More about understanding the distortion mechanism of high-K MLCCs - EDN

EDN

Capacitor voltage coefficient

In a previous article I demonstrated the additional distortion produced when using High-K ceramic capacitors in a system's signal path [1] . The underlying mechanism causing this distortion is the voltage coefficient of capacitance (VCC) of the capacitor. The term VCC is used to describe the change in the value of a capacitor with respect to the magnitude of the applied voltage. Power supply designers are well aware of this behavior as it can directly affect the output ripple or stability of their system, but VCC is often ignored in small-signal circuitry. In order to understand why the capacitance varies with applied voltage and how the VCC varies with other capacitor parameters, it is necessary to first look at a capacitor's basic structure.

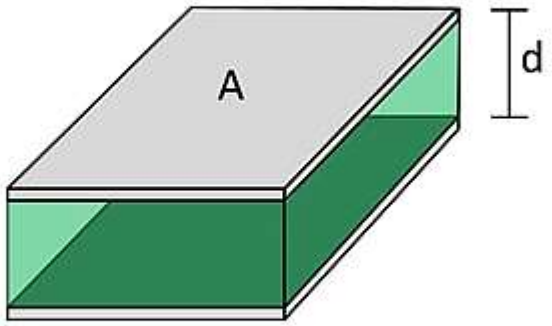

Figure 1. A basic parallel plate capacitor with electrode plates of area *A* and a separation distance *d* .

Figure 1 shows a simple capacitor consisting of two plate electrodes of area A , separated a distance d by a dielectric (green). The capacitance of this structure is given by equation 1:

$$C = \frac{\varepsilon_o \varepsilon_r A}{d} \quad (1)$$

where ε_o and ε_r are the permittivity of free space and relative permittivity of the dielectric, respectively. The magnitude of the electric field applied to the dielectric is a function of the applied voltage and the separation distance between the two plates.

$$|\vec{E}| = \frac{V}{d} \quad (2)$$

The voltage coefficient of many capacitors arises from the electrostatic force on the dielectric when a voltage is applied to the capacitor.

$$F = \frac{\varepsilon_o \varepsilon_r A V^2}{2d^2} \quad (3)$$

Because the dielectric material cannot be infinitely stiff, it is compressed by this force, reducing the separation distance *d* and increasing the capacitance [2] . Multilayer ceramic capacitors, on the other hand, exhibit an additional negative voltage coefficient that arises from other properties of the dielectric.

Ceramic capacitors owe their small size, high capacitance, and low cost to the use of barium titanate in the dielectric, which provides an extremely high relative permittivity [3] . Unfortunately, this material's relative permittivity varies depending upon the intensity of the applied electric field [4] . Reference 4 presents an excellent example of this behavior in single barium titanate crystals, reproduced in **Figure 2** . As the applied electric field is increased, the relative permittivity of the barium titanate is reduced, showing a 55% reduction over the tested range. Therefore, increasing the voltage applied to a ceramic capacitor reduces the relative permittivity of the barium titanate in the dielectric material, causing a decrease in capacitance.

