High Frequency Behavior of Ceramic Multilayer Capacitors

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Abstract—**The impedance of ceramic capacitors, made from different dielectric materials, was measured as a function of frequency from 1 MHz to 1 GHz. Most of the capacitors were of 0805 size and either end terminated or side terminated. The capacitance values ranged from a minimum of 50 pF to 100 nF. The high-frequency impedance measurements demonstrate that the inductance is a factor of two larger in end-terminated than in side-terminated ceramic multilayer capacitors of size 0805. The inductance measured by two independent methods is 0.7 nH for the side-terminated 0805 capacitors. The inductance is only dependent on the geometry of the capacitor and independent of the dielectric material used. The capacitance and, in turn, the dielectric constant, remains constant for Z5U and X7R materials up to 100 MHz. For NPO materials the dielectric constant remains constant up to 1 GHz.**

Introduction

With the trend to faster and faster integrated circuits it becomes necessary to search for capacitors with higher and higher resonance frequencies that remain effective as noise suppressors at high frequencies. To achieve these goals the inductance has to be kept as low as possible and the ceramic material has to retain its dielectric constant at the high frequencies. To clarify the influence of the material and the physical shape of the capacitor on the inductance, the high-frequency behavior of ceramic multilayer capacitors of various sizes with either conventional end terminations or special side terminations was studied in the frequency range of 1 MHz–1 GHz.

Equivalent Circuit

A ceramic capacitor can be represented by a series resonance circuit consisting of a resistor R in series with a capacitor C and an inductor L. The impedance Z of such a series resonance circuit is

$$Z=R+j\left(\omega L-\frac{1}{\omega C}\right). \quad (1)$$

The impedance at low frequencies for a series resonance circuit is dominated by the capacitance C. At high frequencies the impedance is controlled by the inductance L. Resonance occurs at the frequency ω_0 where the impedance due to the inductance is equal to the impedance due to the capacitance. One obtains for the resonance frequency

$$\omega_0=\frac{1}{\sqrt{LC}}. \quad (2)$$

The impedance is a minimum at the resonance ω_0 and is equal to the series resistance R. The value of the resistance does not influence the frequency of resonance. However, a low resistance leads to an underdamped resonance characterized by a sharp drop in impedance. On the other hand, a high resistance leads to an overdamped resonance characterized by a shallow impedance minimum.

The inductance of a multilayer ceramic capacitor can be estimated according to [1]. Because of the small distance between electrodes in a multilayer capacitor the mutual inductance between electrodes is about equal to the self-inductance of a single electrode. The dimensions of the electrode can be approximated by the length l and the width w of the capacitor. For the inductance L of such a capacitor one obtains according to [1] in nanohenry:

$$L=0.125l\,[\ln(2l/w)+0.5+2w/9l] \quad (3)$$

if l is measured in meters.

Equation (3) shows the relationship between the inductance of a multilayer capacitor and its length and width. Since the square of the resonance frequency of a chip capacitor is inversely proportional to its inductance (at constant capacitance), the foregoing suggests that the resonance frequency of a chip capacitor can be increased by decreasing its physical length.

To test this suggestion the impedance was measured in the frequency range of 1 MHz–1 GHz for a number of multilayer capacitors with different temperature characteristics (Z5U, X7R, and NPO) [2], and different sizes with either conventional end terminations or special side terminations. For this study capacitors of 0805 size, [2], that have a footprint of 80 mil by 50 mil (2 mm × 1.25 mm) and capacitors of 1206 size that have a footprint of 120 mil by 60 mil (3 mm × 1.5 mm), were used. The 0805 size capacitors had either conventional terminations with a length of 2 mm or special side termination with a length of 1.25 mm. The 1206 size capacitors were used only with conventional terminations and a length of 3 mm.

