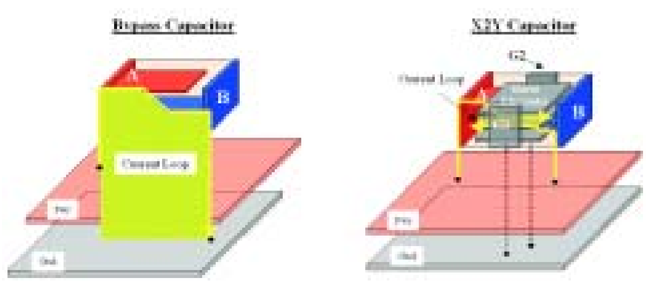

Figure 6. *Current loops of a standard bypass capacitor and an X2Y capacitor.*

Now consider a coaxial cable connected as shown in Figure 7. Mutual inductance is utilized to cancel high frequency noise. A coaxial cable is a conductor within a braided shield. The shielding effectiveness is the cut-off frequency ω_c. If the frequency becomes five times greater than ω_c, the braided shield becomes a lower impedance return path back to the source. The high frequency current is returned onto the shield;[5] and because the area between the conductor and the shield is small, the high frequency current (noise) cancels.

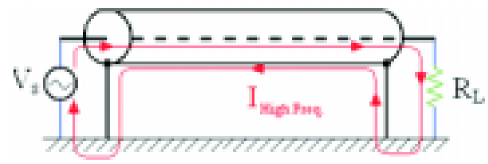

Figure 7. *High frequency current flow in a coaxial cable.*

Next consider two coaxial cables with shields (non-ideal or non-homogeneous) that are welded together and attached to a ground plane at two points (Figure 8). "A" represents the current direction of a signal to a load, and "B" is the signal's return from the load to the source. The distributive electric field (E-Field) along the structure is depicted by the capacitors.[6]

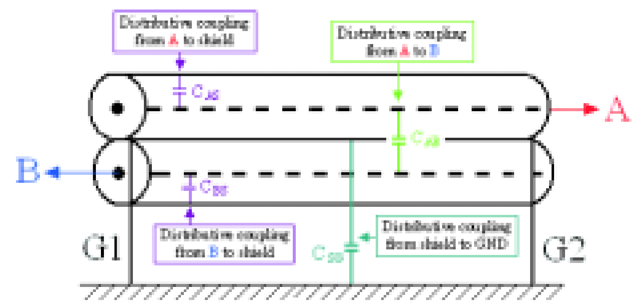

Figure 8. *The parasitics of two coaxial cables are similar to the parasitics of X2Y.*

Figure 9 is a schematic representation of Figure 8 using non-ideal capacitors and lead parasitics for G1 and G2. Assume that the magnetic field (H-Field) is incorporated into the inductors of the non-ideal capacitors.

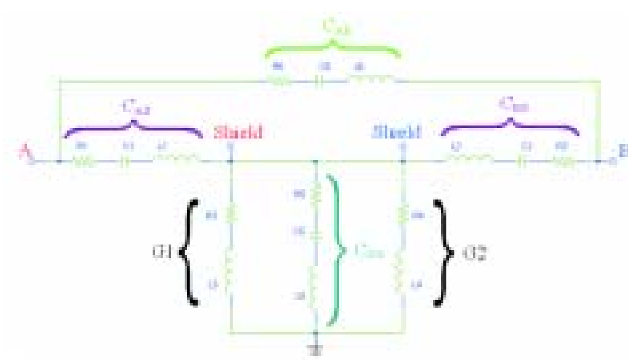

Figure 9. *Schematic of the internal parasitics of X2Y.*

The schematic model in Figure 9 can be used as a general representation of the dual rectangular coaxial structure mentioned earlier. This construct provides an internal model of an X2Y component at high frequency. To simplify the model, five assumptions can be made that reflect actual component behavior.

1. The reference electrodes (Figure 10) are non-homogenous, thus allowing coupling between the A and B electrodes (C_{AB} in Figure 9). **Note:** Figure 10 depicts a seven-layer structure for additional magnetic flux containment.

