Contents

1 Capacitor Characteristics

1.1 Capacitance

An ideal capacitor only has a value of capacitance, which is defined as the ablity to store an electrcial charge.

The equation for a parallel plate capacitor is:

$C = \epsilon_0 \epsilon A/d$

" ϵ_0 is the permitivity of free space and has a value of $8.85 * 10^{-11} F/m$

ϵ is the permitivity of the dielectric

A is the area of the plates

d is the distance between the plates (i.e. the thickness of the dielectric) "

In the case of an ideal capacitor, it only has the property of capacitance (no inductance or resistance), and does not vary over frequency, voltage, or temperature. [23]

Why do I care about this property?

In using a capacitors for bypassing, you want to eliminate signals above the highest frequency of interest (noise). In doing this, you want to choose a capacitor who's capacitance is low (¡1 Ohm), in order to shunt the high frequencies to ground. For an ideal capacitor, you would just choose a large value capacitance and call it a day. Practical parameters (parasitics), make this not so good of a strategy.

In using a capacitor for filtering (such as a single pole low pass filter) you set the cut off of the filter via (1/2*pi*rc) to filter out the frequencies of interest, while passing the frequencies that you desire.

1.2 ESR

Equivalent series resistance is the resistance measured between the leads and the capcitor plate?? It is most important when there are high AC currents flowing, as they will dissipate power through the ESR. [13]

Good:

- Mica
- film [13]

—

ESR is the sum of all of the resistive components of the capacitor. It is typically modeled as a "single series resistance with the capacitance."

We care about high ESR with: high AC currents RF high ripple currents

We don't care about high ESR with: "Precision, high impedance, low level analog circuits" [36, Sect. 3.6.7]

low esr: mica film

Knowing the ESR of a capacitor allows you to know how much power will be dissipated in it when it is filtering a switching power supply.[36, Sect. 3.6.7]

—

Even though ESR is measured in units of ohms and seen as a resistance, it is not the same at all frequencies. Therefore, it is typically given at a particular frequency.

electrolytic bypass – 120Hz tantalums used switchers – 100kHz

eletrolytics – higher at low frequencies [1]

1.3 ESL

Equivalent series inductance is the inductance seen looking into one of the leads of the capcitor. It causes the most problems at high frequencies, where it can dominate the capacitve component of the capacitor. [13]

Good: MLCC

Bad:

- electrolytic
- paper
- plastic film[13]

—

ESL is primarily composed of the capictor's leads that are in series with the capacitive portion of the capacitor. It is modeled as an inductor in series with C. ESL is the main reason for why you need at least 2 capacitors to decouple your power supply. As frequency increases past the point where $X_c == X_{ESL}$, the capacitor's impedance begins to increase with frquency, making it quite useless as a bypass element.

bad:

- electrolytic
- paper
- plastic-film

good:

- mica
- MLCC

Some MLCCs can be self-resonant with a high Q b/c of low ESR. [36, Sect. 3.6.7]

1.4 Dissipation Factor

The dissipation factor of a capacitor is the "ratio of the energy dissipated per cycle to energy stored per cycle." It is a paramater which lumps together the effects of ESR and ESL. DF = power factor ($cos(\phi)$). $DF = 1/Q$. [13]

—

"The ratio of energy dissipated per cycle to energy stored per cycle." "It is also the ratio of the current in phase with teh applied voltage to the reactive current."

D = 1/Q

A capacitor with a lower D is a more efficient component. [36, Sect. 3.6.7]

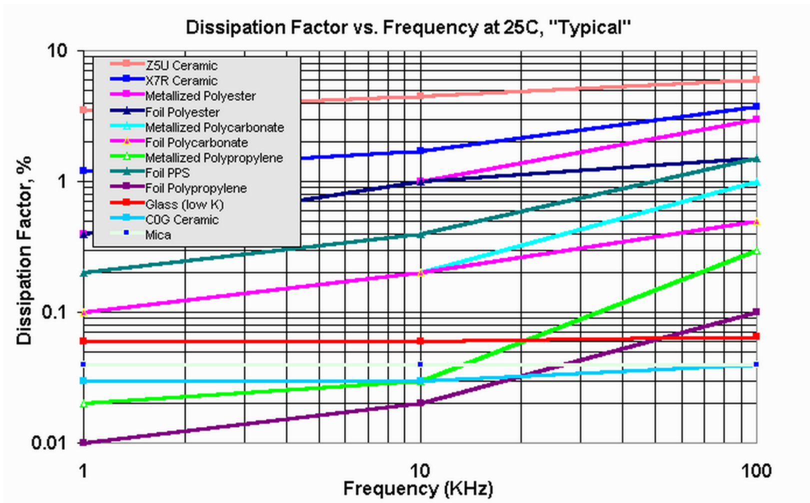
—-

We are particularely concerned about DF when dealing with applications concerning AC or high ripple currents.