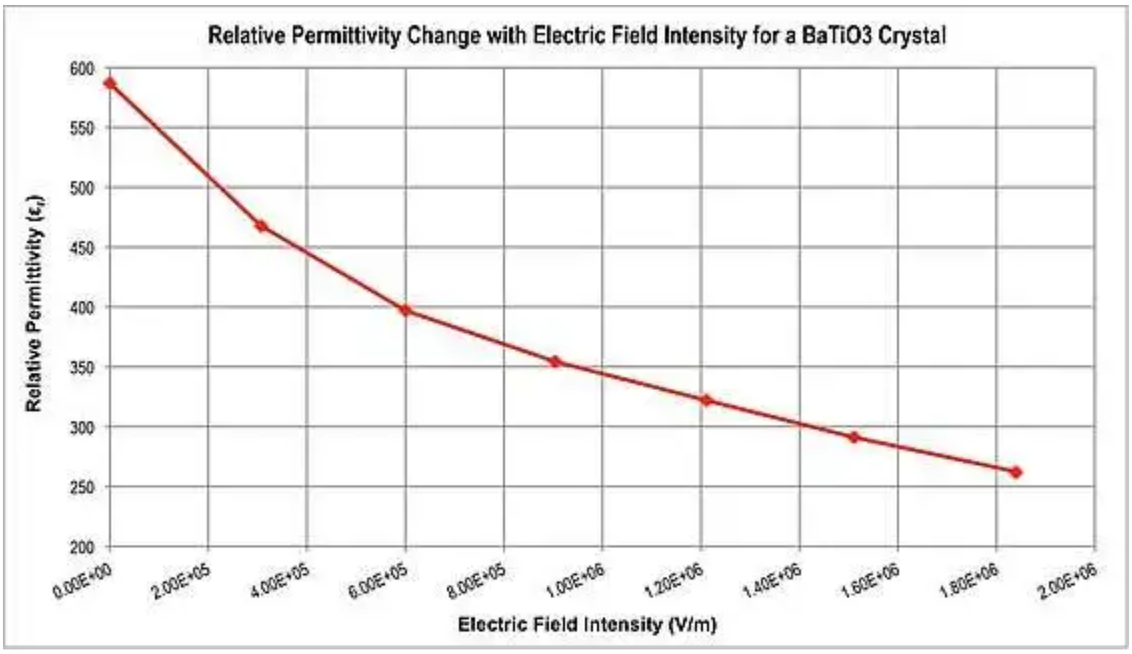

Figure 2. An example of the dependence of barium titanate's relative permittivity on the intensity of the applied electric field.

The electric field intensities in **Figure 2** may seem unlikely to occur in small signal circuits. However, in the pursuit of higher volumetric efficiencies, capacitor manufacturers are able to produce ceramic capacitors with dielectric thicknesses below 5 micrometers, creating surprisingly high electric field intensities [5] . Using equation 2, we can see that applying 1V to a capacitor with a 5 µm dielectric thickness results in an electric field intensity of 200,000 V/m!

Understanding this property of barium titanate allows us to infer some rules for the voltage coefficient of ceramic capacitors. First, the voltage coefficient is worst (greatest change with applied voltage) in ceramic capacitors with the highest barium titanate content. **Table 1** displays the barium titanate content of selected ceramic dielectric types [4] .

Table 1. Barium titanate content of selected ceramic capacitor dielectric types [4]

Dielectric Type	**Barium Titanate Content**
C0G	10% to 50%
X7R	90% to 98%
Z5U	80 to 94%
Z5V	80 to 94%

Second, the voltage coefficient gets worse for smaller packages because the change in the relative permittivity is dependent upon the intensity of the applied electric field. As the capacitor's package size is decreased, the area of the electrode plates is reduced. Therefore, the thickness of the dielectric must be reduced to maintain a certain capacitance.

Voltage coefficient effects

Although we've identified the mechanism for voltage coefficient of capacitance, it may not be immediately clear how this voltage coefficient causes distortion. Consider that because the value of a ceramic capacitor is, in reality, a function of the applied voltage, the equation for current through that capacitor must be modified. As shown in equation 4, the constant *C* for capacitance is replaced with a function *C* , which depends on the applied voltage *V* .

$$i = C(V) * \frac{dV}{dt} \qquad (4)$$

We can extract the function C(V) from typical voltage coefficient curves provided by the capacitor manufacturers in order to illustrate how the capacitance changes for a given input signal. In **Figure 3** , a cubic equation for C(V) of a 10 nF, 50V, X7R capacitor was fit to numerical data (R^2

value .99982) from a manufacturer datasheet [6] . The curve from the manufacturer is intended to show the change in capacitor value for an applied DC voltage. However, we can presume that complex AC signals are composed of extremely short instances of DC voltages. Also, the assumption is made that the voltage coefficient only depends on the magnitude of the applied voltage and not its polarity. Hence, the change in capacitance should be the same for both positive and negative applied voltages. This allows us to use a DC voltage coefficient curve to predict the resulting instantaneous changes in capacitance.