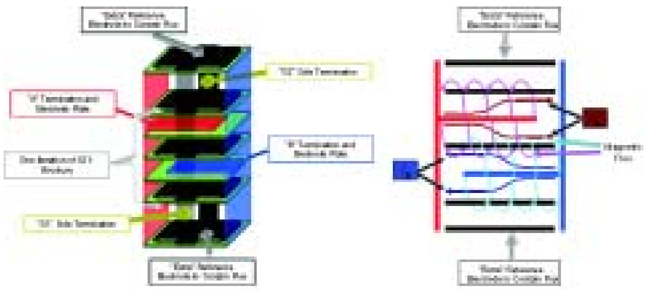

Figure 10. Electrode plate structure of X2Y.

2. C_{SG} (Figure 9) would have greater impedance than the side terminations G1 and G2 because R5 would ideally be infinitely large. Therefore C_{SG} is nominal and the total impedance characteristic for G1 and G2 would reduce to (R3 and L3) // (R4 and L4).
3. Multiple repeating layering sequences (Figure 10) would place the A electrodes in parallel. Therefore, the total impedance characteristic would be primarily capacitive. The same would be true for B electrodes. Therefore, R6 and L6 in Figure 9 would be nominal and could be removed from the model.
4. The current direction of the A and B nodes are 180° out of phase (Figure 8). The magnetic field created by L1 and L2 in Figure 9 would cancel because of the mutual inductance shown in Figure 10.
5. The mutual inductance (Assumption 4) and the capacitance from A to B (Assumptions 1 and 3) can be combined and modeled as a non-ideal transformer.

If these assumptions are incorporated into the schematic model in Figure 9, the model would now look like Figure 11.

X2Y QUANTITATIVE TEST VALIDATION

To validate this model quantitatively, a laboratory setup to measure the insertion loss of an X2Y component is shown in Figure 12. A test fixture from Inter-Continental Microwave (ICM) and a HP8753E Network Analyzer are used to measure from 30 kHz–6 GHz.

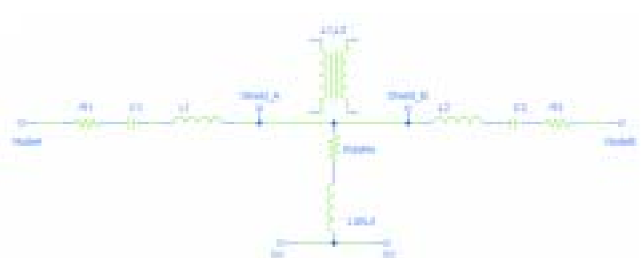

Figure 11. Schematic model of X2Y with the above assumptions.

Figure 12. Validation test setup.

A standard capacitor has one circuit configuration, thus one curve shows insertion loss. X2Y, on the other hand, is a multi-port device which can be attached within a circuit three different ways. The result is three different curves for insertion loss depending on how X2Y is attached. Figure 13 shows the three attachment configurations and the placement in the test fixture to measure insertion loss. Figure 14 shows the insertion loss curves.

Figure 13. Component placement in test fixture.

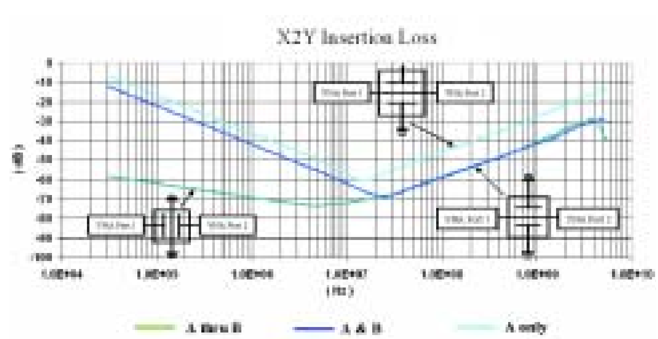

Figure 14. The insertion loss plot of an X2Y component. Unlike standard capacitors, X2Y has three different insertion loss plots depending on how X2Y is connected within the circuit.

