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EIA STANDARD

STANDARD METHOD OF TEST
FOR
EFFECTIVE SERIES RESISTANCE (ESR)
AND CAPACITANCE OF MULTILAYER
CERAMIC CAPACITORS AT
HIGH FREQUENCIES

RS-483



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STANDARD METHOD OF TEST FOR
EFFECTIVE SERIES RESISTANCE (ESR) AND CAPACITANCE
OF MULTILAYER CERAMIC CAPACITORS AT HIGH FREQUENCIES

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STANDARD METHOD OF TEST FOR EFFECTIVE SERIES RESISTANCE (ESR) AND CAPACITANCE OF MULTILAYER CERAMIC CAPACITORS AT HIGH FREQUENCIES

(From EIA Standards Proposal No. 1381, formulated under the cognizance of EIA P-2.1 Working Group on Ceramic Capacitors.)

1.0 SCOPE

- 1.1 This method provides procedures for the measurement of effective series resistance (esr) and capacitance of multilayer ceramic capacitors from frequencies of 25 MHz to 1.25 GHz. A series connection permits the measurement of capacitance from below 1 pF to over 1 nF between frequencies of 130 MHz and 1.25 GHz. There is no maximum value of capacitance for series measurements of esr, but the determination of large values of capacitance at high frequencies suffers from inaccuracy. The esr of capacitors can be measured with this method at frequencies that exceed the self-resonant frequency of the test capacitor. A shunt connection allows the measurement of capacitance from 0 to 200 pF at frequencies from 25 to 910 MHz.

	<u>Resonant Mode</u>	<u>Frequency Range</u>	<u>Measurable Capacitance</u>
Series Mode	$\lambda/4$	130 to 250 MHz	> 1 nF to < 1 pF
	$3\lambda/4$	390 to 500 MHz	"
	$5\lambda/4$	650 to 750 MHz	"
	$7\lambda/4$	910 to 1000 MHz	"
	$9\lambda/4$	1170 to 1250 MHz	"
Shunt Mode	$\lambda/4$	25 to 130 MHz	200 pF to 0 pF
	$3\lambda/4$	265 to 390 MHz	100 pF to 0 pF
	$5\lambda/4$	530 to 650 MHz	30 pF to 0 pF
	$7\lambda/4$	785 to 910 MHz	30 pF to 0 pF

- 1.2 The limits shown for frequency and capacitance for shunt measurements may be exceeded, provided the test specimen is not at or near its self-resonant frequency, and the precautions of Section 6.0 are observed.

2.0 SUMMARY OF METHOD

- 2.1 A resonant, coaxial transmission-line, short-circuited at one end and open-circuited at the other, whose fundamental resonant frequency and Q-factor are known, is perturbed with a test specimen. The specimen may be connected in series at the short-circuited end of the line, or in shunt at the open-circuited end. Measurements of the new resonant frequency and the Q-factor of the system permit the calculation of the effective high-frequency series resistance and capacitance of the test specimen.
- 2.2 The coaxial line with its test specimen is excited at the closed end of the line with a stable rf generator. Its output frequency must be displayed with six or seven significant digits and an accuracy of ± 5 ppm, or better. The frequency of the generator is adjusted for resonance, which is detected with an rf millivoltmeter that is loosely coupled to the open end of the line. The Q-factor of the system is measured using the bandwidth technique ($f/\Delta f$) at the half-voltage points of the resonant response.

3.0 SIGNIFICANCE AND USE

- 3.1 Of special importance is the lack of other suitable test methods and apparatus for the characterization of low-loss capacitors at frequencies between 100 and 1000 MHz.
- 3.2 Admittance and impedance bridge techniques have been unsuccessful because of imperfect bridge components and the extreme resolution needed to separate the loss from the major parameter, especially when the Q-factor of the test specimen is several hundred, or more. Undeterminable circuit losses also invalidate lumped-element resonant techniques, and the modest resolving power of present-state network analyzer make S-parameters unsuitable for measuring the loss of capacitors.
- 3.3 The resonant transmission-line has no adjustable elements to alter circuit conditions in an unprescribed manner; the only variable is frequency, which can be measured with an accuracy of several parts per million; or better; the loss of the line is measurable and predictable as a function of frequency; the intrinsic Q-factor of the transmission-line is sufficiently high to support accurate measurements of low-loss capacitors; and test specimens can be inserted in the line with little degradation of initial conditions.
- 3.4 The good reproducibility of measured test specimen parameters afforded by this test method is largely dependent upon the resolution and absolute accuracy of the generator output frequency, and the relative accuracy of the rf millivoltmeter between full and half-scale. The accuracy of the measurement is also dependent upon minimal coupling to the transmission-line from the generator, and to the millivoltmeter.
- 3.5 The good repeatability of measurements makes this test method well suited for the design, development, and research of high frequency capacitors. It is also appropriate for quality auditing and lot testing for production.