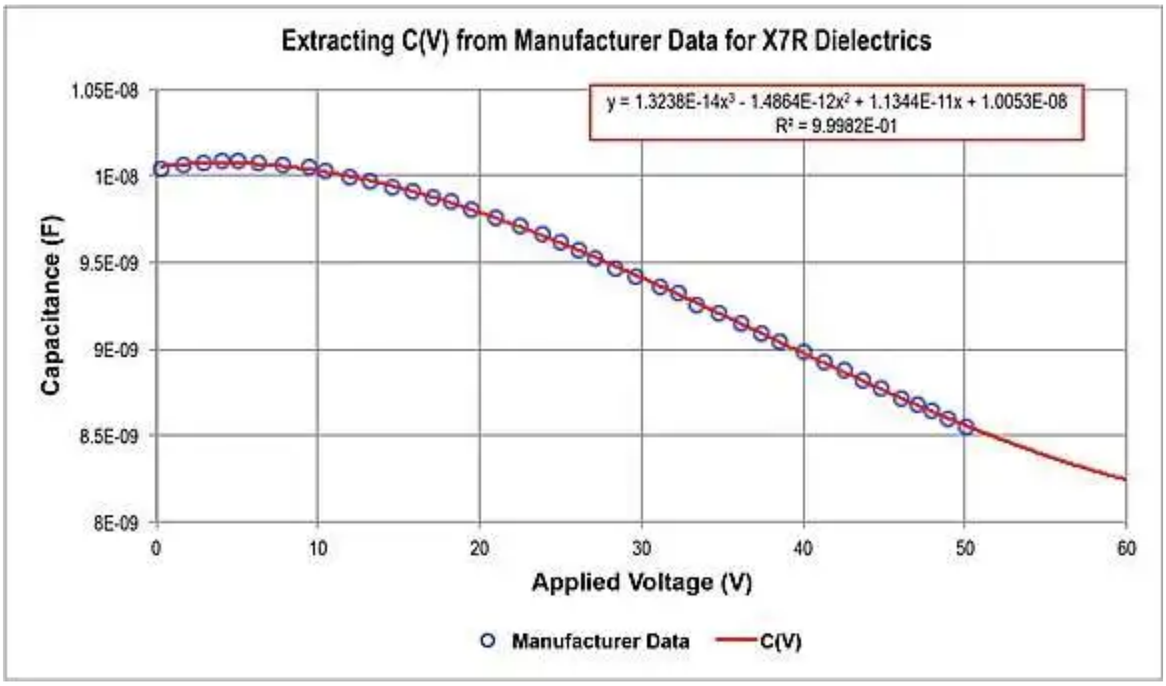

Figure 3: An equation for voltage coefficient of capacitance is extracted from manufacturer data

Figure 4 shows the predicted effect of an applied 50 Vpk, 1 kHz sine wave on the capacitance of a 10 nF, 50V X7R capacitor. The capacitance value dips over the period of the sine wave, reaching a minimum of 8.56 nF at the maximum applied voltage of 50V.

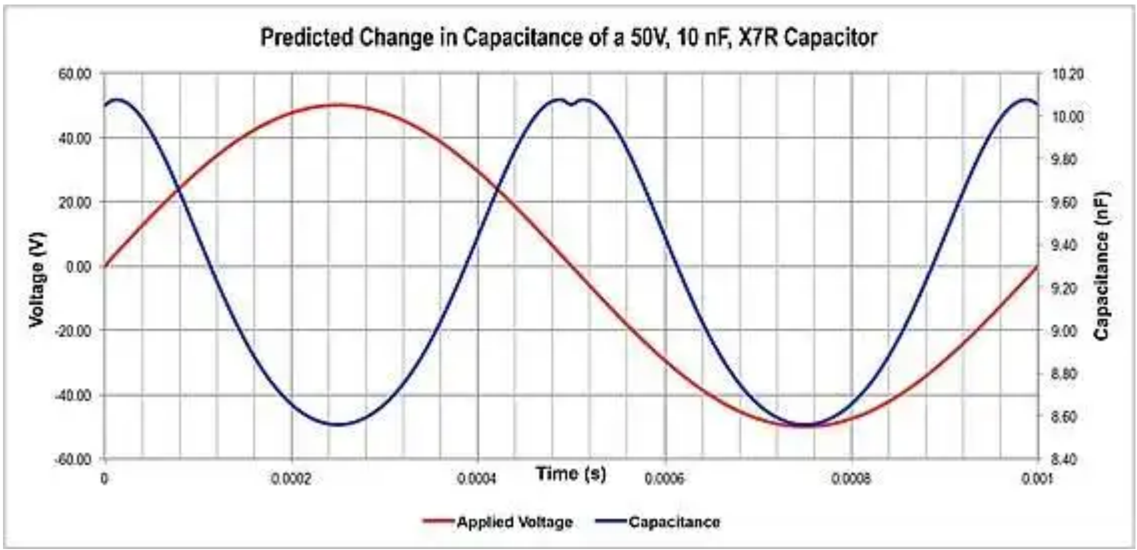

Figure 4: The predicted instantaneous change in capacitance of a 10 nF, 50V, X7R capacitor resulting from an applied 40Vp sine wave.

