INVESTIGATION OF THE MICROCOMB CAPACITOR

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THIS IS AS RECEIVED FROM CUSTOMER.

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CHAPTER I

INTRODUCTION

The microcomb capacitor is a recently developed solid state thin film device. The capacitor consists of two coplanar interdigitated microcomb plates located above or within a dielectric. The dielectric material of the capacitor is prepared by a variety of methods such as vacuum deposition, anodic oxidation or ion implantation by the use of an accelerator. A diagram of a typical microcomb capacitor is shown in Figure 1.

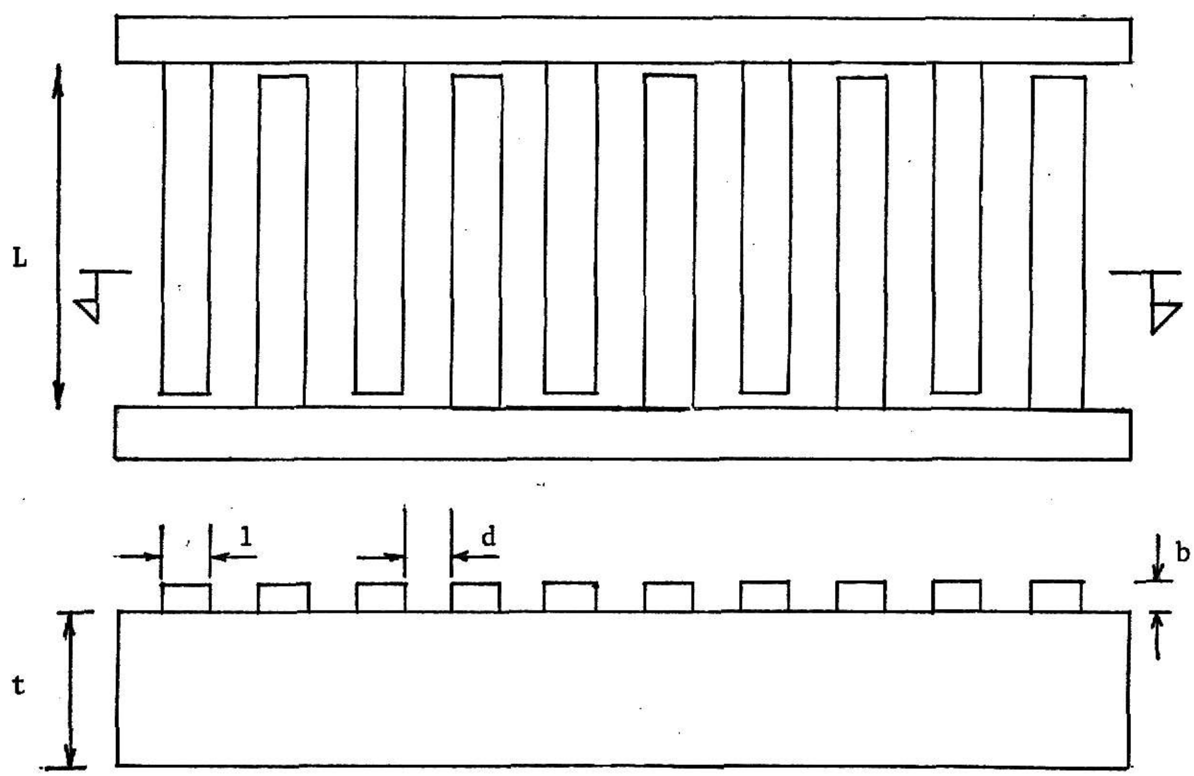


Figure 1. A microcomb capacitor.

The above diagram and the subject matter presented here are taken from a British patent application by Lucas (2). It is maintained in the patent application that the potential advantage of the microcomb capacitor is its high degree of flexibility to adjust its characteristics to any particular application. It also appears that it is possible to obtain a low dielectric loss and a negative temperature coefficient of resistance for the capacitor, which are desirable, by the use of implantation techniques. Furthermore it is possible to trim the capacitor so as to obtain an accurate value of capacitance. The inherent advantage of a microcomb capacitor is its ease of fabrication. By use of special configuration the capacitor can be used in the GHz range (2).

Cohen *et al.* have investigated the properties of the microcomb capacitor where a laser beam is used to cut the gap of the capacitor. Apart from this investigation little experimental work has been done. The aim of the present investigation is to examine the theory of the microcomb capacitor and to show how it can be fabricated by the use of the photolithographic process. Since this experiment has not been performed before, the agreement between the theory and the experiment needs to be pointed out. Theoretical justification is presented for the experimental results obtained, and possible improvements in experimental methods are also indicated.

CHAPTER II

REVIEW OF LITERATURE

Thin film devices are labeled by the method used in their fabrication. Thin film capacitors are essentially fabricated in a parallel plate configuration (17). The electrode of the capacitor can be deposited by vacuum evaporation, or by sputtering (18, 19, 20). The dielectric material between the capacitor electrodes may be deposited by anodic oxidation or other methods--such as vacuum deposition etc. (8). The usual metals used for electrodes are tantalum, titanium, and aluminum. The dielectric material is an important factor in obtaining an efficient capacitor. Many dielectric materials do not give ideal performance in one aspect or another (16). Some of the desirable characteristics are break-down voltage, frequency dependence, reliability of the component and its life expectancy (11). The selection of the dielectric material has usually been restricted to the oxides of aluminum, silicon, tantalum or titanium including barium titanate. These dielectric materials can be deposited either by anodic oxidation or by vacuum deposition.

Microphotography has been employed successfully for fabrication of thin film devices. The method of making the master patterns required for microminiature circuits has been developed to a considerable degree of perfection by use of photoresists and microphotographs. Vacuum deposition of dielectric and conductive films making use of in-contact and out-of-contact masks has been accomplished by previous investigators. The etching process is carried out by selectively removing metal films of micron thickness without severe undercutting (6).

Recently, capacitors of extremely small gap widths have been fabricated by the use of a laser beam. A thin film of chrome gold was deposited on the substrate of barium titanate or sapphire and gaps were cut in the metal film by the use of a laser in order to form capacitors. One of the investigators, Cohen, has reported a considerable degree of success (9). Cohen _et al._ indicated that the use of a microcomb configuration for the gap gave higher specific capacitance.

Kaiser and Castro have made use of an analytical model for a microcomb capacitor, and they presented an equation for the calculation of the capacitance on the assumption that the dielectric constant of the material is very high (10). The experiments of Cohen _et al._ confirmed the validity of the analytical expression for the capacitance with substrates of very high relative dielectric constant. But considerable deviation was found for dielectrics with dielectric constants of less than 10. They ascribed this deviation to the assumption made in their analysis which did not hold good for substrates with low values of relative dielectric constants. Their frequency tests indicated a flat response of capacitance for frequencies up to 4 GHz, which showed that their capacitors were reliable at this frequency. The acute sensitivity to gap widths lower than 1 mil suggested to Cohen _et al._ that high specific capacitance could be achieved by adopting very small gap widths for the microcomb capacitors. Their experimental investigation could proceed down to a gap width of 1/2 mil. These experiments indicate that a specific capacitance of 4.5×10^{-4} pF/mil^2 had been achieved by use of lasers to cut the gaps. Gaps of less than 1/2 mil and a corresponding higher specific capacitance could be achieved with laser machining. It was estimated by Cohen _et al._ that it would be possible to obtain a specific capacitance of 1×10^{-2} pF/mil^2 by reducing the gap width to 0.2 mil. They also reported that by using laser machining capacitors with leakage currents of less than 10^{-9} amperes at 40 V were obtained.

The main disadvantage of a conventional thin film capacitor is that it cannot be altered or trimmed to give the desired value of capacitance once it has been fabricated. This situation is a very serious disadvantage, especially when it is known that protective coatings, such as silicon nitride, change the capacitor's parameters considerably. It is in this regard that the major advantage of a microcomb capacitor exists. Not only is it possible to adjust accurately the parameters of a microcomb capacitor after it is fabricated, but also it is possible to obtain an accurately controlled temperature coefficient of resistance. A microcomb capacitor is easier to fabricate since it involves deposition on only one surface thus obviating the necessity for critical adjustment in registration or alignment. Since a microcomb capacitor is a relatively new concept, the theory involved needs to be studied in greater detail; this study is the subject of the following chapter.

CHAPTER III

THEORY

Dielectric Losses

Dielectric losses are of primary importance in the design of an efficient microcomb capacitor (1), and they are dependent on the polarization moments of the dielectric. The various polarization vectors are out of phase with one another, and hence give rise to a complex dielectric constant and to consequent losses. In an isotropic dielectric held in a static electric field the polarization vector $\vec{P}$ is parallel to the electric field vector $\vec{E}$ and the displacement vector $\vec{D}$ (9). That is,

$$\vec{D} = \varepsilon_o \vec{E} + \vec{P} = \varepsilon_o \varepsilon_s \vec{E} \tag{3-1}$$

where $$\vec{P} = \varepsilon_o \chi \vec{E} \tag{3-2}$$

ε_o is the absolute dielectric constant of vacuum, and $\varepsilon_s = 1 + \chi$, ε_s being the static relative dielectric constant and χ, the susceptibility, the ratio of bound charge density to free charge density.

If $\vec{E}$ is a time varying field, the polarization vector $\vec{P}$ has two parts: $\vec{P}_1$, which is independent of frequency, and $\vec{P}_2$, which is frequency dependent and lags behind the applied field. The displacement $\vec{D}$ is expressed by

$$\vec{D} = \varepsilon_o \vec{E} + \vec{P}_1(\varepsilon_o, \chi_1) + P_2(\varepsilon_o, \omega, \chi_2), \tag{3-3}$$

where χ_1 and χ_2 are the d.c. and a.c. susceptibility, respectively, and τ is the characteristic time of the relaxation process causing the delay of P_2.

The behavior of P_2 is described by the following differential equation:

$$\frac{d\,\vec{P}_2}{dt} = \frac{\vec{P}_o - \vec{P}_2}{\tau} \tag{3-4}$$

where P_o is the equilibrium value, and P_2 is any intermediary value at time t. For a particular time varying electric field $\vec{E}$, $\vec{P}_o = K\vec{E}_e{}^{jwt}$, where K is a constant related to the nature of the material and inversely proportional to the absolute temperature.

The solution of the above differential equation is given by

$$\vec{P}_2 = \frac{\vec{P}_o}{1 + jw\tau} \tag{3-5}$$

Equation (3-1) can be written for time varying fields as

$$\vec{D} = \varepsilon\,\vec{E} \tag{3-6}$$

where ε, the complex dielectric constant, is given by $\varepsilon' - j\,\varepsilon''$. If equation (3-5) is rationalized, then it is determined that

$$\varepsilon' = \varepsilon_1 + \frac{\varepsilon_s - \varepsilon_1}{1 + (\omega\tau)^2} \tag{3-7}$$

$$\varepsilon'' = \omega\tau\,\frac{\varepsilon_s - \varepsilon_1}{1 + (\omega\tau)^2} \tag{3-8}$$

with

$$\varepsilon_s = 1 + \chi_1 + \chi_2 \tag{3-9}$$

$$\varepsilon_1 = 1 + \chi_1. \tag{3-10}$$

From the foregoing, the dielectric loss is found to be equal to the ratio of

$\varepsilon''/\varepsilon'$ where ε'' and ε' are respectively the imaginary part and the real part of the complex relative dielectric constant. By use of the above result, the expression for flux density can be written as

$$\vec{D} = \varepsilon_o \vec{E} e^{j\omega t} (\varepsilon' - j\varepsilon'').$$

If a voltage V is applied to the capacitor of area A and of shunt specific conductance σ, the expression for current i is expressed as $i = V\sigma A + \varepsilon_o\varepsilon''\omega AV + j\varepsilon_o\varepsilon'\omega AV$ or $i = (G + Go)V + j\omega CV$ where Go is the shunt conductance and G is the dielectric loss (1). The loss component of the current flowing in the dielectric is consequently due to shunt conductance as well as to the dielectric loss component which is proportional to $\omega\varepsilon_o\varepsilon''$.