4.0 SYMBOLS

4.1 The equations needed to translate measured quantities into test specimen parameters make use of a number of symbols which are defined here.

- Q_0 = short-circuited Q-factor of transmission-line at f_0 (Section 8.3).
- f_0 = frequency of line resonance when the electrical length equals $\lambda/4$ (Section 8.3).
- Q'_0 = open-circuited Q-factor of transmission-line at f'_0 (Section 8.5).
- f'_0 = a frequency slightly lower than f_0 . f'_0 is used instead of f_0 for calculations of series measurements to avoid attributing the discontinuity inductance of the series test fixture to the test specimen. Note: f'_0 would equal f_0 if the connecting pads of the test specimen were equal in shape and area to the contacts of the series fixture (Section 9.0).
- Q_{sc} = short-circuited Q-factor of transmission-line at f_{sc} (Section 8.2).
- f_{sc} = frequency of line resonance when the electrical length is an odd multiple of a quarter-wavelength, i.e., $(3/4)$, $(5/4)$, etc.¹
- Q_{oc} = open-circuited Q-factor of transmission-line at f_{oc} (Section 8.4).
- f_{oc} = frequency of line resonance when the electrical length is a multiple of a half-wavelength (line is open-circuited at both ends).¹
- Q_1 = short-circuited Q-factor of transmission-line at the measurement frequency, f_1 (Section 9.0).
- Q'_1 = open-circuited Q-factor of transmission-line at the measurement frequency, f_1 (Section 9.0).
- f_1 = measurement frequency, (frequency of system resonance with the test specimen connected to the line.) $f_1 = \omega_1/2\pi$
- f_a = frequency above resonance where the rf millivoltmeter indicates one-half the voltage shown at resonance.
- f_b = frequency below resonance where the rf millivoltmeter indicates one-half the voltage shown at resonance.
- x = slope of Q_{sc} vs frequency, on a log-log plot (Section 8.3).
- x' = slope of Q_{oc} vs frequency, on a log-log plot (Section 8.5).
- r_f = resistance of the series fixture at a specified frequency (Section 9.0).

¹Subscripts assigned to these frequencies are denoted by the number of quarter wavelengths they represent, i.e., f_2 is the half-wavelength frequency. (2/4)

4.0 SYMBOLS (continued)

- r_0 = resistance of the series fixture at f_0 (because $f'_0 \approx f_0$, it may also be considered the resistance at f'_0 , with an error, generally, of less than 0.2%) (Section 8.6).
- Q_m = Q-factor of the system (line with test specimen) at f_1 (Section 9.0).
- Z_0 = characteristic impedance of the transmission-line.
- βl = electrical length of the line, in degrees, at a frequency denoted by the subscript, or superscript, assigned to β , i.e., $\beta' l$, $\beta_1 l$.

4.2 The following symbols relate to the test specimen.

- C = effective series capacitance of the test specimen.
- X_C = reactance of the test specimen (below the self-resonant frequency, f_r).
- r = esr = effective series resistance of the test specimen.
- Q = Q-factor of the test specimen. $Q = X_C/r = 1/\omega_1 C r$.
- L = series inductance of the test specimen.
- f_r = self-resonant frequency of test specimen, owing to series capacitance and self inductance. $f_r = 1/2\pi\sqrt{LC_0}$
- C_0 = series capacitance of the test specimen at a frequency sufficiently low to exclude the effect of the series inductance: generally at 1 MHz.

5.0 APPARATUS

5.1 Measuring Instruments

In addition to the resonant coaxial-line, the system is comprised of a stable signal generator and a sensitive rf millivoltmeter.