$DF = ESR/X_c$

DF is comprised of:

1. Metal losses
   (a) Resistance of leads
   (b) Resistance of end terminations



[2]

Figure 1: Dissipation Factor vs Frequency

(c) Resistance of metal foil or film

2. insulation resistance (small)

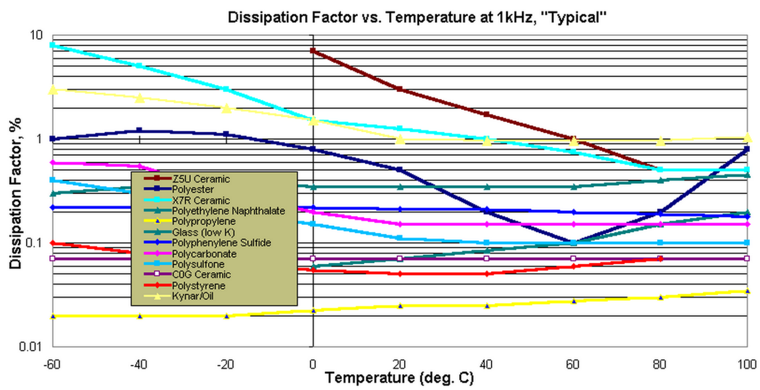
3. dielectric losses

[1]

1.5 List

[29]

1. ESR
2. ESL
3. Leakage Current
4. Dielectric Absorption
5. Quality Factor
6. Dissipation factor (or dielectric loss)

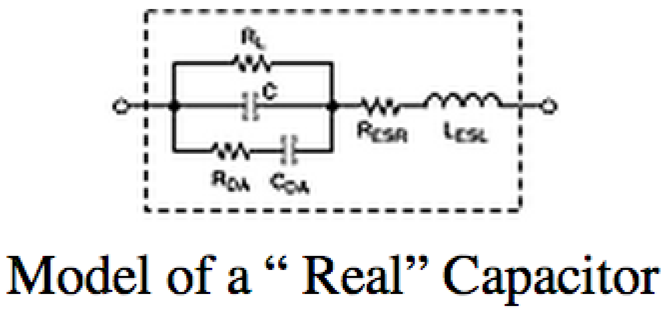


[3]

Figure 2: Dissipation Factor vs Temperature

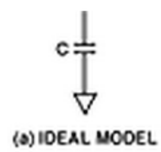
7. Loss Tangent
8. Self Resonant Frequency
9. Capacitance stability with time
10. Capacitance stability with temperature
11. Capacitance stability with applied valtage
12. High-frequency properties and effects
13. Voltage rating and dielectric strength
14. Insulation resistance
15. Isolation resistance
16. Insulation resistance variations with temperature
17. Pulse operation and surge rating
18. Effects of radiation
19. Effects of vibrariton and shock

"With many types of capacitors, further derating is required as the operating frequency increases."[36, Sect. 3.6.7]



[13]

Figure 3: Complete Model



[13]

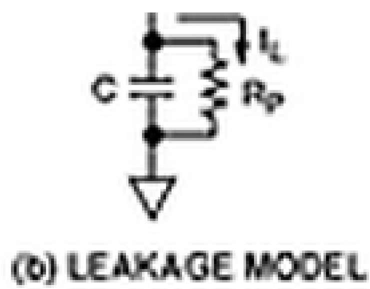
Figure 4: Ideal Model

1.6 Models

The ideal capacitor model will only bring you so far before you need to graduate to a more complex understanding. The industry typically calls any paramaters beyond the basic capcitor model "parasitic effects," because they typically degrade the performance of a capcitor from the ideal. Nonetheless, they are present in every capcitor to varying degrees. It is imparative to know which models to use in which circumstances.