<u>The Distributed Effects of the Capacitor</u>

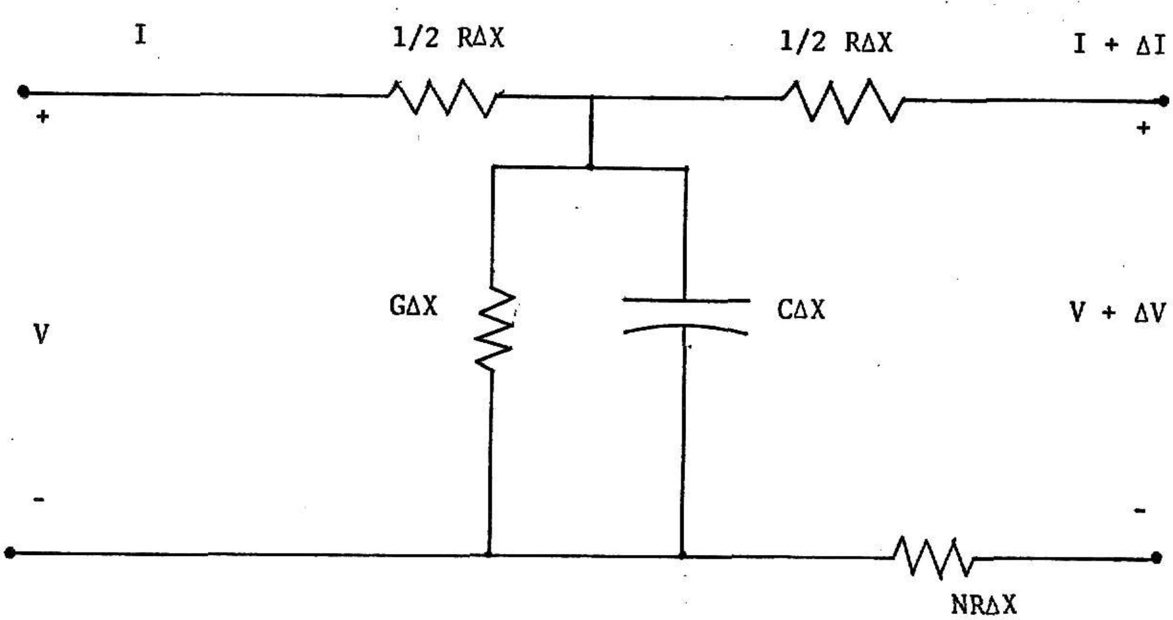


Figure 2. Distributed network.

The distributed effects of a thin film capacitor have to be taken into account when an accurate assessment of its performance is required. The lumped approximation does not suffice when dimensions of the order of the mean free path of the electrons are considered. For very thin film capacitors, the size effect due to diffuse scattering also has to be taken into account when dimensions of the order of 400 angstroms or less are encountered (24). This size effect comes into play when the mean free path of the electrons in the film is comparable to the thickness of the film. In such a case, the collisions between the conduction electrons occur mostly at the surface of the film, and consequently the resistivity of the film increases.

The distributed nature of capacitance and resistance of the thin film capacitor is similar to that of a transmission line, as far as the equivalent circuit is concerned. The well known expression for the impedance of a transmission line can be applied to the thin film capacitor, assuming it to be a two-port transmission line (see Figure 2).

If C and R represent per unit length capacitance and resistance in Fd/m and ohm/m respectively, if N is a constant that relates the resistance per unit length of the two plates of the capacitor, and if G represents all shunt losses including those caused by surface leakage and dielectric losses, the equation for input impedance can be expressed as

$$\text{Input} = \frac{R(N+1) \qquad \text{Coth}\{[(G + j\omega c)(N+1)R]^{1/2} \times L\}}{[(G + j\omega c) \times (N+1) \times R]^{1/2}} \qquad (3\text{-}11)$$

where L is the length of the conduction path of the capacitor and ω is the frequency (1). When the above expression is simplified, the expression for dielectric loss, which is equal to Tan δ, is expressed as

$$\text{Tan}\ \delta = \frac{B.\ \text{Sin UB}\ .\ \text{Cos UB} - A.\ \text{Sinh UA}.\ \text{Cosh UA}}{A.\ \text{Sin UB}.\ \text{Cos UB} + B.\ \text{Sinh UA}.\ \text{Cosh UA}.},$$

where

$$B = \sqrt{\frac{-G}{\omega C} + \sqrt{1 + (\frac{G}{\omega C})^2}}, \qquad A = \sqrt{\frac{G}{\omega C} + \sqrt{1 + (\frac{G}{\omega C})^2}},$$

and $$U = \sqrt{\frac{\omega(N + 1) RCL^2}{2}}. \qquad (3\text{-}12)$$

The value of tan δ at any frequency can be found by substituting the value of the frequency in the above expression and evaluating it. On evaluation, the value of tan δ,

$$\text{At } U \approx 0, \text{ is } = -G/\omega C \qquad (3\text{-}13)$$

and $$\text{At } U \approx \infty, \text{ is } = -1. \qquad (3\text{-}14)$$

Hence for very high frequencies the value of tan δ is finite and tends to be equal to -1.0; whereas for lumped impedances the tan δ will tend to be infinity (1). The distributed effects of the microcomb capacitor tend to lower tan δ and the dielectric loss.

Furthermore, tan δ can be further reduced by keeping the series plate resistance and the lead resistance of the capacitor as low as possible. If the connecting leads of the capacitor are made of gold, the resistance will be minimum. Also, if an overlayer of a thick conductor is provided for the capacitor electrodes in order to effectively reduce the resistance by increasing the cross section of current flow and decreasing the length of the current flow path, tan δ can be further reduced. These are some of the aspects worth remembering when constructing a microcomb thin film capacitor (1).

Capacitance Calculation by Computer Method

The standard methods of numerical analysis can be applied to compute the capacitance of a microcomb capacitor. Laplace's equation is solved in two dimensions by the iteration method with a suitable relaxation factor. This procedure is particularly suited to the use of a digital computer.

Laplace's equation is written in two dimensions as

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} = 0, \tag{3-15}$$

if the system is assumed to be very long in the Z dimension and free of electric charge. This differential equation may be replaced by a finite difference approximation. To do so, one must consider the nine points of the X-Y plane shown in Figure 3.

Referring to Figure 3, one observes that ε_1 and ε_2 are the relative permittivities of the two dielectric media. Since the surface charge at the interface is assumed to be equal to zero, then Gauss' Law is $\nabla \cdot \vec{D} = 0$ everywhere in the system or

$$\frac{\delta D_x}{\delta x} + \frac{\delta D_y}{\delta y} = 0. \tag{3-16}$$

Also, $$\vec{D} = \varepsilon\vec{E} = -\varepsilon\vec{\nabla}V = -\varepsilon\frac{\delta V}{\delta x}\vec{a}_x - \varepsilon\frac{\delta V}{\delta y}\vec{a}_y \tag{3-17}$$

with the $\vec{a}_x$ component given by,

$$\left.\frac{\delta V}{\delta x}\right|_{\text{at } a} \simeq \frac{V_1 - V_0}{h}$$

where h is the separation distance between V_0 and V_1, which is taken to be

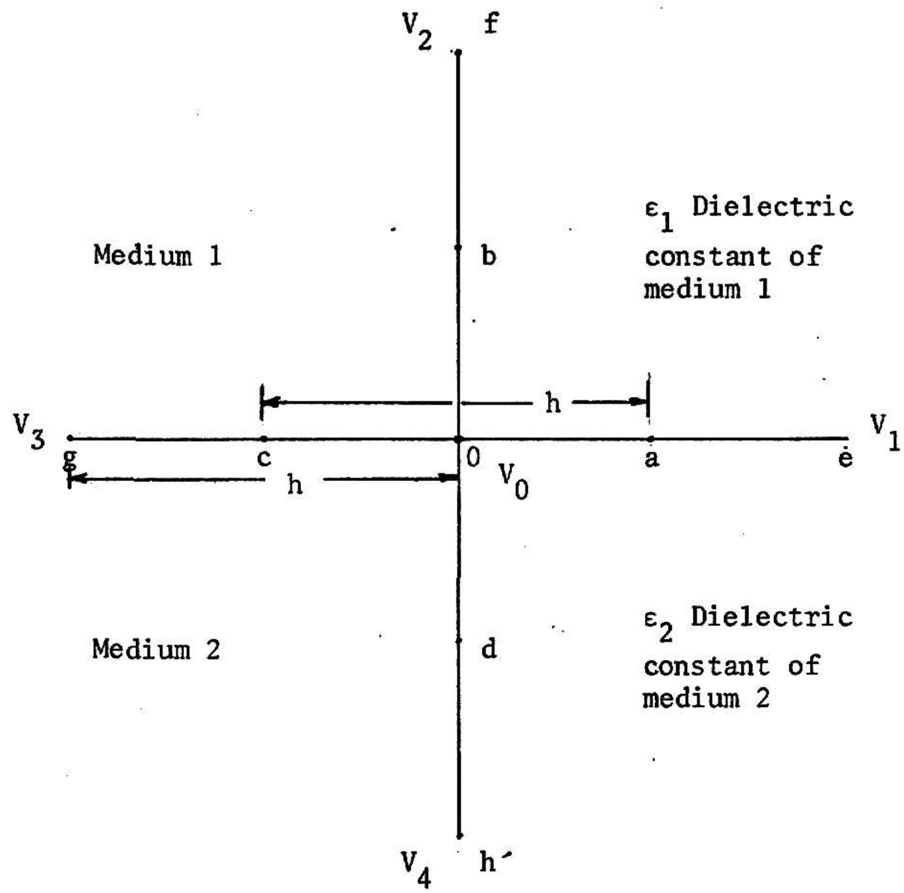


Figure 3. The finite-difference approximation for calculation of $\nabla^2 V$.

small. Likewise,

$$\left.\frac{\delta V}{\delta x}\right|_{\text{at } c} \simeq \frac{V_0 - V_3}{h} \tag{3-18}$$

$$\left.\frac{\delta D_x}{\delta x}\right|_{\text{at } o} \simeq \frac{\left.\varepsilon \frac{\delta V}{\delta x}\right|_{\text{at } a} - \left.\varepsilon \frac{\delta V}{\delta x}\right|_{\text{at } c}}{h} \simeq \frac{\varepsilon(V_1 + V_3 - 2V_0)}{h^2} \tag{3-19}$$

where ε is either ε_1 or ε_2 in the above equation, since ε does not change in the X direction. Similarly, the $\vec{a}_y$ component is determined by the following procedure.

$$\left.\varepsilon_1 \frac{\delta V}{\delta y}\right|_{\text{at } b} \simeq \frac{\varepsilon_1(V_2 - V_0)}{h} \tag{3-20}$$

$$\varepsilon_2 \frac{\delta V}{\delta y}\bigg|_{\text{at } d} \simeq \frac{\varepsilon_2 (V_0 - V_4)}{h} \tag{3-21}$$

$$\frac{\delta D_y}{\delta y}\bigg|_{\text{at } o} \simeq \frac{\varepsilon_1 \frac{\delta V}{\delta y}\Big|_{\text{at } b} - \varepsilon_2 \frac{\delta V}{\delta y}\Big|_{\text{at } d}}{h} \simeq \frac{\varepsilon_1 (V_2 - V_0) - \varepsilon_2 (V_0 - V_4)}{h^2} \tag{3-22}$$