The effect of the voltage coefficient on the current waveform in the capacitor can be produced by inserting into equation 4 the cubic equation for C(V) extracted in **Figure 3** . **Figure 5** compares the ideal current waveform of a 10 nF capacitor for a 50 Vpk, 1 kHz sine wave to the actual waveform when including the effects of the voltage coefficient. The voltage coefficient distorts the current waveform into a more triangular shape, indicating the introduction of odd harmonics into the signal path.

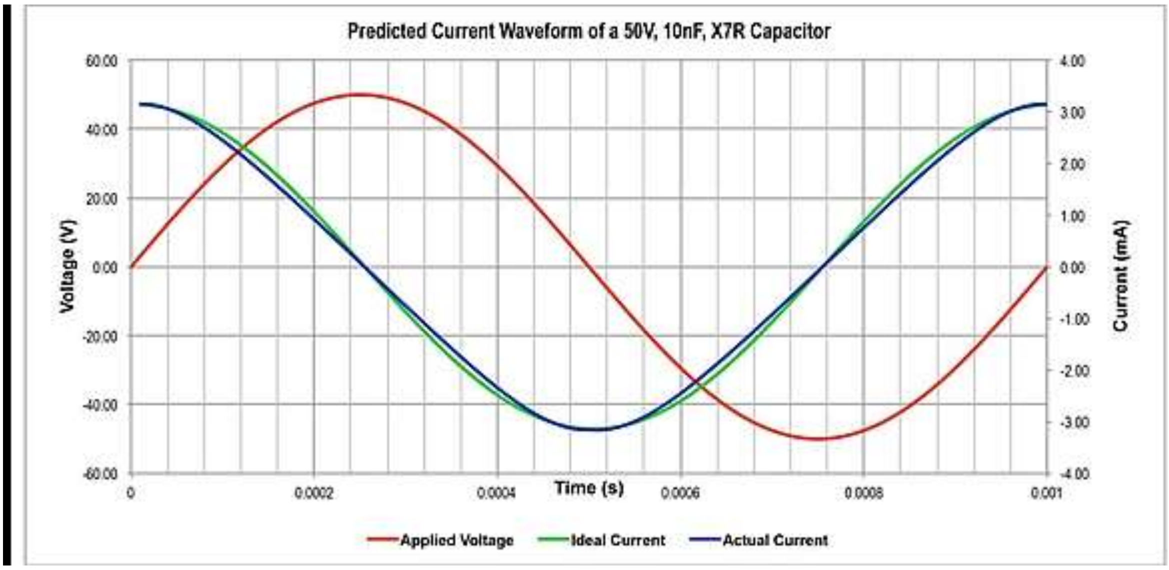

Figure 5: Ideal and actual current through a capacitor considering voltage coefficient effects

In the previous example, a 50 Vpk sine wave was chosen such that the distortion of the current waveform would be visibly noticeable. However, these effects begin at much lower voltages.

Simulating with non-ideal capacitors

The effect on the current waveform may seem miniscule, but the degree to which it degrades the total harmonic distortion of a circuit can be surprising. In order to prove this, a SPICE model for a polynomial non-linear capacitor (polycap) given in reference 5 was modified to incorporate the cubic equation for voltage coefficient, C(V). This model approximates a nonlinear capacitor using a controlled current source whose output current is defined by the polynomial equation for C(V), as well as the derivative of the applied voltage with respect to time, dV/dt. The time derivative is determined by applying a copy of the applied voltage across a known capacitance CREF, and measuring the resulting current [5] .

```
* Polynomial Nonlinear Capacitor Model
* Modified from 'A Nonlinear Capacitor Model for Use in PSpice'
* Microsim Application Notes, Microsim Corporation
*
.subckt polycap 1 2 params: C0=1.0053e-8 C1=1.1344e-11 C2=-1.4864e-12 C3=1.3238e-14
```

```
Ecopy 3 6 1 2 1.0     ; copy V(t)
Vsense 0 6 0V          ; Ammeter
Cref 3 0 1.0E-6        ; to get 1E-6*dv/dt
*
Gout 1 2 VALUE =
+ {(C3*abs(V(1,2)*V(1,2)*V(1,2)) + C2*abs(V(1,2)*V(1,2)) + C1*abs(V(1,2)) + C0) * I(Vsense)*1E6 }
* ----------------------------------------------------------------------------------------------------   --------------------
*                                        C(V)                                                               dV(t)/d
.ends polycap
```

Figure 6: SPICE netlist for a nonlinear capacitor. The values for the coefficients were extracted from manufacturer data given in Figure 3.