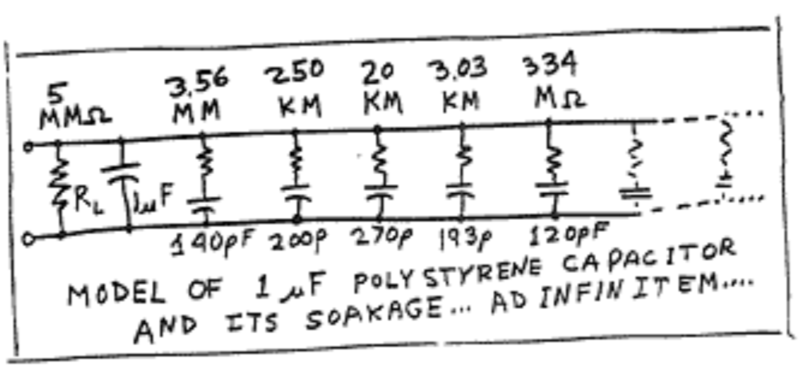
1.7 Voltage Dependence

"Materials with high permitivity tend to have characteristics which are voltage dependent."[23]



[13]

Figure 5: Leakage Model



[27]

Figure 6: Dielectric Absorption Model

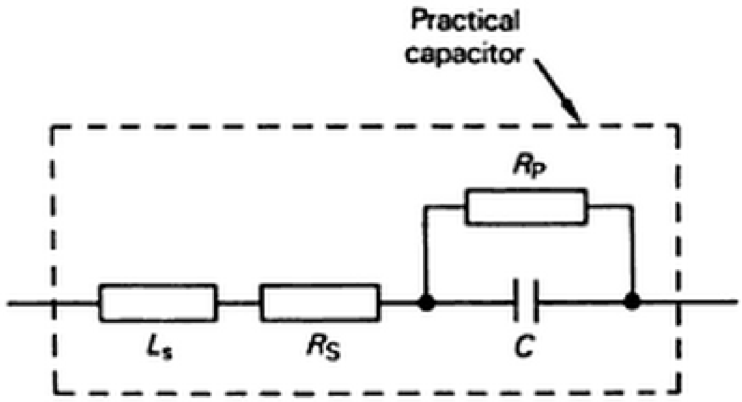


Fig. 4.1. Equivalent circuit of a capacitor.

[23]

Figure 7: Practical Model

1.8 Equivalent Circuits

1.8.1 Ls, Rs, C, & Rp

Refer to Figure: 7 for this section.

"

R_P is the leakage or insulation resistance

R_S is the series resistance

ESR is the ac resistance and incorporate both R_P and R_S.

L_S is the self inductance

$Z = (R_S^2 + X_C^2)^{1/2}$

$cos(\phi) = R_S/Z$

$tan(\delta) = R_S/X_C$

where:

Z is the impedance of the capacitor

$X_C = 1/2\pi fC$ and is the capacitor reactance at frequency f.

$cos(\phi)$ is the power factor

$tan(\delta)$ is the loss angle, loss tangent, or dissipation factor of the capacitor.

"

[23]

Power factor varies with temperature, but plummets below 0DegC. Dissipation factor is sensitive to moisture.[23]

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1.11 Leakage

As opposed to the ideal capcitor, which can hold its charge indefinitely, real capcitors have a leakage component. Over time, this parallel resistance bleeds aways the charge stored on the capcitor. This will happen with a time constant of C*R_l. This parameter is especially important in circuits such as sample and hold applications. [13]

Good:

- teflon
- poly* [13]
- film
  - polypropylene
  - polystyrene [36, Sect. 3.6.7]

[1]

Bad:

- Electrolytic
- Aluminum

- Tantalum [13] [36, Sect. 3.6.7]

—

Certain capacitors can leak at rates of only 2.7mV/day. $\tau = 10$ years. – rap??

—

A charged capacitor will discharge with a time constant of C*RL. [36, Sect. 3.6.7] This is assuming that there is no external volatge source, at which you would leak at V / (RL + ESR) ??? maybe?