Combining results and assuming V_1 and V_3 are in Medium 1, the Laplace equation is found to be equal to

$$\frac{\delta D_x}{\delta x} + \frac{\delta D_y}{\delta y} = 0 = \frac{\varepsilon_A (V_1 + V_3 - 2V_0)}{h^2} + \frac{\varepsilon_1 (V_2 - V_0) - \varepsilon_2 (V_0 - V_4)}{h^2} \tag{3-23}$$

where $\varepsilon_A = (\varepsilon_1 + \varepsilon_2)/2$ is the average permittivity at the interface. After multiplying thru by h^2 and $\frac{1}{\varepsilon 0}$, V_0 is expressed by

$$V_0 \simeq \frac{1}{2\varepsilon_A + \varepsilon_1 + \varepsilon_2} \times (\varepsilon_A (V_1 + V_3) + \varepsilon_1 V_2 + \varepsilon_2 V_4) \; . \tag{3-24}$$

The above expression becomes exact as h approaches zero, but is sufficiently accurate for very small h values. The iterative method merely uses the above expression to determine the potential at every coordinate of an n x m matrix superimposed over the microcomb geometry. The process is repeated over the entire n x m coordinates of the matrix-field as many times as are necessary until the values no longer change. To facilitate fast convergence to the ultimate invariant and correct value of potential, a relaxation method is used. Relaxation consists in multiplying each residual, Δv, which is expressed as

$$\Delta V = V_0 - \frac{\varepsilon_A (V_1 + V_3) + \varepsilon_1 V_2 + \varepsilon_2 V_4}{2\varepsilon_A + \varepsilon_1 + \varepsilon_2} \; , \tag{3-25}$$

by an empirically determined factor. In the present method of over-relaxation the residual, which is the difference between the present potential and the potential that just preceded it, is multiplied by a factor of 1/2 and added to the present potential. This is the over-relaxed value of the potential to be used in the subsequent calculations. That is, if A is the weighted average of the four adjacent voltages as given by (3-24) then the new potential at that point is given in terms of A and the previous potential by

$$(V_o)_{new} = (1 - ALP)(V_o)_{old} + (ALP)A. \tag{3-26}$$

Where ALP is the over-relaxation factor, which is equal to 1.5.

By using this procedure of successive relaxation and iteration the potential distribution of the whole n x m matrix field is obtained. The capacitance, C, is calculated as follows. It is known that the flux and equipotential lines always cross at right angles, and that they form more or less rectangular figures. A typical rectangle is shown in Figure 4. The development of its bounding lines into the paper marks out a boxlike space. All the flux crossing through the box enters through the top (V_1) and leaves through the bottom (V_2) equipotential surface; none can cross through the sides, for the sides are defined by flux lines, which may not intersect. At the middle of the box, let the distance between box sides be w. The flux density in the box, assuming unit depth, is then approximately $\vec{D} = \frac{\psi}{w}$, (3-27)
where ψ is the flux. The accuracy of this approximation may be judged from the variation of boxwidth, for ψ is the same through both top and bottom.

The magnitude E may be calculated as follows. In the box, E = - grad V gives, approximately,

$$= \frac{V_1 - V_2}{h} = \frac{\Delta V}{h} \tag{3-28}$$

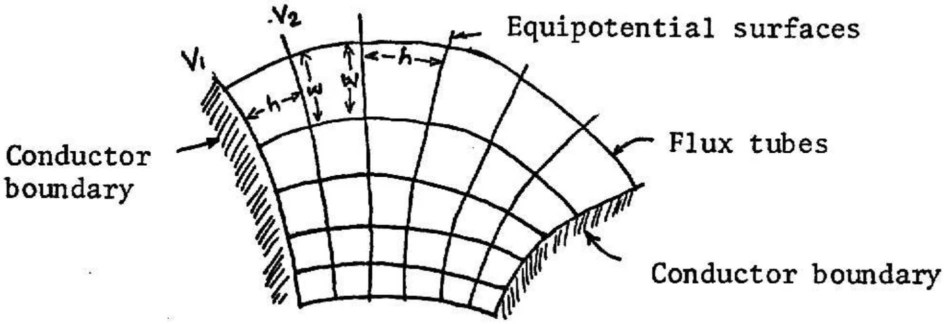


Figure 4. Flux lines and equipotential lines forming an approximate rectangle.

where h is the height of the box in the middle. Now $\vec{D} = \varepsilon \vec{E}$; equations (3-27) and (3-28) may be combined to give

$$\frac{\psi}{w} = \frac{\varepsilon \Delta V}{h}$$

or rewriting

$$\frac{\psi}{\Delta V} = \frac{\varepsilon w}{h} \tag{3-29}$$

It should be noted that if the curvilinear figure is a square, so that w = h, then

$$\frac{\psi}{\Delta V} = \varepsilon, \tag{3-30}$$

a constant clearly independent of the size of the square provided both w and h are sufficiently small.

The total charge Q which is resident on the conductor surface due to the applied voltage V, is calculated by the summation,

$$Q = \Sigma\psi = \Sigma\varepsilon\Delta V \tag{3-31}$$

The summation is performed by adding the potentials of the matrix around any closed path enclosing the conductor. Let this sum be equal to V(K). A second summation is performed by adding the potentials along a closed path enclosing and adjacent to the first closed path. Let this sum be equal to V(K + 1). Then the capacitance is given by

$$C = \frac{V_{(k)} - V_{(k + 1)}}{V} \quad \text{Fd/m}, \tag{3-32}$$

where ε_o is the dielectric constant of the vacuum and V is the applied potential in volts. Several such summations can be performed and their average value computed.

The results of the computer output were summarized in the graph in Figure 5. The calculations were performed for d = 1 = 5 microns and t = 17.5 microns where d is the width of the gap of the capacitor and t is the thickness of the capacitor substrate-dielectric (see Figure 1). The calculations were repeated for $d = \frac{10}{3}$, $1 = \frac{20}{3}$ and t = 17.5 microns. These results were found to agree closely with the analytical expression of the microcomb capacitor, under conditions of zero electrode thickness, b, which is obtained by extrapolation of the graph of the capacitance vs. electrode thickness, b, down to zero value (see Figure 5).

Empirical Formula for a Microcomb Capacitor

An estimation of capacitance from the knowledge of electrostatics is accomplished if some approximations are made. The shape of the flux of the microcomb capacitor is assumed to be semicylindrical in the substrate. The flux outside of the substrate is assumed to be negligible because of the high

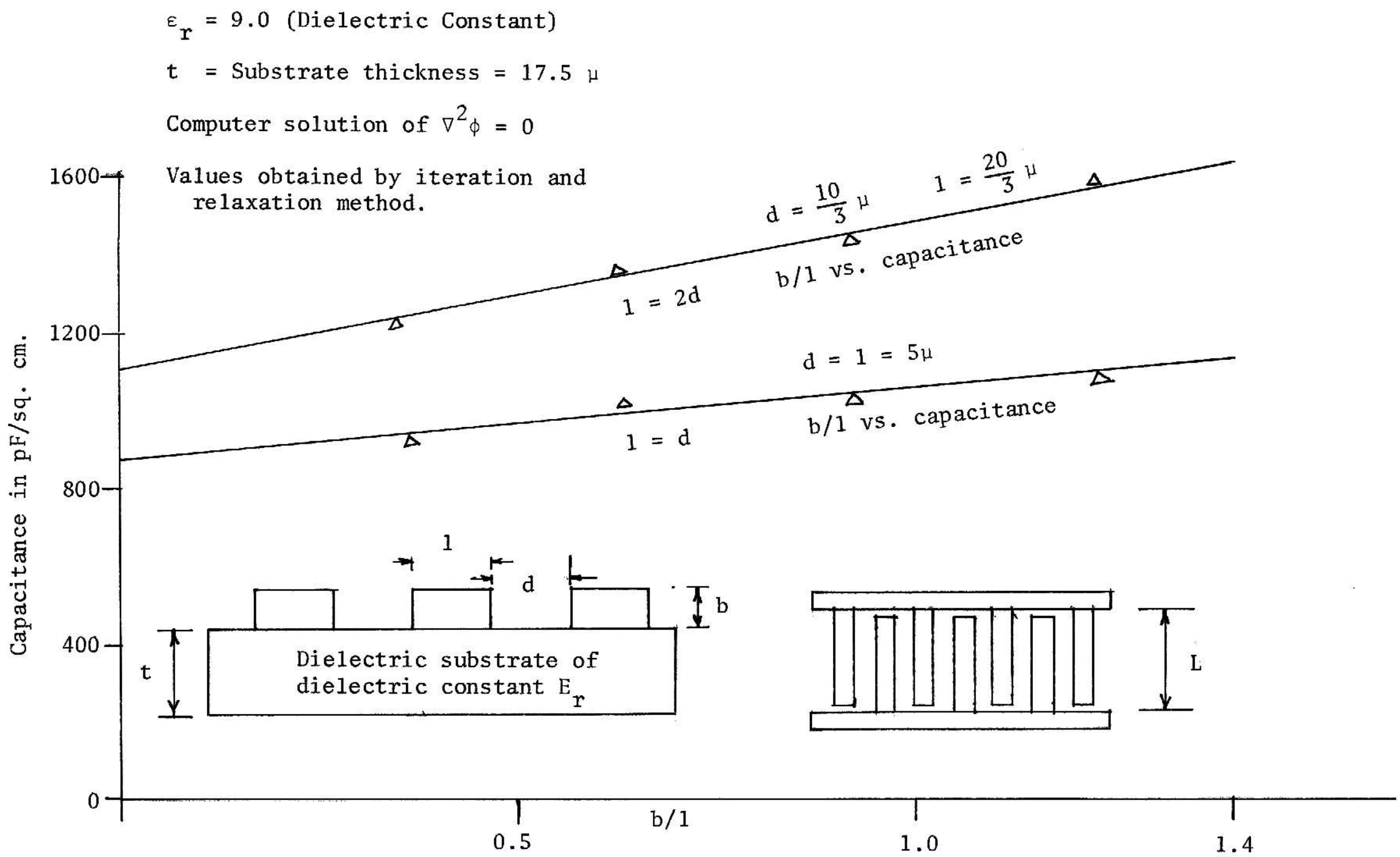


Figure 5. Calculation of capacitance by use of a digital computer.

dielectric constant of the substrate. The resulting capacitance is mainly fringe capacitance in nature, and no flux above the surface of the substrate is assumed to exist. The capacitance of any space is the ratio of the total electric flux passing through the space to the total electric potential applied across it.

If the magnitude of the electric flux density is $\vec{D}$, the electric flux passing across any surface of area S for a uniform field is

$$\psi = D \times S \times \text{Cos } \theta$$

where ψ is the electric flux, and θ the angle between $\vec{D}$ and the surface normal to S.

The electric-potential rise, V, along the flux lines is expressed as $V = \vec{E} \cdot \vec{l}$, where l is the length of the flux lines, and E is the electric field intensity. If the lengths of the flux lines are not the same, then the average length of the flux lines should be taken. For simplicity's sake, a semicylindrical region in the substrate is assumed to carry all the flux; hence, the volume of the flux path per unit length which is perpendicular to the plane of the paper is $= 1/2\ \frac{\pi}{4}\ [(d + l)^2 - d^2]$ and the mean flux path is $= \frac{\pi}{4}\ (l + 2d)$. The capacitance per unit length is

$= \dfrac{\varepsilon_0 \varepsilon_r (\text{Volume of the flux})}{(\text{Mean flux path})^2}$ where ε_r is the relative dielectric constant of the substrate and ε_0 is equal to 8.854×10^{-12} Fd/m.

The above formula is based on the assumption that the flux lines follow a semicircular path, but in reality this is not true. The flux lines tend to find the shortest path across the gap, and so some flux lines jump across the gap at the edges of the electrode and consequently have a shorter length.