The model accepts four parameters: C0, C1, C2, and C3. These can be positive or negative and define the capacitor's voltage coefficient equation. Because the cubic equation for C(V) extracted in **Figure 3** is only defined for voltages greater than zero, the absolute value function must be incorporated to accurately model the capacitance value for both positive and negative voltages. This approach was found to be much more accurate than attempting to fit a polynomial over the entire range of possible voltages (both positive and negative).

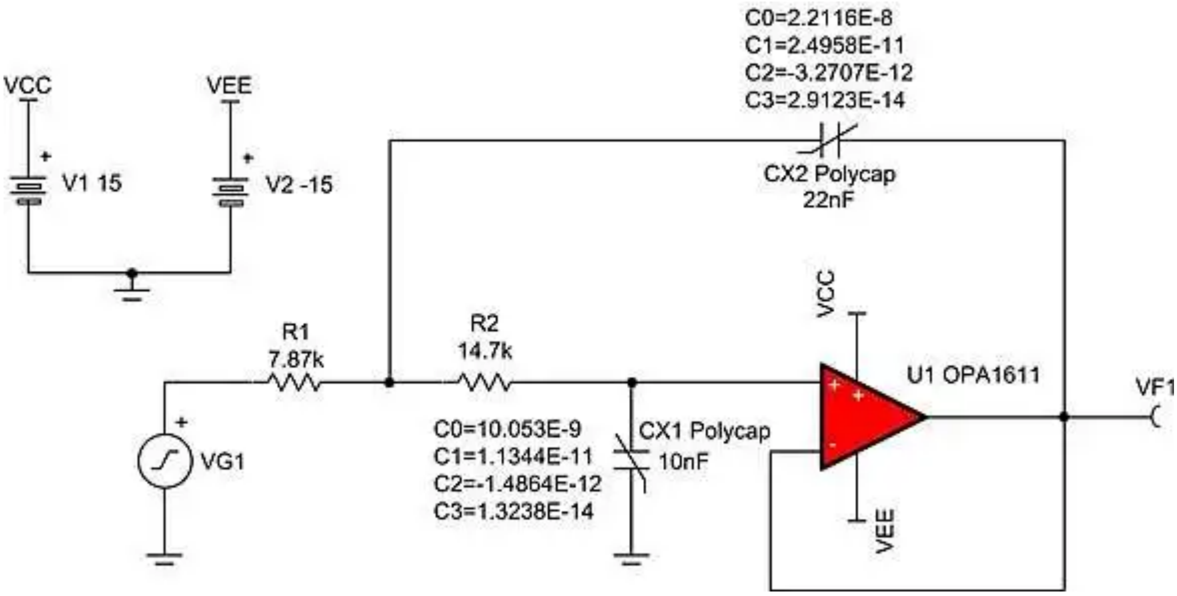

Figure 7. Simulation schematic of a Sallen-Key 1 kHz lowpass filter with X7R capacitors shown as CX1 and CX2.

The Sallen-Key 1 kHz lowpass filter from my previous article was simulated using polynomial nonlinear capacitor models for 10 nF and 22 nF, 50V X7R capacitors. **Figure 7** shows the simulation schematic incorporating X7R capacitors CX1 and CX2.

TINA was used to perform a Fourier Spectrum analysis of the output of the filter for a 500 Hz, 1Vrms input signal. A 65536 sample FFT was performed on an 80 ms sample of the output signal to produce the spectrum. In order to avoid the use of windowing, the time steps of the simulation were constrained and the input signal was chosen to be a coherent frequency. Any harmonics in the output spectrum are the result of the capacitors' voltage coefficient because the distortion characteristic of the operational amplifier (op amp) is not modeled below the full power bandwidth limitation.

