Letters

Comments on "High Frequency Performance of Multilayer Capacitors"

Gordon Kent and Mark Ingalls

We are pleased to see this addition to the analysis of high-frequency (HF) capacitors in the above paper.[1] As the authors acknowledge, the transmission-line model was suggested in *The RF Capacitor Handbook*, by V. F. Perna, 1979 edition, and it has certainly influenced the thinking of some engineers. We have developed this approach over a period of years, and it has proved very fruitful, particularly when applied throughout the microwave spectrum. Its principal disadvantage is the reluctance of many engineers to deal with distributed parameter networks.

The HF capacitor presents a challenging analytical problem. In a typical application, the external dimensions of the capacitor and connecting circuitry are small enough compared to a free-space wavelength so that quasi-static analysis is applicable. In the interior, however, the high dielectric constants used imply a guided wavelength which may be comparable to the capacitor dimensions. In fact, there are numerous broad-band applications for which the capacitor is several wavelengths long at the upper frequencies. Out-of-band performance at the high-frequency end is also an important consideration for electromagnetic compatibility. Although quasi-static theory may be appropriate for exterior circuitry, a more complete field-theoretic analysis may be required for the interior at the upper end of the spectrum.

The problem is further complicated by the effects of neighboring electrodes and connection configuration. Ground planes produce images which change the effective dielectric constant [1], wire bonds add inductance, and the location of the driving point affects the excitation of resonant modes [2]. Experimental confirmation is often inhibited by the lack of good data on interior dimensions and the properties of the materials. This is particularly true for the multilayer capacitors (MLC's).

The analysis in the above paper[1] applies quasi-static theory in the guise of capacitance, inductance, and resistance matrices to the interior of the capacitor. We are not persuaded that this approach is justified even if it is not extended to frequencies much above the first resonance. Our objections can be based on two hypothetical experiments with the type B connection of a parallel-plate capacitor. For both experiments, we assume no fringing fields, no radiation, nearly perfect materials, and plates thicker than the skin depth to shield the interior of the capacitor from exterior fields.

In the first experiment, we divide the capacitor horizontally with a perfectly conducting sheet as indicated in Fig. 1. The voltages $\mathrm{V_A}$ and $\mathrm{V_D}$ between terminals A and G and between D and G are

$$\mathrm{V_A} = -ji_0(\mathrm{Z}_0/2)\cot\beta l \quad \text{and} \quad \mathrm{V_D} = ji_0(\mathrm{Z}_0/2)\cot\beta l \qquad (1)$$

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[1] A. T. Murphy and F. J. Young, *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2007–2015, Sept. 1995.

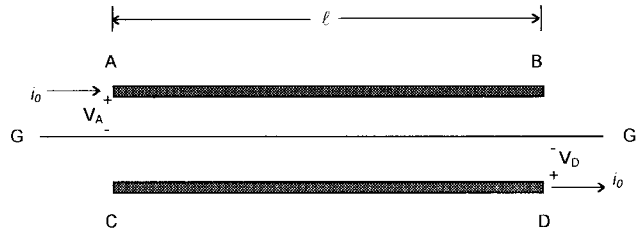

Fig. 1. Diagram of the first hypothetical experiment.

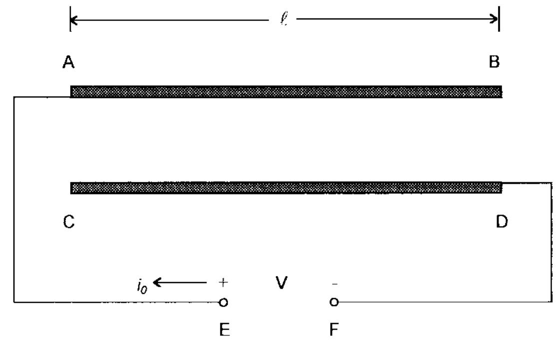

Fig. 2. The connections from A to E and from D to F are perfectly conducting sheets.

where Z_0 is the characteristic impedance of the undivided line. Since the net current in the dividing sheet is zero, nothing changes when it is removed. The impedance one would measure between A and D, after accounting for lead reactance, is just

$$\mathrm{Z_{AD}} = -j(\mathrm{Z}_0/2)\cot\beta l = \mathrm{Z_{AC}} \qquad (2)$$

which is the impedance of the type A connection.

If one objects to this argument for its lack of a good definition of $\mathrm{Z_{AD}}$, we consider for the second experiment a configuration for measuring the impedance as shown in Fig. 2. On the E–F plane, we assume unique definitions of current and voltage so the VI^* correctly represents the complex power. We also assume that the fields problem in the volume bounded by the conducting sheets and the AC face of the capacitor can be solved. Thus, we can calculate the stored energy in this volume and the relation between the voltage V at E–F to the voltage across AC. In the quasi-static approximation, the current is i_0 at both E and A. The voltage across AC differs from V by the drop across the series inductance ($\mathrm{L_S}$), in effect the inductance of the current loop formed by the connecting plates. The impedance measured at E–F will be the impedance $\mathrm{Z_{AC}} + j\omega\mathrm{L_S}$. If part of $\mathrm{L_S}$ (say $\mathrm{L_{DC}}$) can be attributed to the current on the under side of the capacitor, then we would infer that:

$$\mathrm{Z_{AD}} = \mathrm{Z_{AC}} + j\omega\mathrm{L_{DC}}. \qquad (3)$$

In this approximation, the current on the underside is independent of x and not governed by transmission-line equations.