Since the flux lines cannot cross one another or intersect at any place, some flux lines are forced to take a longer route to the opposite electrode. Because of this situation the actual capacitance measured after the fabrication is found to be approximately half the theoretical value. This modified formula is $C/\varepsilon_r = 0.364/1 + 2d/t$ pF/in. if $1/t \gg 1$ and if $.03 \lesssim d/t \lesssim .2$, where ε_r is the relative dielectric constant of the substrate. If $1/t < 1$, the above formula requires modification by the use of a multiplication factor, f, which is computed from the analytical expression for C (see Figure 6 and Figure 7). Similarly for the other ranges of d/t, multiplication factors are computed which agree with experimental results (see Figure 8). The reason for deriving these formulas is that their simplicity aids in making the calculations. The analytical expression of Castro involves the computation of the ratio of two hyperbolic tangents and then finding the ratio of two complete elliptical integrals, with these hyperbolic tangents, as their arguments. If this procedure can be replaced by a simple expression without sacrificing very much accuracy, the author feels the effort in determining these simple expressions is justified.

For extremely small gap widths (less than 10 microns), the capacitance is found by experiment to increase rapidly with decreasing gap width. A multiplication factor to be applied to the empirical formula in such a case is derived and presented in Figure 8.

Both the analytical expression of Castro and the author's empirical expression were derived on the assumption that the flux outside of the substrate is negligible. This situation exists only in the case of substrates of very high dielectric constants equal to approximately 400. For substrates of low dielectric constants, however, considerable flux exists outside of the

b = Electrode thickness
1 = Electrode width
d = Gap width
t = Thickness of substrate of dielectric constant E_r

Curve A for d/t = 1.0
" B " = 0.5
" C " = 0.3
" D " = 0.2

For explanation of symbols see Figure 5.

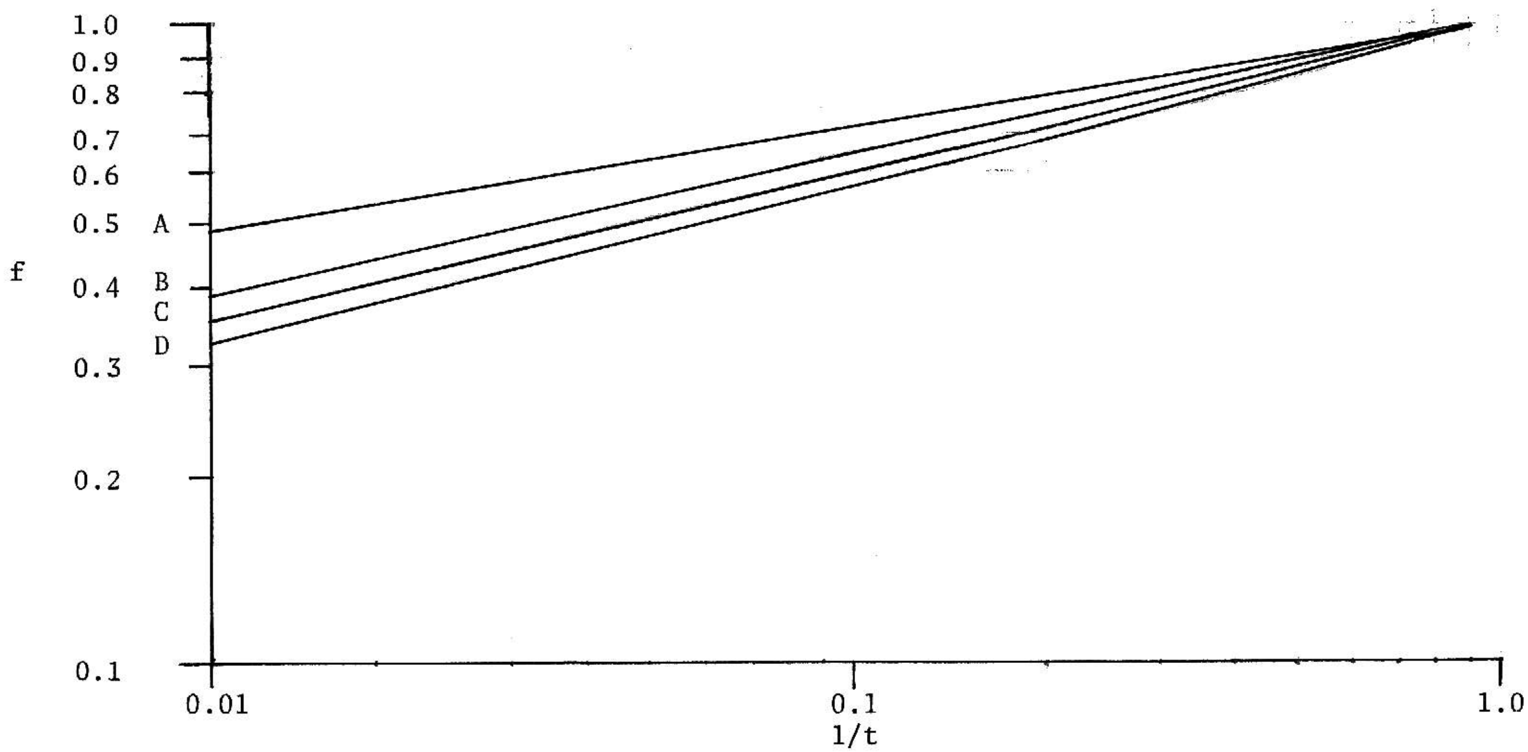


Figure 6. Exact multiplying coefficient f vs. 1/t for various d/t ratios (range of d/t = .2 to 1.0)

b = Electrode thickness
l = Electrode width
d = Gap width
t = Thickness of substrate of dielectric constant E_r

Curve E for d/t = 0.1
" F " = 0.05
" G " = 0.003
" H " = 0.002
" I " = 0.001

For explanation of symbols see Figure 5.

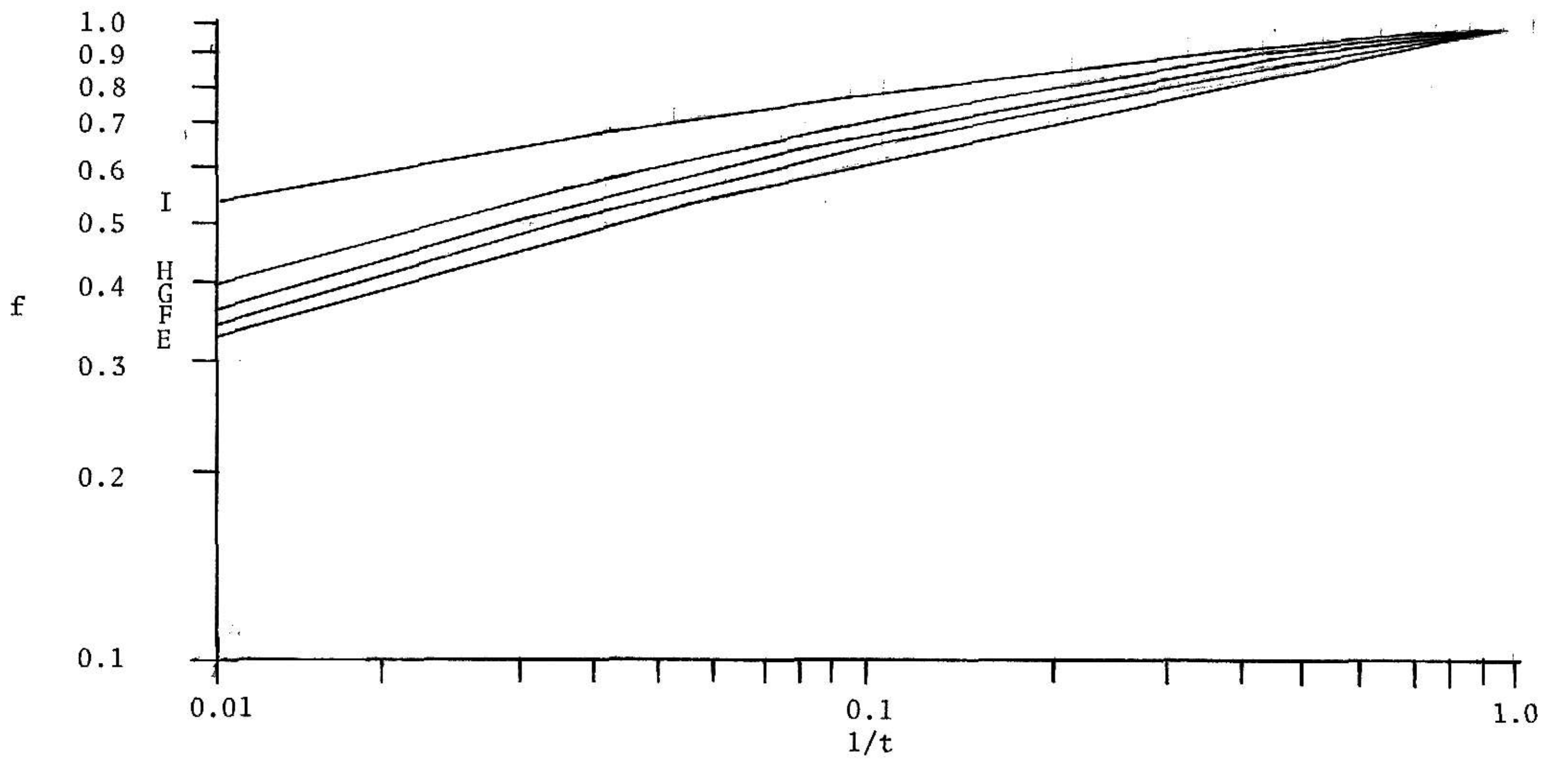


Figure 7. Exact multiplying coefficient f vs. 1/t for various d/t ratios (range of d/t = .001 to .1).