The generator should have the following salient features:

1. Nominal 50-ohm impedance.
2. Continuously adjustable output level with a maximum of at least +13 dBm.
3. Frequency coverage of 25 to 1250 MHz, with frequency doublers, if necessary.
4. Frequency accuracy of ± 5 ppm, and stability of 0.1 ppm/hr.
5. Frequency resolution of 100 Hz.
6. Harmonic content: 30 dB or more below carrier.

5.1 Measuring Instruments (continued)

The rf millivoltmeter should have the following characteristics:

1. Full-scale ranges of 1 and 3 mV.
2. Frequency coverage of 25 to 1250 MHz.
3. Accuracy of $\pm 1.0\%$ at 1.5 mV, relative to 3 mV, f.s.
4. Probe Input:

For use at 25 - 500 MHz:

- Capacitance - <2.5 pF at 3 mV.
- Conductance - <200 μ S at 100 MHz and 3 mV.
 <2 mS at 500 MHz and 3 mV.

For use at 25 - 1250 MHz:

- Capacitance - <1.5 pF at 3 mV.
- Conductance - <150 μ S at 500 MHz and 3 mV.
 <1 mS at 1250 MHz and 3 mV.

5.2 Resonant Coaxial-Line

This test method specifies four frequency bands for shunt connected measurements, and five bands for series connected measurements. The frequency of measurement within each band is a function of the impedance and length of the line, and the effective value of the capacitance of the test specimen at that frequency. In the interest of reproducibility it is imperative that a common line impedance and length be used for all measurements so that common test frequencies result.²

- 2 The Model 34A Resonant Coaxial-Line, designed for this method of testing multilayer ceramic capacitors, is available from Boonton Electronics Corp., Parsippany, NJ 07054. The Model 34A, or its equivalent, is recommended for these measurements.

6.0 PRECAUTIONS

- 6.1 In addition to the obvious need for the accurate presentation of generator frequency and rf millivoltmeter indications, the validity of this method of test depends upon a linear rise of line attenuation with frequency (on a log-log plot). This is achieved if the line loss is series loss, only (conductor loss). This is true at frequencies below four or five hundred MHz, as evidenced by measurements of the intrinsic Q-factors of the transmission-line. At higher frequencies, however, two sources of loss appear which are manifested as additional line loss, and will, if not removed, cause the apparent attenuation of the line to rise above its normal value. One source is radiated energy from the open end of the line, which increases with frequency and is evidenced as added series resistance in the line. It is eliminated by adding a conductive tube to the open end. As such, it is an extension of the outer conductor and it prevents the spillage of flux beyond the center conductor, and the energy is contained within the line.
- 6.2 A second source of loss is the capacitive coupling from the center conductor to the input resistance of the rf millivoltmeter probe. A good rf detector probe (passive, non-sampling type) exhibits an equivalent parallel input resistance that is virtually independent of level below 10 mV. It is constant at 100 k Ω below 10 MHz, and above 40 MHz it decreases approximately 12 dB/octave. The corner frequency is about 20 MHz. The influence of the coupled loss is increasingly apparent above 500 MHz. The solution rests in a special high impedance probe with the same sensitivity as a normal probe but more than 10 times the input resistance (Boonton Model 34-1A, or equivalent).
- 6.3 If the measurement frequencies are confined to the bands below 500 MHz, satisfactory results obtain without the use of the special rf probe. For measurements over the full range, the special high-impedance probe can be used at all frequencies, and the shield (conductive tube) should be used for all series measurements. It may be convenient to remove the shield for shunt measurements below 500 MHz, but its use is recommended above 500 MHz and whenever it is possible at lower frequencies, by using the shield in place of the outer wall clamp.

7.0 TEST SPECIMENS

7.1 Series Connection

The series connection is used to measure non-leaded, multilayer, ceramic capacitors. Test specimens are placed in a fixture between parallel surfaces of coin silver. Pressure is applied to the fixture to contact opposing terminal pads and support the specimen. It is evident that the terminal pads of the specimen should be sensibly parallel, and lightly coated with solder, if possible, to provide a shallow meniscus on each surface. The pliancy of the solder allows it to yield to slight irregularities, which improves the potential for a good electrical connection.