Experimental and Calibration Procedures

To investigate the effects of length on the resonance frequency of multilayer chip capacitors high-frequency measurements are required. High frequency measurements are always very sensitive to details of the test setup, which will, therefore, be described in detail. To obtain consistency from test to test, software was written using a Hewlett-Packard computer, model #9836 in conjunction with two H-P impedance analyzers. For low frequencies the model H-P #4192A and for high frequencies the model H-P #4191 were used. The computer performed the following tests and calculations on

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each chip capacitor:

(1) make capacitance and dissipation factor (DF) measurements for each capacitor at 1 kHz;

(2) make impedance versus frequency measurements from 1 MHz to 1 GHz for each capacitor;

(3) determine the minimum of impedance in this frequency range and measure the resistance and resonance frequency for each capacitor;

(4) measure inductance values for each capacitor at 0.3 GHz (for NPO capacitors at 0.5 GHz or 1 GHz);

(5) calculate the inductance of each capacitor from its measured capacitance at 1 kHz and its resonance frequency;

(6) store the test data for subsequent tabulation and plotting.

Prior to testing, gold plated flanged pins, provided by H-P, were soldered to the termination of each of the capacitors to improve the contact between capacitor and test fixture. To compensate for the capacitive and inductive effects of these pins, two of them were soldered together and used as a short during calibration of the impedance analyzer.

All impedance and inductance measurements were made with the high-frequency impedance analyzer model #4191 that was equipped with a coaxial test fixture. The fixture included a shorted, an open, and a 50-Ω termination. Only the latter two were used to calibrate the instrument. The open termination was designed to serve also as a sample holder [3]. It contains a thumbscrew with brush assembly that can be screwed down on the center electrode. The device under test is placed between the center electrode and the thumbscrew with brush assembly that holds the device under test in place.

Prior to making any measurements, the high-frequency impedance analyser was calibrated using the instrument's autocalibration function. Normally, the autocalibration function measures the three terminations mentioned previously, at frequencies specified by the user, and performs error correction calculations based on the calibration data obtained from these measurements. For calibrating the instrument to measure the chip capacitors, the open termination with the shorted pins in place of the device under test was used instead of the shorted termination. This procedure was used to compensate for the effects of the pins in the calibration.

To determine the accuracy of the calibration the two pins soldered together were mounted in the test fixture and the pin's impedance was measured from 1 MHz to 1 GHz. Ideally, the impedance of the shorted pins should be zero over the entire frequency range. In reality the impedance of the shorted pins is less than 5 mΩ over the entire frequency range. This resistance turns out to be less than one-tenth of the lowest resistance measured and, therefore, can be neglected.

TABLE I
TEST RESULTS FOR SIDE- AND END-TERMINATED CHIP CAPACITORS

Cap. ID	Cap.(nF) @ 1 kHz	DF (%) @ 1 kHz	Res.(Ω) @ f_{res}	f_{res} (MHz)	Ind.(nH) @ 0.3 GHz	Ind.(nH) Calculated
Side Terminated Capacitors - Size 0805						
Z5U S1	5.3	1.5	0.8	83	0.8	0.7
Z5U S2	5.5	1.9	1.0	126	0.9	0.3
Z5U S3	75	1.8	0.06	18	0.8	1.0
Z5U S4	86	4.0	0.1	21	0.8	0.7
X7R S1	2.4	1.3	0.6	110	0.8	0.9
X7R S2	2.5	1.3	0.4	110	0.8	0.8
X7R S3	35	1.4	0.1	32	0.9	0.7
X7R S4	38	1.6	0.07	32	0.7	0.7
NPO S1	0.04	0	0.7	759	0.4*	1.1
NPO S2	0.04	0	0.5	759	0.5*	1.0
NPO S3	0.6	0	0.3	219	0.6**	0.9
NPO S4	0.6	0	0.14	219	0.7**	0.8
Cap. ID	Cap.(nF) @ 1 kHz	DF (%) @ 1 kHz	Res.(Ω) @ f_{res}	f_{res} (MHz)	Ind.(nH) @ 0.3 GHz	Ind.(nH) Calculated
End Terminated Capacitors - Size 0805						
Z5U E1	9.8	1.6	0.1	42	1.5	1.5
Z5U E2	10.0	2	0.1	42	1.5	1.4
Z5U E3	43	2.1	0.3	24	1.3	1.0
Z5U E4	50	2.6	0.2	21	1.3	1.2
X7R E1	2.8	1.1	0.6	83	1.4	1.3
X7R E2	2.9	1.1	0.4	83	1.4	1.3
X7R E3	20.5	1.6	0.12	32	1.2	1.2
X7R E4	21.5	1.4	0.15	32	1.2	1.2
NPO E1	0.05	0	0.5	660	0.8*	1.3
NPO E2	0.05	0	0.3	660	0.7*	1.2
NPO E3	0.6	0	0.13	190	1.0**	1.2
NPO E4	0.6	0	0.11	190	1.0**	1.2
Cap. ID	Cap.(nF) @ 1 kHz	DF (%) @ 1 kHz	Res.(Ω) @ f_{res}	f_{res} (MHz)	Ind.(nH) @ 0.3 GHz	Ind.(nH) Calculated
End Terminated Capacitors - Size 1206						
X7R E5	102	1.5	0.05	14	1.5	1.3
X7R E6	103	1.7	0.06	14	1.5	1.3