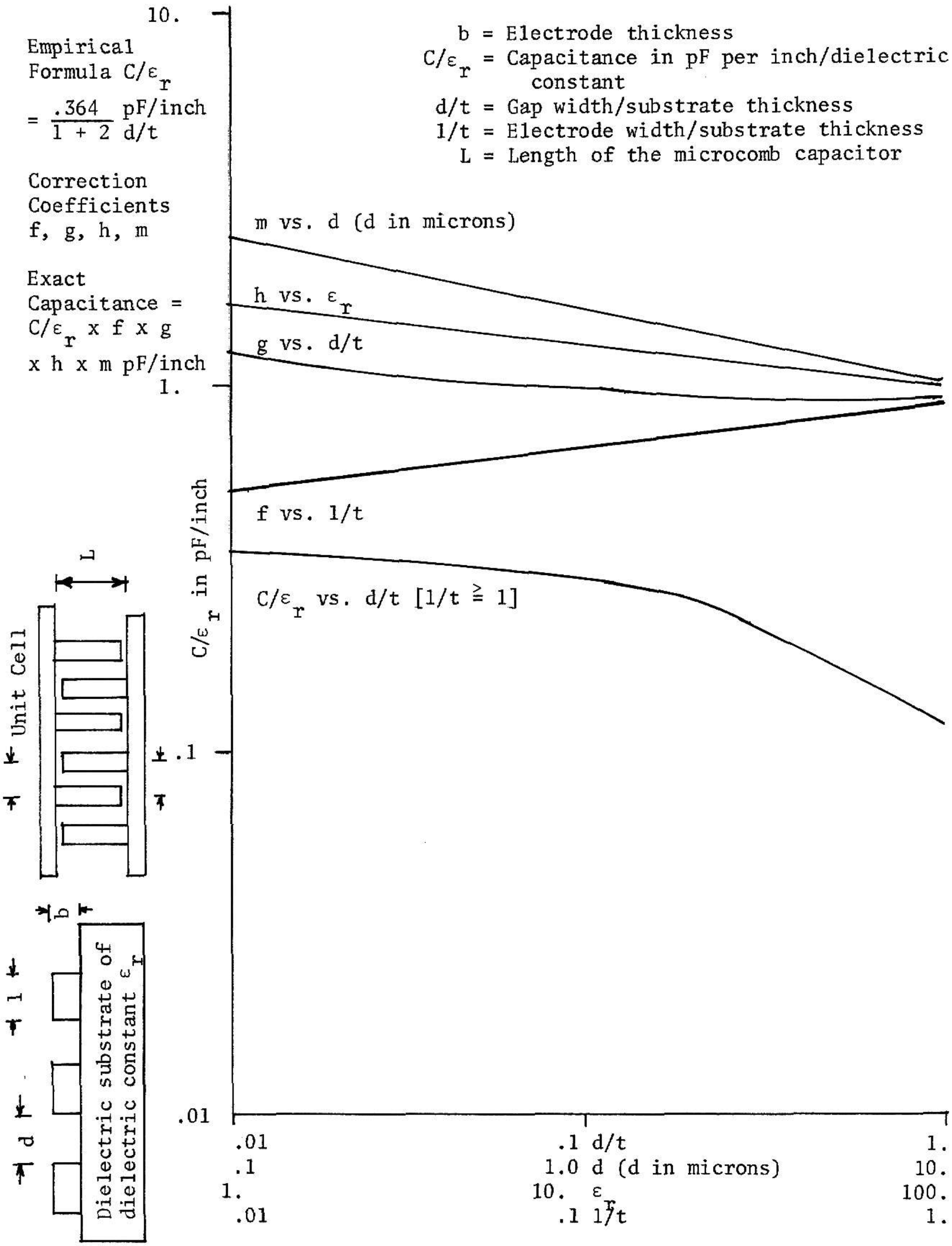


Figure 8. Practical values for capacitance C/ε_r for various d/t and l/t ratios.

substrate. To find the flux that lies outside of the substrate, it is assumed that the reduction of the substrate flux because of the leakage flux is similar to the reduction of the substrate flux produced by the reduction of electrode width. In the case of a high dielectric substrate with $\frac{1}{t} = 1$, let C be the capacitance. When 1 is reduced and $\frac{d}{t}$ is made equal to $\frac{1}{t}$, which is called normalizing, a reduction of the substrate flux results, with an accompanying reduced capacitance C*. A similar leakage of flux exists in a low dielectric substrate giving rise to reduced capacitance. The ratio of C/C* is similar to the ratio of the capacitances of the high dielectric and the low dielectric. It is evident from the analytical expressions that the ratio of C/C* for 1/t = 1, d/t = 1/20, and for $\frac{1}{t} = \frac{1}{20}$, $\frac{d}{t} = \frac{1}{20}$, respectively, is 2. The leakage flux is assumed to be zero for capacitors having $\varepsilon_r = 400$ and the leakage flux is equal to the substrate flux for a hypothetical capacitor having $\varepsilon_r = 1$; hence, the ratio of the total flux divided by the substrate flux is equal to 1 in the case of capacitor of $\varepsilon_r = 400$ and the same ratio is equal to 2 in the case of the hypothetical capacitor of $\varepsilon_r = 1$. It appears that the leakage factor, defined, by the total flux divided by the substrate flux, may be equal to the ratio of capacitance for $\frac{1}{t} = 1$ to the value of capacitance for

$$\frac{1}{t} = \sqrt{\frac{\varepsilon_{r1}}{\varepsilon_{r2}}}\ .$$

This hypothesis was verified and found to be true according to the author's experimental results. In particular for $\varepsilon_{r1} = 10$ and $\varepsilon_{r2} = 400$, by substituting in the above formula, $\frac{1}{t}$ is given by

$$\sqrt{\frac{10}{400}}\ . = \sqrt{\frac{1}{40}}\ , = \frac{1}{6.4} = .157.$$

For the ratio of $\frac{1}{t}$ = .157, C/C* is obtained by the expression

$$\frac{C \;\; (\text{for } 1/t = 1,\ d/t = .157)}{C^* \; (\text{for } 1/t = .157,\ d/t = .157)}$$

which is equal to 1.3.

The above multiplication factor, 1.3, for a dielectric constant of 10 agrees closely with the experimental results of Cohen et al. Similarly multiplication factors for other low dielectrics were calculated, and a curve was drawn (see Figure 8).

Analytical Expression for Capacitance

Since the microcomb capacitor is not a conventional thin film capacitor, the expression for the capacitance of a conventional thin film capacitor does not apply. The capacitance is obtained by the fringe flux that exists mostly in the dielectric substrate. Castro has derived for this situation an analytical expression which is expressed as follows:

$$C = .1125\ \varepsilon_r\ \frac{F\left(\sqrt{1 - \frac{\alpha^2}{\beta^2}},\ \pi/2\right)}{F\left(\frac{\alpha}{\beta},\ \frac{\pi}{2}\right)} \ : \text{pF/in}$$

where ε_r is the relative dielectric constant

$$\alpha = \text{Tan h}\ \left(\frac{\pi d}{4t}\right)$$

$$\beta = \text{Tan h}\ \left(\frac{\pi 1}{2t} + \frac{\pi d}{4t}\right)$$

and F is the complete elliptic integral with the argument shown in the parenthesis of the function (Appendix).

A computer output for capacitance for various l/t, d/t ratios was obtained. Curves were drawn for C/ε_r vs. d/t where C is the capacitance in pF/in with l/t, ranging from 1 to .001, as the parameter (see Figure 9). The leakage factors derived by use of the above curves for low dielectrics were found to agree closely with the experimental factors obtained by Cohen *et al* (9).

The author's experimental results confirmed the validity of the dependence of the substrate thickness upon the value of the capacitance. Furthermore, the author's experimental results agreed closely with the values obtained by use of the author's empirical expression.

Units Conversion and Comparison of the Computer Results with the Analytical and Empirical Formulas

If one gave the capacitance in pF/cm^2 whereas the capacitance in pF/in is desired, the conversion from the former to the latter may be obtained by finding the length of the microcomb capacitor strip in 1 cm length and dividing the capacitance in pF/cm^2 by this length which will give the capacitance as pF/cm. The resulting quantity is multiplied by 2.54 to give the capacitance as pF/in. A similar calculation in the reverse order gives the conversion from capacitance in pF/in to the capacitance in pF/cm^2. For a typical case in which a fine conductor pattern is deposited on the substrate having limbs of 1 cm length, widths of 0.010 inch and gap widths also of 0.010 inch, there will be approximately $\frac{1 \text{ cm}}{(.02)} \times 2.54 \approx 20$ cms of parallel strip of the capacitor per square cm (see Figure 10).

The empirical formula for the capacitance C/ε_r is

$= \frac{.364}{(1 + 2\ d/t)(1 + d)}$ pF/in^2 when $l/t \geqslant 1$ and $(1 + d)$ is in inches or

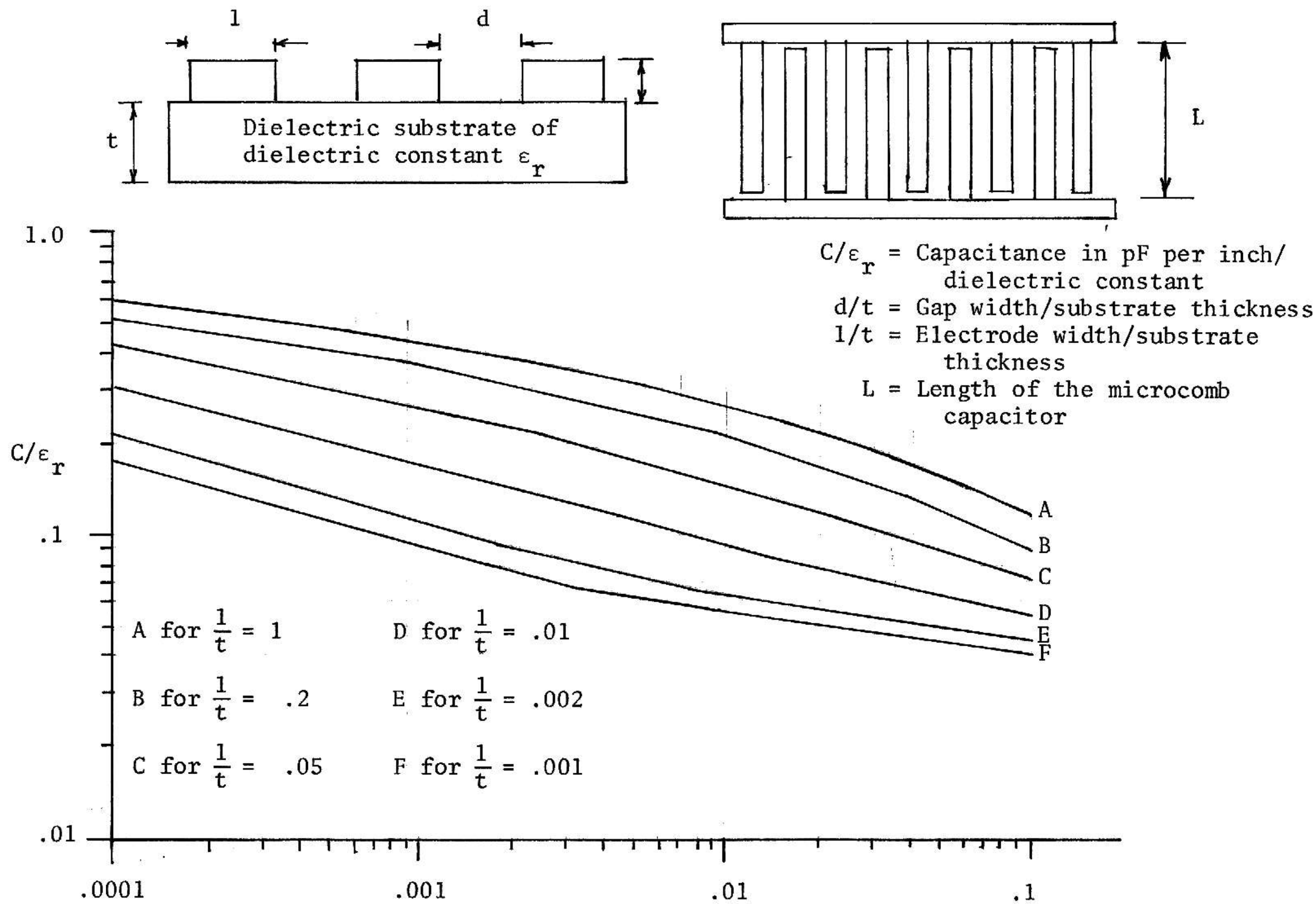


Figure 9. Theoretical values of C/ε_r vs. d/t for various l/t ratios.

$\frac{.364}{2.54\ (1 + 2\ d/t)(1 + d)}$ pF/cm^2 when $1/t \gg 1$, and $(1 + d)$ is in centimeters. For the case in which $1/t < 1$, the appropriate multiplying factor, f, is applied to the above formulae to arrive at the correct value of the capacitance (see Figure 6 and Figure 7).

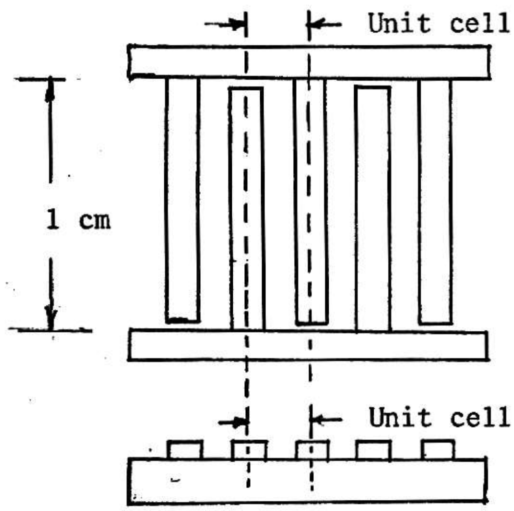


Figure 10. Calculation of capacitance by geometrical method.