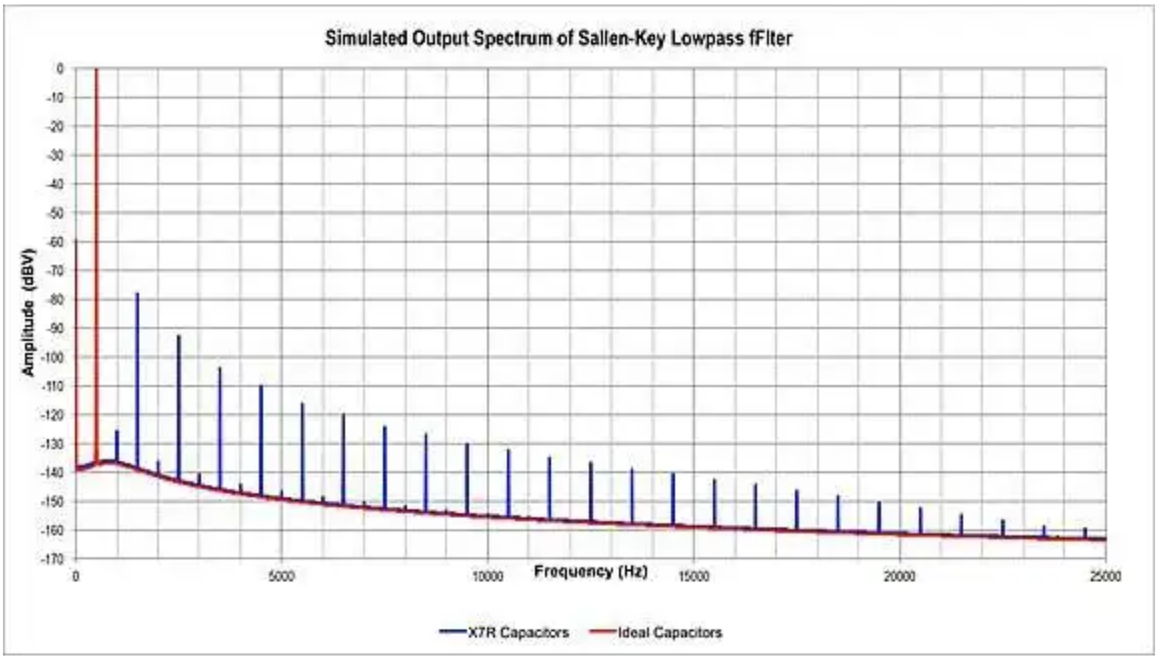

Figure 8. TINA Fourier spectrum analysis of a 500 Hz sine wave applied to the filter circuit using nonlinear capacitor models (top) and ideal capacitor models (bottom).

Figure 8 shows the simulated output spectrum of the circuit when using the modeled X7R capacitors (blue) compared to idealized capacitors (red). The simulation shows a large number of predominantly odd order harmonics are produced when using X7R capacitors in the filter circuit, which agrees with the results from the first article. As expected, the simulation using ideal capacitors shows only a spur at the fundamental frequency. The amplitude of the harmonics in the simulation, on average, are 10 dB lower than that measured in the actual circuit. This is most likely because the capacitors used in the first article had more pronounced voltage coefficients than those chosen for the simulation model.

Conclusion

In ceramic capacitors, the relative permittivity of the dielectric is changed by the intensity of the applied electric field, giving rise to a substantial voltage coefficient. This effect is worst in high-K dielectric types and smaller package sizes. As a result, the value of the capacitor is changing instantaneously due to the applied signal, causing distortion in the current waveform. We demonstrated this by producing a SPICE model for a capacitor that replicates the voltage coefficient of a typical 50V X7R capacitor. The X7R capacitor models produced a large number of harmonics when used to simulate a Sallen-Key lowpass filter. In wide dynamic range applications where a substantial voltage may appear across a capacitor, it is best to select C0G, polypropylene film, or silvered mica capacitors to avoid excess distortion.

References

Caldwell, J., Signal Distortion from High-K MLCCs, EDN, June 16, 2013.

Van der Veen, M., Non-linear distortions in capacitors, Audio Engineering Society: Convention Paper 7500, 124th Convention, May 17-20th 2008, Amsterdam, Netherlands.

Kahn, M., Multilayer Ceramic Capacitors – Materials and Manufacture, AVX Corporation.

Rehrig, P., et. al., Dielectric and Electromechanical Properties of Barium Titanate Single Crystals Grown by Templated Grain Growth, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 47, NO.4, July 2000.

Liu, D., Sampson, M., Some Aspects of the Failure Mechanisms in BaTiO3-Based Multilayer Ceramic Capacitors, CARTS International, March 26-29, 2012, Las Vegas, NV.

Surface Mount Multilayer Ceramic Chip Capacitors for Automotive Applications, Vishay Vitramon, Doc. Number 45040, Rev: June 13, 2013.

MicroSim Applications Notes, MicroSim Corporation, ver. 8.0, June 1997.

For more information about SPICE or TINA visit here.

About the Author

John Caldwell is an analog applications engineer for TI's Precision Analog Linear Applications group. John received his MSEE and BSEE from Virginia Tech, Blacksburg VA. He has three pending patents and has published several papers. In 2009, John was a recipient of the coveted Engibous Prize in Texas Instruments Analog University Competition. John can be reached at .