* Inductance measured at 1 GHz
** Inductance measured at 0.5 GHz

IMPEDANCE MEASUREMENTS AND RESULTS

The impedance of each of the ceramic capacitors was measured as a function of frequency from 1 MHz to 1 GHz in equal logarithmic steps. Upon completion of each frequency sweep, the computer was programmed to select the lowest impedance value corresponding to the series resistance R and the frequency at this point, namely the resonance frequency $f_{res} = \omega_0/2\pi$. After making these assignments, the inductance of each capacitor was measured at 0.3 GHz (for NPO capacitors at 0.5 GHz or at 1 GHz).

To determine the validity of the impedance measurements the results were plotted in a double logarithmic plot of impedance versus frequency. In such a plot, according to (1), a linear relationship should exist on either side of the resonance, which was indeed observed. In some Z5U capacitors deviations occured at frequencies above 0.7 GHz. The most suitable frequency for inductance measurements, i.e., a linear relationship in the double logarithmic plot, that covers most capacitors was determined to be 0.3 GHz. For the NPO capacitors with their low capacitance values, the resonance frequency interfered and the test frequency had to be raised to 0.5 GHz and finally to 1 GHz.

The results of these measurements are presented in Table I.

In addition, the inductance of each capacitor was calculated with the help of (2) using the measured resonance frequency ω_0 and the capacitance values measured at 1 kHz. The results are also shown in Table I.

Discussion

Comparing the inductance measured on the side-terminated capacitors with the one measured on the end-terminated capacitors it becomes clear that the former show a substantially lower inductance than the latter. The average inductance for the side-terminated capacitors is 0.7 nH whereas the average inductance for the end-terminated capacitors is 1.2 nH. The inductance in each group of capacitors is constant indicating that the inductance is indeed only a function of the physical size of the capacitor as required by (3) and not of the dielectric material. Although the inductance values derived from (3) do not agree well with the measured ones, especially for the small 0805 sized capacitors, (3) ranks the capacitors in the proper order.

In the last column of Table I the inductance of the capacitors is calculated with the help of (2) from the capacitance value at 1 kHz and the resonance frequency. The inductance values calculated in this manner are in good agreement with the values measured directly. This result reinforces the accuracy of the measured values.

From a materials point of view the good agreement between measured and calculated inductance values is interesting because it implies that the capacitance value of the capacitor has not changed up to the resonance frequency. In the case of the Z5U and X7R capacitors this result indicates that the material is useful up to a frequency of about 100 MHz. In this context the lower calculated result for capacitor Z5U S2 in comparison with the measured one might be significant. It is an indication that the dielectric constant for the Z5U material decreases above 100 MHz.

The relatively low values of inductance measured for the NPO capacitors in comparison to the calculated values might be due to the closeness of the test frequency to the resonance frequency, which lowers the inductance values.

The series resistance measured at resonance, Table I, decreases with increasing capacitance value for all types of capacitors. Since the capacitor size is constant this must be due to the large number of electrodes in high value capacitors. The lowest value of resistance was measured in the X7R 1206 capacitor which contains the highest number of electrodes.

Conclusion

The high-frequency measurements presented demonstrate a difference in inductance of a factor of two between end-terminated and side-terminated ceramic multilayer capacitors of size 0805. The inductance measured by two independent methods is about 0.7 nH for side-terminated 0805 capacitors. The inductance is only dependent upon the size of the capacitor and independent of the dielectric material used. The inductance decreases with decreasing length and increasing width. The capacitance and in turn the dielectric constant seem to remain constant for Z5U and X7R materials up to about 100 MHz. For NPO materials the dielectric constant remains constant up to about 1 GHz.

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References

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