In the case of a microcomb capacitor, when the conducting electrode width is 1, each such electrode must be considered as providing electrodes for two adjacent capacitors and an effective electrode width which is only half the total width in one unit cell of the microcomb capacitor should be considered in any calculation. However, in the case of straight gap capacitors, which are not 'microcomb' in the strict sense but are however related to the "microcomb" capacitor by the fact that they also give rise to capacitance by two electrodes deposited on the same side of the substrate, the full width has to be taken into account in finding the capacitance. The agreement of the analytical expression with the computer calculation of capacitance is explained in the following analysis.

A matrix of 100 x 22 is chosen for the electrostatic field in which the potential distribution is calculated by the iteration method. Out of the 100 rows, 30 rows are taken to represent the electrode thickness of the microcomb capacitor and 50 rows, the substrate. The remaining 20 rows represent the free space over the top of the electrode. The full thickness of the substrate on a comparative basis would require a larger matrix of rows, much more than an economical computation would warrant; therefore, the 50 rows of the matrix are made to represent only a part of the substrate truncated at the bottom. The potential, at the top of the substrate, of the electrode is known to be 100% of the applied potential. The potential of the bottom of the substrate is taken to be zero or ground potential. Since the representation is that of a truncated substrate, the last row of the matrix does not represent the bottom of the substrate, but is an intermediate layer of the substrate in which the potential is not at zero potential but is at some intermediary potential which is estimated approximately to be 30% of the applied potential. The assumed potential for the intermediate layer will determine the thickness of the substrate. In Figure 11, t represents the thickness of the substrate, R represents the assumed potential of the intermediate layer representing the truncated bottom of the substrate (30% of the applied potential), and x represents the difference between the thickness t and the height of the lower truncated portion of the substrate. From Figure 11 it is evident that x/t is equal to R/100, from which equation it follows that t is equal to 70 rows, since (t - x) is equal to 50 rows. Similarly, columns 1 to 11 represent half of the electrode width and the remaining 12 to 22 columns represent half of the gap width. If the capacitance of a microcomb capacitor with a unit cell of 10 microns is desired (see Figure 10), it is necessary to equate the 10

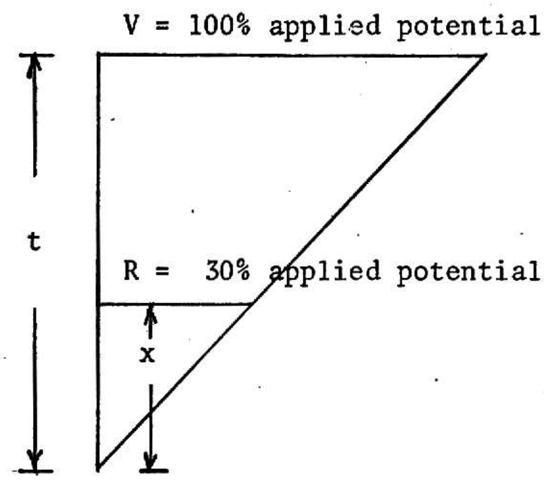


Figure 11. Pertaining to the calculation of the thickness of the substrate.

columns which represent half the gap width with half the gap width of a unit cell which is 5 microns. Likewise, half of the electrode width of 10 columns needs to be equated with half the electrode width of the unit cell. In the same proportion, the substrate thickness is calculated and found to be 17.5 microns, since 4 computer columns represent one micron width on the above basis of calculation. Having found the gap width, d, the electrode width, l, and the substrate thickness, t, the ratios d/t and l/t are found to be 20/70 and 10/70 respectively. (Only half the electrode width is taken into account since this is a microcomb capacitor of interdigitated gaps.) For the above values of d/t and l/t the capacitance is obtained from the formula given by $C/\varepsilon_r = (0.364 \times \varepsilon_r/(1 + 2 \cdot d/t) \times f \times g \times h \times m$ pF/in.

The multiplying factors f, g, h and m are appropriate if $l/t < 1$, if $.03 \leqslant \frac{d}{t} \leqslant .2$, if relative dielectric constant, $\varepsilon_r < 10$, and if gap width < 10 microns, respectively. In the computer program,

$l/t = .15$

$d/t = .3$

f (for $l/t = .15$) = .7 From graph of Figure 8

g (for $d/t = .3$) = .935 From graph of Figure 8

h (for $\varepsilon_r = 9$) = 1.325 From graph of Figure 8

m (for $d = 5$ microns) = 1.15 From graph of Figure 8

and $\varepsilon_r = 9$, C/ε_r is obtained as follows:

$$C/\varepsilon_r = \frac{.364 \times .7 \times .935 \times 1.325 \times 1.15}{1.6} = .226 \text{ pF/in}$$

and $C = 9 \times .226 = 2.05$ pF/in.

The length of a parallel strip of a capacitor of one centimeter width is found to be 1000 cm. The capacitance per square centimeter is obtained from the above expression to be as follows:

$$C = \frac{1000 \times 2.05}{2.54} \text{ pF/cm}^2 = 810 \text{ pF/cm}^2.$$

The computer calculation gave 840 pF/cm^2 for zero electrode thickness, b, which is shown by the graph in Figure 5. The two values agree within reasonable limits.

Another computer solution is found, and a second curve is drawn corresponding to a d/t ratio of 0.2 and l/t ratio of 0.4. For various values of electrode thickness, b, the capacitance is computed and the curve is extrapolated to give the capacitance at zero value for electrode thickness, b. A capacitance equal to 1140 pF/cm^2 is obtained as shown by the graph in Figure 5.

Using the empirical formula to calculate the capacitance in pF/in, C/ε_r for $\frac{l}{t} = .4$

and $d/t = .2$ is obtained as follows:

$$C/\varepsilon_r = \frac{.364}{1 + .4} \times f \times g \times h \times m \text{ pF/in}$$

Where f (for $1/t = .4$) = .870 From graph of Figure 8

g (for $d/t = .2$) = .920 From graph of Figure 8

h (for $E_r = 9$) = 1.325 From graph of Figure 8

m (for $d = \frac{10}{3}$ microns) = 1.24 From graph of Figure 8

and $\varepsilon_r = 9$, $C = \dfrac{9 \times .364 \times .870 \times .920 \times 1.325 \times 1.24}{1.4} = 3.07$ pF/in

The capacitance/cm^2 is obtained by the expression,

$$\frac{1000 \times 3.07}{2.54} = 1160 \text{ pF/cm}^2.$$

The above value agrees closely with the computer calculations making use of the numerical method. In both cases, the agreement has been found to be within 10%, in over ten calculations.

CHAPTER IV

EXPERIMENTAL METHODS AND RESULTS

Fabrication

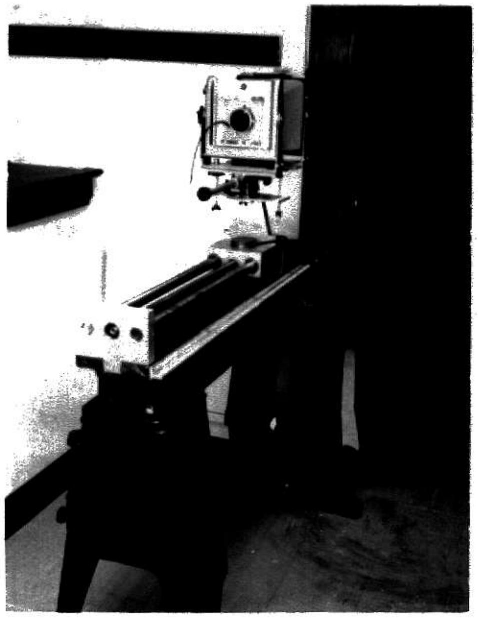
The microcomb capacitor was fabricated by use of microphotography and photomechanical processes. Photographic methods were used to reduce the master patterns to the required size; the photochemical processes were utilized to make the mask of a suitable metal. The experimental procedure consisted of the following steps:

1. The preparation of the layout for the pattern of the microcomb capacitor.
2. The photographic reduction of the artwork.
3. The preparation of a clean substrate.
4. Vacuum deposition of a metal film on the substrate.
5. The photoresist application and the subsequent exposure of the substrate to ultraviolet light through the photomask.
6. The development of the substrate and subsequent etching.
7. The stripping of the resist from the substrate.

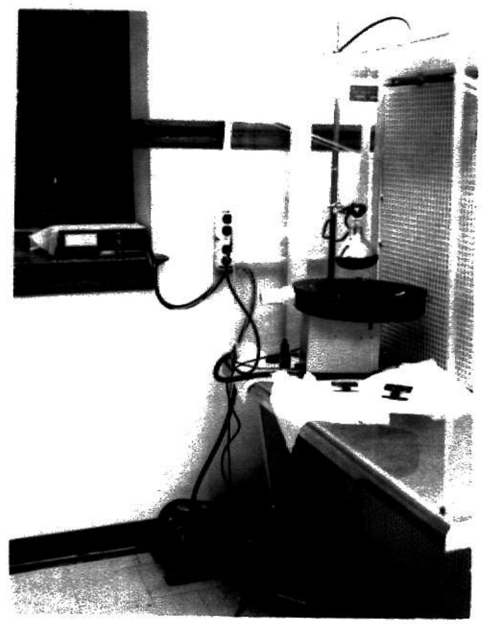
The photographic equipment consisted of a camera with a high-resolution lens of 210 mm focal length, which is completely corrected for spherical aberration. The camera was mounted on a suitable stand facing an adjustable lightbox, which illuminated the layout of the microcomb capacitor from the rear through the diffuse light of a frosted glass sheet, mounted on the lightbox. The microcomb capacitor layout was prepared on a transparent plastic sheet and attached to the glass sheet of the lightbox. A 1/16" black tape served as the mask. The artwork of the capacitor pattern was reduced by a factor of 10. The time of the exposure and the aperture of the lens were adjusted for maximum resolution and were found to be 1/2 second and f/16, respectively. The photographic plate used for exposure was a high resolution micro-flat photosensitized glass plate, especially suited for microphotography. The development of the exposed photographic plate was done in a dark room using the recommended safelight, D19 developer, stopbath, and fixer. The developing times which gave consistently good results were found to be 2-3 minutes in the D19 developer, 15 seconds in the stopbath and 10 minutes in the fixer bath, followed by a wash in running water for 15 minutes. The negative so obtained is the desired photomask.

The third step was the preparation of the clean substrate. The substrate was a thin copper sheet on a polyester resin. First the substrate was cleaned in a plain detergent and then immersed in an 8% hydrochloric acid solution for 5 minutes. It was kept in a vapor degreaser containing iso-propyl alcohol for 2-3 minutes. After a clean surface was obtained in this manner, it was washed in de-ionized water and kept on the clean air bench which was pressurized to proper pressure and filtered to eliminate dust particles. The subsequent steps of this process were carried out in the clean air bench.