SPICE MODEL OF X2Y

Based on Figure 11, an X2Y model was developed to simulate the X2Y behavior in a circuit design. The properties of the model were based on insertion-loss measurements carried out with a vector network analyzer (VNA). For this analysis, the X2Y component was measured in two different test fixtures. The first was the ICM-fixture (Figure 12 & Figure 13); the second was a small FR-4 substrate mounted

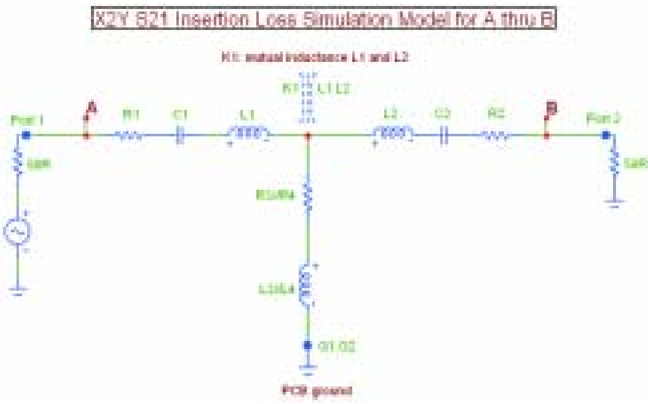

Figure 15. X2Y Spice model with connections to the 2 test-ports of a VNA.

in a Wiltron test fixture. The substrate was designed with a 50-ohm micro-stripline, on which the X2Y was mounted.

The A&B attachment mode used to connect the two halves of the component was represented by a PCB track with parasitics Lpcb and Rpcb. This track was also shown in the A&B and A-only models (Figure 16). Although the PCB parasitics were relatively small, they had a minor influence on the insertion loss performance. The parasitics enabled the model to simulate small real-life resonances, as a small "hump" visible in some A&B-mode insertion loss measurements under certain attachment scenarios. Based on the separate insertion loss measurements taken, the model was first developed with the idea that three separate models might also be needed, one for each X2Y attachment mode. After several simulation runs, it appeared that all three attachment modes could be based on one model that used the same values. Rather than varying the values in the model, the connections between the A, B, and ground nodes were varied. These adjustments were necessary to represent the correct attachment mode.

Another key factor in the model was the (non-ideal) inductive coupling between the internal A and B portions of the X2Y. This coupling was modeled as a transformer (representing the mutual inductance) coupling L1 of the A-capacitor and L2 of the B-capacitor (Figure 15). When in the A&B attachment mode, currents with the same magnitude flowed in opposite directions through the inductances L1 and L2. Assuming optimal coupling (100% or k = 1), the inductance contributions of L1 and L2 would be totally eliminated, and the mutual inductance of the X2Y virtually eliminated. In this case, the only remaining inductance was associated with the ground terminations (modeled as L3 and L4). However, in the actual X2Y the k-factor was never 100% mainly because the overlap of the opposing electrodes was not 100%. After several tests and simulation runs, it appeared that the best fit-to-measured data was obtained with k-factor values between 0.7 and 0.75 (70% – 75% coupling).

Figure 15 depicts the basic X2Y model for the A through B attachment mode, which is compared to the circuit schematic in Figure 11. The actual X2Y-model is situated between the A, B, and G1/G2 nodes. In actual practice, the A&B model requires a PCB-track represented by Lpcb and Rpcb (including its impedance) to connect the A and B nodes. Removing the B-half connection results in the A-only model. The latter two models are shown in Figure 16.

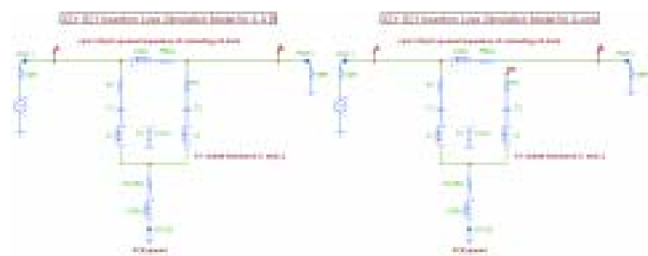

Figure 16. X2Y Spice models for A&B and A-only, including the PCB-track, connected to the 2 ports of a VNA.