In the above paper[1], (A6) and (A7) show ac currents in the x direction of $i_0/2$ flowing in both plates. These codirectional currents cannot be determined from the transmission-line equations [3]; they must arise, if they exist at all, from external connections to the source.

Since they are independent of x, the corresponding current densities have no transverse component and do not contribute to the charge on the capacitor plates. In the example of Fig. 2, there is a current of i_0, independent of x, but it is an exterior current. It serves as the return for the current flowing from the interior at C and has no effect on the charge or energy in the interior of the capacitor.

Equations (A1)–(A4) in the above paper[1] should be applied only to the interior of the capacitor and to the oppositely directed current. Accordingly, one should put $i_0 = 0$ in (A4). Then (A5) is homogeneous, as it should be, and the solutions (A6) and (A7) for Fig. 2 are

$$i^{\mathrm{T}}(x) = i_0 \sinh \alpha(l - x)/\sinh \alpha l \tag{4}$$

$$i^{B}(x) = i_0(1 - \sinh \alpha(l - x)/\sinh \alpha l). \tag{5}$$

In (5), we have added the return current so that the condition at $x = 0$ is satisfied.

These arguments suggest that $\mathrm{Z_{AC}}$ is the unique representation of the capacitor per se, but the user should recognize that the connection configuration may result in a different driving point impedance. Most often, a series inductance is added so that the first series resonance is lowered. Our analysis also implies that the dissipated power in the B-type connection should exceed that of the A-type connection, a conclusion apparently contrary to that of the above paper.[1]

The first resonance of a capacitor is not easy to measure [4]. The value of $|\mathrm{Z_{AC}}|$ is small relative to the 50-Ω characteristic of the typical measurement system, and its minimum is often too broad to allow a good frequency determination. Moreover, the frequency of zero phase critically depends on the location of the reference plane, which is difficult to establish with precision. To put it differently, the resonance frequency is sensitive to the unknown reactance of the connection. In contrast, the first anti-resonance (parallel resonance) is a sharply defined maximum of $|\mathrm{Z_{AC}}|$, insensitive to the reference plane or connection reactance.

We have treated the multilayer capacitor (MLC) as a periodically loaded transmission line [5], derived by folding a parallel plate line [2]. The model has been confirmed, more or less, by measurements of anti-resonances, and it has been invaluable for explaining how resonances are affected by the mounting on microstrip lines. One would presume from the model that the first resonance should occur at a frequency no less than half that of the first anti-resonance. After measurements of countless samples, we could conclude that this presumption was probably correct, notwithstanding the poor quality of the data. It is contrary to the data displayed in Fig. 12 of the above paper.[1] Our data also showed nearly harmonic relations between the frequencies of antiresonances, contrary to that shown in Fig. 12. We have no explanation for this discrepancy.

Our differences with the above paper[1] are indicative of the fact that the problem of the HF (microwave) capacitor is not completely solved. Nevertheless, the transmission-line concept has been of great value to Dielectric Laboratories, Inc., in the design of capacitors and the development of application notes. The analysis appears in current catalogues and over 15 000 copies of software for aiding circuit designers [6] have been distributed to practitioners in the RF and microwave community.

References

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Author's Reply

F. J. Young

In the above paper[1] we established a model based upon the theory of coupled transmission lines which is well known and follows directly from Maxwell's equations [1]. In that model each plate acts as a coupled transmission line to which signals and loads can be applied at both ends. We solved Maxwell's equations for TEM propagation in all space to obtain the matrices describing the coupled transmission lines used to represent the multilayer capacitors. The proper terminations for coupled transmission lines representing multilayer capacitors were discussed and utilized in the analyses of multilayer capacitors for which experimental results were available. In all cases, we present enough information about the capacitors that everyone can make their own calculations to verify these results. That is certainly not true in the references cited by Kent and Ingalls.

The first "experiment" of Kent and Ingalls is an attempt to use a single transmission line to model a type-B connection in a two-plate capacitor. A type-B connection implies the presence of a ground plane through which the return current flows to the signal source. With a type-B connection a simple two-plate capacitor can be represented only by two coupled transmission lines. The horizontal division of the capacitor by a fictitious conducting sheet in the first "experiment" is an attempt to model the capacitor as a single transmission line with only one velocity of propagation. Although the same current that enters at terminal A exits at terminal D in this model, the model does not permit the correct electric fields to exist in the dielectric between the plates. In fact, the inclusion of the horizontal conducting sheet and the attendant voltages given by (1) of Kent and Ingalls causes a discontinuity in the electric field where the horizontal conducting sheet is located. This can be true only if there is charge on the sheet. This violates one of the simplest Maxwell equations.

The second "experiment" is another attempt to represent a multilayer capacitor with a type-B connection by a single transmission line. Here the importance of the return current is admitted but not handled correctly. If one is going to use transmission line models, the correct ones must be used. The fields in all space must be handled in accordance with Maxwell's equations as they are in the theory of coupled transmission lines or in full-wave three-dimensional (3–D) models. The statement that Kent and Ingalls' analysis implies a conclusion about the relative power dissipation of the two connections is not substantiated by any presented evidence, so it can hardly be used to challenge the conclusions of the above paper. [1]

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