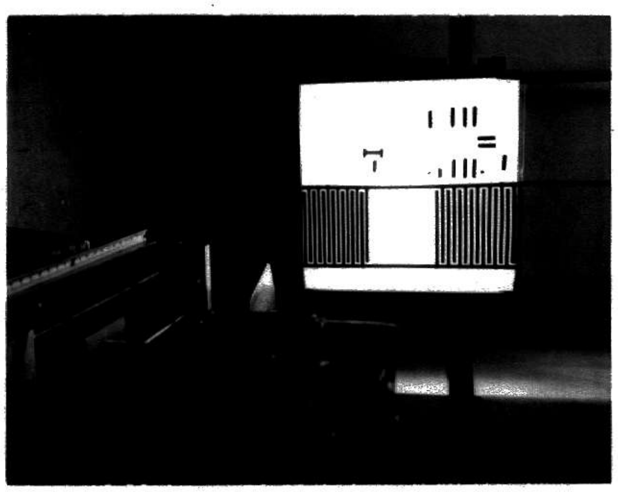
The fourth step would normally be vacuum deposition of a metal film on the substrate. This procedure was not necessary in view of the fact that the substrate was a thin copper sheet on a polyester resin. If a dielectric substrate were chosen, then the deposition of a metal film would be necessary. The fifth step was photoresist application. An apparatus called a spinner was used for this purpose (see Figure 12). The spinner consisted of a chuck on which the substrate was placed and subsequently held by means of an applied vacuum. A variable speed motor and a timer enabled the spinner to rotate at



Microphotographic camera and assembly



Spinner situated in the clean air bench



Microcomb capacitor art work

Figure 12. Pertaining to the fabrication of the microcomb capacitor.

any desired speed for any predetermined length of time. These parameters are set on the dial of the controller of the spinner. The remaining apparatus was an infra-red heat lamp used to dry the substrate, and a photoresist filter and syringe. The infra-red lamp was adjusted to keep the substrate at 180° F. The drying took place for approximately 10 minutes. The Kodak thin film resist was mixed with an equal volume of Kodak thin film resist thinner to render the resist less viscous. Later it was filtered through a millipore filter with a syringe attached to its head, before application to the substrate. This procedure removes solid matter from the resist and renders the resist homogeneous. The filtered resist was squirted through the syringe uniformly in a thin layer to cover the whole substrate and to leave no air bubbles. Then the vacuum pump was started so that the vacuum that is applied to the chuck holds the substrate. The R.P.M. was adjusted to 3000 and the timer was kept at one minute. After a few seconds of operation the spinner was stopped with the foot-switch, and the substrate was examined to determine if it had a uniform and thin coating of the resist. After this procedure was accomplished the spinner was started and allowed to run for a minute. The substrate was then kept for approximately 10-15 minutes under the heat lamp, where the temperature was about 180° F on its surface. The resist film attained a shiny surface indicating that all the solvents had evaporated from the substrate.

The next step was exposure of the masked substrate to ultraviolet light. For this purpose the photomask of the microcomb pattern was placed under a microscope and examined for any defects. After making certain that the mask was free from dust particles, it was placed in intimate contact with the substrate and exposed to an ultraviolet light source, provided by a sunlamp. The sunlamp was held 2 feet away from the substrate. The time of exposure was not critical if it was more than 2 minutes. An exposure time of four minutes was adopted.

After the exposure to ultraviolet light, the substrate was developed by using the Kodak thin film resist developer. The developing time was about 2-3 minutes. The substrate was held with a pair of teflon tongs in a slightly slanting position, and the developer was sprayed with slight jet-like squirts periodically, until all the substrate area was clear of any removable resist. After making sure that all corners and sharp edges were wetted by the spray, the substrate was rinsed with "KTFR Rinse" to wash away all the particles on the substrate in order to expose a clear image. High resolution was obtained by adopting this method. The substrate was baked again, but at a temperature of 140° F for 5-10 minutes.

After being baked the substrate was removed from the clean air bench for etching. The type of etchant used depends upon the metal film to be etched. If the metal film on the substrate is copper, ammonium persulfate solution (30%) (or 30% nitric acid) is used for etching; if the metal film is aluminum, an ammonium hydroxide solution (30%) is used. The etching time is dependent on the temperature of the etchant. The temperature should not exceed 120° F for copper or aluminum, and the corresponding etching time is 5-7 minutes. After etching away all the unwanted metal, the substrate was stripped of the resist by employing the organic resist stripper whose trade name is AZ_4. The resulting pattern was the desired microcomb capacitor. After drying the pattern under a warm heat of the heat lamp (infra-red lamp at 100° F), it was kept in a clean glass desiccator.

The next procedure after fabrication of the microcomb capacitor was testing its value and characteristics. The capacitance was measured at various frequencies. The dielectric loss factor and the dielectric constant of the substrate were found by conducting the following experiments, with the use of a Boonton Q Meter.

Testing

The capacitance of the microcomb capacitor was measured by resonating the Q meter with the microcomb capacitor connected in the circuit and again resonating the circuit with the microcomb capacitor disconnected while observing the difference in capacitance of the tuning capacitor.

The dielectric loss factor or tan δ was measured in the following manner: A coil having an inductance that would resonate to the desired frequency with a tuning capacitance of about 50 pF plus the capacitance of the microcomb capacitor was selected. This coil was connected to the coil terminals of the Q meter. The oscillator was set to the desired frequency and the oscillator output was set equal to the 250 value on the Q range meter. Next the Q meter was resonated by means of the Q meter tuning capacitor. This capacitor setting should be C_1 and the reading on the Q voltmeter should be Q_1. Next the microcomb capacitor was connected to the capacitor terminals of the Q meter and the circuit was re-resonated. This resonant capacitor setting should be C_2, and the reading on the Q voltmeter should be Q_2. The dielectric loss factor was obtained by the use of the following equation:

$$\text{Tan } \delta = \frac{C_1(Q_1 - Q_2)}{(C_1 - C_2)\, Q_1Q_2}$$

The dielectric constant of the substrate on which the microcomb capacitor was fabricated was found experimentally in the following way. A sample of the dielectric material whose dielectric constant was to be measured was inserted in a parallel plate capacitor, so that the distance between the plates was exactly equal to the dielectric thickness. The capacitance of this specimen was measured by the Q meter. Next, the dielectric material was removed, and the resultant air dielectric capacitance was measured by using the same procedure. The ratio of these two values, which was greater than 1, was the dielectric constant of the material. Two microcomb capacitors were fabricated and their capacitance values checked with the predicted values. The dielectric loss factor was also measured and determined to be as tabulated in TABLE 1.

TABLE 1

MICROCOMB CAPACITOR PARAMETERS

d = gap-width in mils	l = electrode-width in mils	Thickness of the dielectric substrate t in mils	Measured average capacitance in pF	Analytical value of capacitance in pF	Empirical value of capacitance in pF	Tan δ	Dielectric constant $\varepsilon\nu$	Range of frequency
1	6	62.5	12.7	12.2	12.2	.005	2.1	1-25 mHz
2	6	62.5	7.6	7.8	7.8	.005	2.1	1-25 mHz

CHAPTER V

CONCLUSIONS

The following conclusions were drawn from this analysis:

1. The capacitance of the microcomb capacitor is a function of the substrate thickness, among other variables, according to Castro's analytical expression. Since the author's experimental results confirm the validity of the analytical expression, it may be concluded that by varying the substrate thickness various values of specific capacitance are obtained for the same gap width and electrode width. The experimental results of Cohen et al. also confirm the above conclusion.

2. The experimental results of Cohen et al. have indicated that capacitance increases much more rapidly as a function of gap width for gap widths less than 1/2 a mil. It then appears possible, to obtain very high specific capacitance by employing extremely small gap widths.

3. Gap widths of the order of a few microns are highly desirable. These extremely small gap widths are possible to obtain with the photolithographic process. The author could not verify the above experimentally with gap widths of less than one mil.

4. From the analytical expression, it is clear that for any d/t value, maximum capacitance is available for $\frac{l}{t} = 1$ which means that l is at least equal to t. For the microcomb configuration of equal gap width and electrode width, it is possible to use more length of the capacitor strip by making the dimensions of the gap and electrode as small as is practicably possible. If an electron beam printing is used, it is estimated that it is possible to obtain a micron gap width. If the electrode width, gap width and the

substrate thickness are made equal to one another, it would appear to be possible, however, that maximum specific capacitance may be obtained. This prediction needs to be verified.

5. When dielectric films of less than 1 micron are considered, implantation methods offer many advantages. By implanting the dielectric by an accelerator, it appears to be possible to achieve a specific capacitance C/ε_r, of approximately 2.5 pF/mil^2. Since this specific capacitance has not been achieved, the possibility of doing so deserves further investigation.

6. The microcomb capacitor is of considerable importance in monolithic integrated circuits. The present analysis will enable one to make a microcomb capacitor using the photolithographic process, and to calculate its capacitance after it has been fabricated, by using the normalized curves presented in Figure 8 and Figure 9.

CHAPTER VI

RECOMMENDATIONS FOR FUTURE INVESTIGATION

1. Since the present investigation was made for gap widths of a few mils, exhaustive experimentation is needed in the range of gap widths of a few microns, in order to realize the potential advantage of the microcomb capacitor. This procedure could not be performed because of limitations in the apparatus which was used to obtain ultra clean substrates.

2. Experimental investigation to optimize the capacitance in the range of gap widths less than half a mil is recommended.

3. For micron range gap widths, the use of implantation of dielectrics should be studied because the method is ideally suited for that range of investigation.

4. Studies of the ways and means of depositing thin dielectric films of high dielectric strength and minimum loss need to be undertaken.

5. Thin dielectric films deposited by conventional methods present a problem in that they are not free from microfissures. This defect causes a high leakage current. It is estimated that it is possible to implant boron in silicon and fabricate a microcomb capacitor so as to obtain a specific capacitance of 2.5 pF/mil^2. This possibility compares very favorably with the performance of the conventional thin film capacitors. Further experimental investigation could be made to examine the validity of this estimate.

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APPENDIX

APPENDIX

The capacitance between two thin film conductors deposited on a high dielectric constant substrate is calculated by P. S. Castro and H. R. Kaiser by using the Schwartz-Christoffel transformation. The conductor-substrate configuration is shown in Figure 13. The conductors and dielectric are of infinite length perpendicular to the Z plane and the capacitance between these conductors will be calculated per unit length. Since the dielectric constant of the substrate is assumed to be very high compared with the surrounding air dielectric (or vacuum), all of the flux is confined to the dielectric.

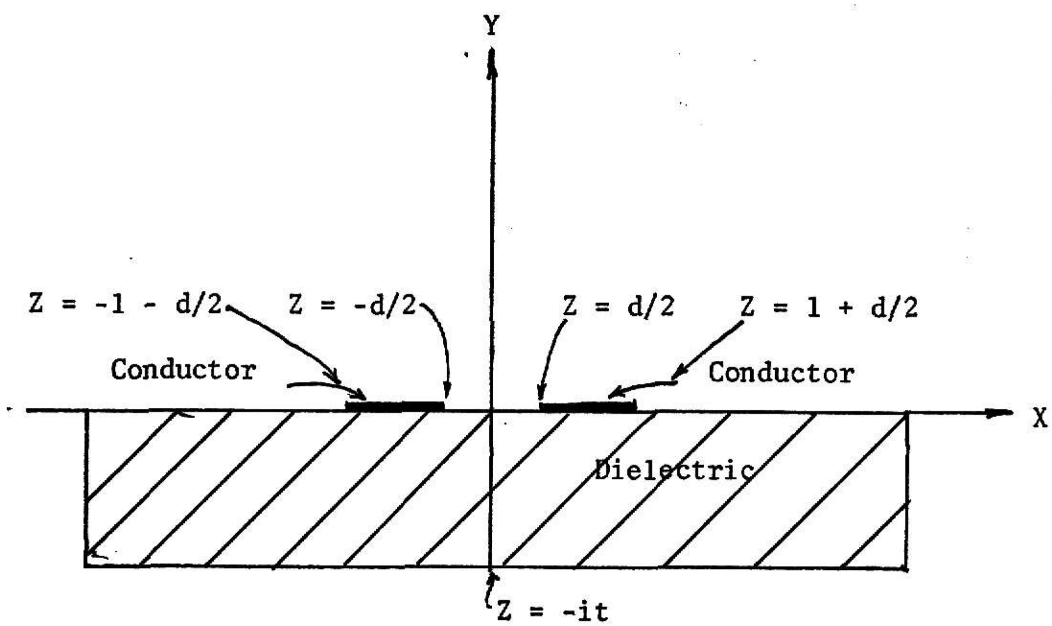

Figure 13. Schwartz-Christoffel transformation-Z-plane.