In Figures 17 and 18 note that the simulated responses fit rather well with the measured data plotted in Figure 11. The high-frequency portions of the A-through-B and A&B plots run on top of each other, indicating that the model fits both attachment modes. In addition, the A-only and A&B plots also fit the measured data, which typically show a 6-dB difference in the capacitive part and an approximately 12-dB difference at frequencies beyond the component self-resonant frequency.

One part of the simulation results does not match the insertion loss measurements at the low frequency portion of the A-through-B measurement, where the capacitor is capacitive. The simulated model shows a response that runs flat, while the measured insertion loss plot shows a slight slope or hump. It is not clear why the measured data run this way, and this response is present only for certain component sizes and capacitance values. At present, it is unpredictable and therefore hard to model as accurately as the other measurements.

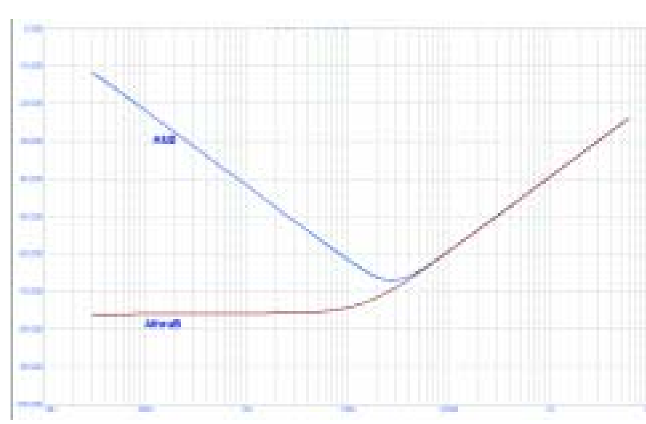

Figure 17. Simulated results of the AthruB mode vs. the A&B mode.

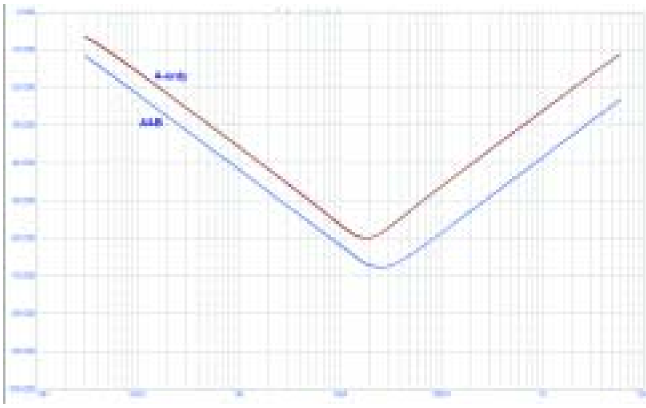

Figure 18. Simulated results of the A&B mode vs. the A-only mode.

CONCLUSION

The unique structure of X2Y components replaces the inductive behavior that standard capacitors exhibit at frequencies above self-resonance with a more desirable coaxial one. By using the dual rectangular coaxial model, an analytical model of the internal parasitics of an X2Y component can be constructed. This model is validated by quantitative data taken in the laboratory and SPICE simulations.

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James P. Muccioli *is the Chief Technology Officer for X2Y Attenuators, LLC. A NARTE-certified EMC and ESD Engineer, Jim serves on the board of the IEEE EMC Society and was selected as an IEEE Fellow in 1998 for contributions to integrated circuit design practices for minimizing electromagnetic interference.*

Dale Sanders*, an Application Consultant Engineer for X2Y Attenuators, LLC, develops application notes using the X2Y technology and conducts R&D development testing at the X2Y Detroit test lab. Dale serves as the vice-chair of Professional Services, IEEE Southeastern Michigan EMC society. Dale received his BSEE from University of Michigan, Dearborn.*

Bart Bouma *received his BSEE in 1982. He joined Philips Consumer Electronics in 1984, where he specialized in RF and developed television tuners and satellite tuners for both analog and digital reception. In 2001 he joined the Yageo/Phycomp application group located in Roermond, working on applications with X2Y® capacitors and MLCC's.* ■