A Schwartz-Christoffel transformation will be used to map the Z plane of Figure 13 on the w plane of Figure 14.

Next an inverse transformation from this half plane on to a finite box like figure in ρ plane is made as shown in Figure 15, reducing the problem to one of finding the capacitance of an elementary parallel plate capacitor.

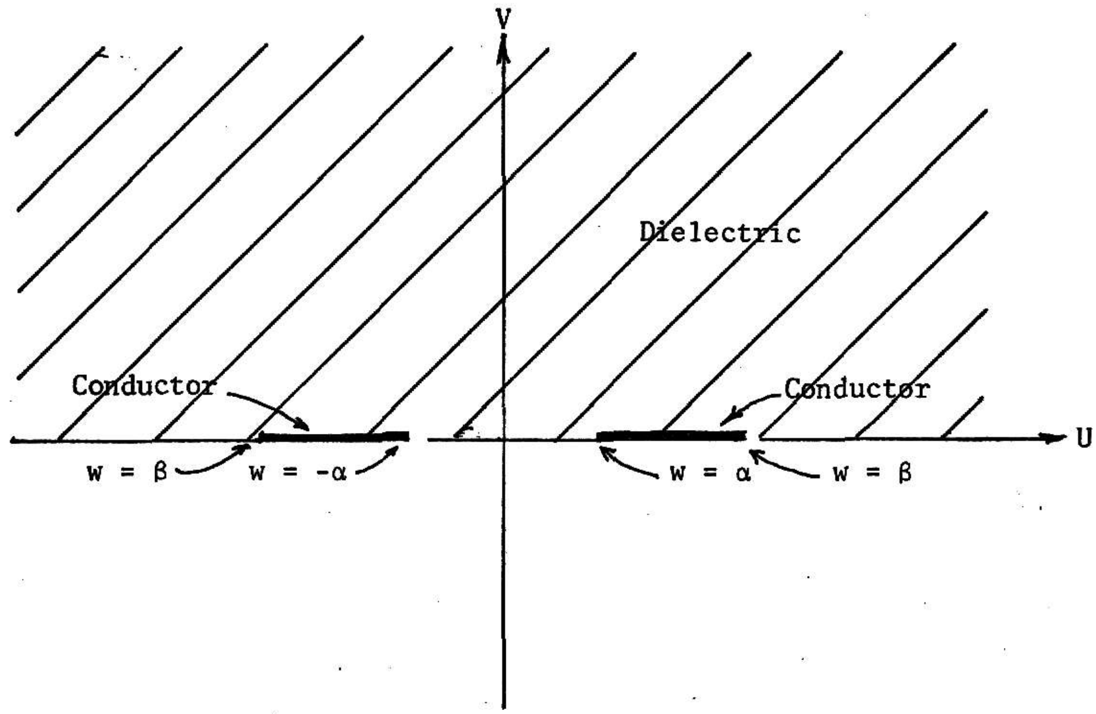

Figure 14. Schwartz-Christoffel transformation-w-plane.

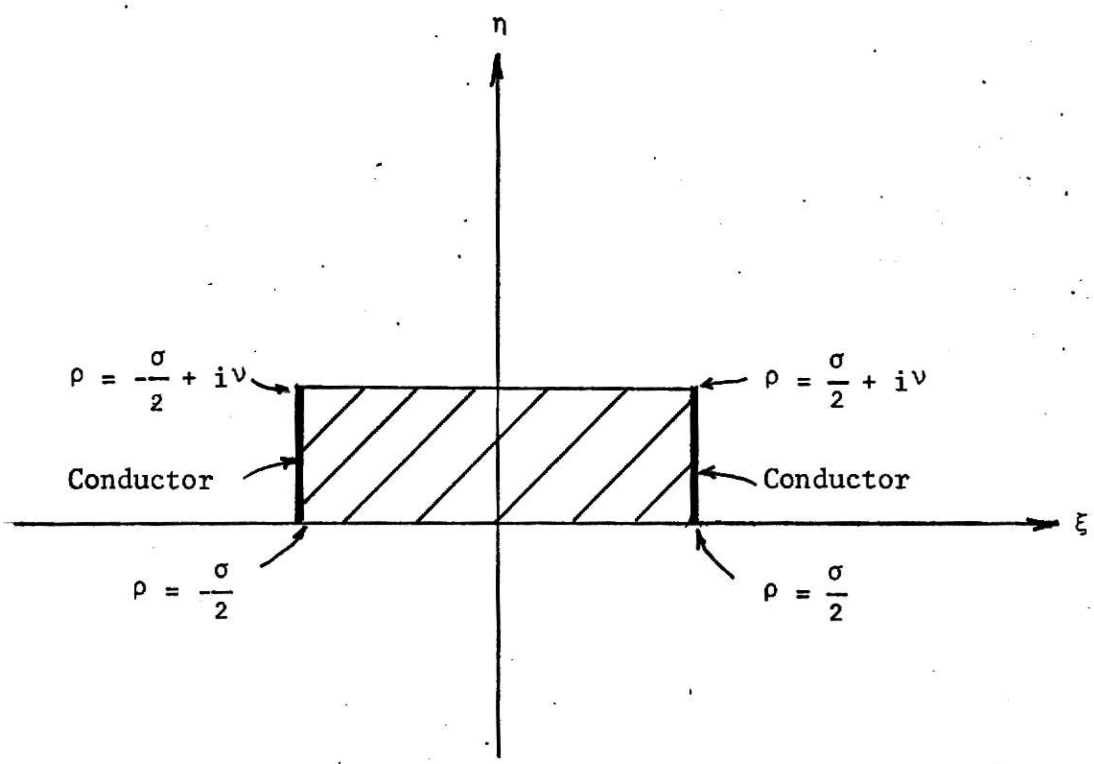

Figure 15. Schwartz-Christoffel transformation-ρ-plane.

The transformation relating the Z and w planes is obtained by Schwartz-Christoffel transformation as

$$Z = \int_0^w \frac{dw}{w^2 - \nu^2} \tag{1}$$

In substituting the limits as

$$Z = -it \qquad \text{for } w = \infty$$

We get

$$\nu = \pi/2t \qquad \text{and} \qquad Z = \frac{1}{2\nu}\left[\log \frac{w - \nu}{w + \nu} - i\pi\right] \tag{2}$$

or

$$w = -\frac{\pi}{2t} \tan h \frac{\pi Z}{2t} \tag{3}$$

When

$$Z = d/2, \ w = -\alpha = \frac{-\pi}{2t} \tan h \frac{\pi Z}{2t}$$

$$Z = d/2 + 1, \ w = -\beta = -\frac{\pi}{2t} \tan h \left(\frac{\pi 1}{2t} + \frac{\pi d}{4t}\right)$$

or

$$\alpha = \frac{\pi}{2t} \tan h \frac{\pi d}{4t} \tag{4}$$

and

$$\beta = \frac{\pi}{2t} \tan h \left(\frac{\pi 1}{2t} + \frac{\pi d}{4t}\right) \tag{5}$$

Next, performing the second transformation from w plane to ρ plane we obtain

$$\rho = \int_0^w \frac{dw}{\sqrt{(\alpha^2 - w^2)(\beta^2 - w^2)}}$$

The point $w = \alpha$ goes into point $\frac{\sigma}{2}$ given by

$$\rho = \frac{\sigma}{2} = \int_0^w \frac{dw}{\sqrt{(\alpha^2 - w^2)(\beta^2 - w^2)}} \tag{6}$$

The point $w = \beta$ goes into point $\frac{\sigma}{2} + i\nu$ given by

$$\rho = \frac{\sigma}{2} + i\nu = \int_0^\beta \frac{dw}{\sqrt{(\alpha^2 - w^2)(\beta^2 - w^2)}} \tag{7}$$

So,

$$i\nu = \beta - \alpha = \pm i \int_\alpha^\beta \frac{dw}{\sqrt{(w^2 - \alpha^2)(\beta^2 - w^2)}} \tag{8}$$

where the plus sign must be taken for the ν value

$$\nu = \int_{\alpha}^{\beta} \frac{dw}{\sqrt{(w^2 - \alpha^2)(\beta^2 - w^2)}} \tag{9}$$

and from equation (7)

$$\sigma = 2 \int_{0}^{\alpha} \frac{dw}{\sqrt{(\alpha^2 - w^2)(\beta^2 - w^2)}} \tag{10}$$

The elliptic integral (9) can be converted to standard form by change of variable

$$w = \beta\sqrt{1 - x^2 \left(1 - \frac{\alpha^2}{\beta^2}\right)}$$

so,

$$\nu = \frac{1}{\beta} \int_{0}^{1} \frac{dx}{\sqrt{(1 - x^2)\left(1 - x^2 \left(1 - \frac{\alpha^2}{\beta^2}\right)\right)}}$$

or

$$\nu = \frac{1}{\beta} F\left[\sqrt{1 - \frac{\alpha^2}{\beta^2}}, \frac{\pi}{2}\right] \tag{11}$$

where F is the standard complete elliptic integral of the first kind, with argument $\sqrt{1 - \frac{\alpha^2}{\beta^2}}$.

Similarly $\frac{\sigma}{2} = \int_{0}^{\alpha} \frac{dw}{\sqrt{(\alpha^2 - w^2)(\beta^2 - w^2)}}$ can be transformed by putting

$w = \alpha x$ to become,

$$\sigma = \frac{2}{\beta} \int_0^1 \frac{dx}{\sqrt{(1 - x^2)\ (1 - x^2 \frac{2\alpha^2}{\beta^2})}}$$

or

$$\sigma = \frac{2}{\beta} \ F(\frac{\alpha}{\beta}, \frac{\pi}{2}) \tag{12}$$

where F is the standard complete elliptic integral of the first kind, with argument α/β. The parallel plate capacitance in the ρ plane is simply

$$C = \frac{\varepsilon_0 \varepsilon_r \nu}{\sigma}$$

where ε_r is the relative dielectric constant of the substrate or

$$C = \frac{\frac{\varepsilon_0 \varepsilon_r}{2} F\left[\sqrt{1 - \frac{\alpha^2}{\beta^2}}, \frac{\pi}{2}\right]}{F\ (\frac{\alpha}{\beta}, \frac{\pi}{2})} \text{ farads/meter} \tag{13}$$

where $\frac{\alpha}{\beta}$ is given by

$$\frac{\tan h\ \ (\pi d/4t)}{\tan h\ \ (\frac{\pi 1}{2t} + \frac{\pi d}{4t})} \tag{14}$$

The numerical value of $\frac{\varepsilon_0}{2}$ = .1125, when C is expressed in pF/inch. So

$$C = .1125\ \varepsilon_r\ F\left[\sqrt{1 - \frac{\alpha^2}{\beta^2}}, \frac{\pi}{2}\right] \Big/ F\ (\frac{\alpha}{\beta}, \frac{\pi}{2}) \cdot \text{pF/inch.}$$

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INVESTIGATION OF THE MICROCOMB CAPACITOR

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ABSTRACT

The microcomb capacitor, which consists of a number of co-planar, intermeshing, conducting plates, has been analyzed theoretically by several methods. The theoretical analyses have been compared with a small number of experimental results.

There is some evidence that useful microelectronic capacitors may be fabricated by use of the ion implanted dielectrics and photolithographically prepared plates.

The full theoretical analysis involved distributed network theory, Schwarz-Christoffel transformations, and the numerical solution of Laplace's Equation making use of the digital computer. Expressions have been obtained for capacitance values of structures formed on high dielectric constant substrates which can be further modified for substrates with low dielectric constants. This information is presented in the form of normalized curves.