—

aka Insualtion resistance (low leakage) aka leakage current (high leakage)

Bad: Electrolytics (worst)

Good

- Film ($IR1/\alpha\epsilon$)
- COG ceramics

1.12 Quality Factor

$Q = 1/D$

$Q = X_c/R_{ESR}$

"Ratio of the energy stored to that dissipated per cycle." It is the capacitor's ability to store charge. It can also be thought of as an efficiency measurement.

"The rate of heat conversion is generally in proportino to the power and frequency of the applied energy. Energy entering the dielectric, however, is attenuated at a rate proportional to the frueqnecy of teh elcetric field and the loss tangent of the material." [36, Sect. 3.6.7]

1.13 Space Charge

"Space charge is charge in the dielectric, electrons, protons, nad ions, that is moved around by the applied voltage." Charge will build build up in the capacitor over time. They electrons are not able to return to their holes quickly due to the high dielectric resistance.

[1, Space Charge]

1.14 Dielectric Absorption

Dielectric absorption is the name of the phenomenon that happens when a charged capcitor is quickly discharged and then left in the "open" state. After a certain amount of time, the voltage can restablish itself on the capacitor through charge that was trapped inside. This is why certain large value capacitors are shipped with a resistor acress their terminals. This burn resistor dissipates any voltage that would build up across the terminals of the capitor through.

Good: poly*

Bad: MLCC

—

Also known as dielectric soakage. Dielectric absorption (DA) is the ability of capacitors to recover a portion of their voltage when they are charged up and then rapidly discharged for a short amount of time. This effect can be dangerous, as a "discharged" capacitor can recover enough voltage to shock you.[27]

"This was well known in as early as the 1700s." [27] 1900s - said that DA was caused by molecules being polarized and then loosing their polarization when the applied voltage was removed. DA also affects charging of capacitors. If you charge a capacitor to its working voltage, it will continue to need charge for some time after stabalizing at a voltage. Also DA is "fairly" linear.

The model for DA in a capacitor is C in parallel with R in parallel with a series of series RC sections. One should not forget about leakage when thinking about DA.

Polypropylne capacitors have low DA.

—

DA is commonly seen as a problem in long period integrators. [28]

—

"At high frequencies, this means that the capacitor cannot complete its discharge, and this has the same effect as a loss in capacitance."[23]

—

DA has hysteresis like properties.

"Dielectric absorption is a hysteresis-like internal charge distribution within the dielectric that causes a capacitor that is quickly discharged and then open-circuited to appear to recover some of its charge."

"charge memory effect that will cause errors in sample and hold circuits"

bad: MLCC

DA = % of charge stored in the dielectric. The rest of the charge is stored on the plates

DA = $V_{self-charge}/V_{before-discharge}$, with defined charge and discharge values or ratios. [36, Sect. 3.6.7]

—-

"DA aka 'soakage' 'voltge retention' 'return voltage'

In the model in Figure:6, we see that the parallel RC branches typically consist of high valued resistors with capacitors which are of lower values than the main C.

MIL-C-19978D – 5min/5sec/1min sequence of charge, discharge, wait, and then measure.

good: teflon polystyrene polypropylene

bad: electrolytics high-k ceramics oil-filled

Typically, capacitors which have a high insulation resistance and a low μ have much better DA characteristics.

"However, while the RC model is usefull for predicting how DA will behave, it does not reflect the underlying physics." [1]

1.15 Insulation Resistance

"This is a measure of the resistance to a dc current flow through the capacitor under steady-state conditions."[36, Sect. 3.6.7]

2 History of Capacitors

2.1 Leyden Jar

Capacitors have their origins in the Leyden jar; developed by Ewald Jrgen von Kleist in 1745 and independently by Pieter van Musschenbroek in 1746. [16]

The Leyden jar was typically made from a glass jar with metal sheets spread on the inside and outside. Electricity could be stored by charging the jar with an electrostatic device and the removing the jar. This breakthrough in the study of electricity was exremely important to scientists, as it allowed electricity to be stored and then used later. [16] — The most common design for the Leyden jar was to use a glass jar with metal foil lining the inside and out. Then inner surface was typically charged via an electrostatic generator, while the outer surface was connected to ground. The charge would stay on the metal foil untill a short or small resistance was connected between them. Charge could be stored this way, allowing scientists, and showmen, to use greater amount of charge than they could generate at any one moment.

— "At this stage, the pursuit of electrical knowledge was restricted by the limited amount of eletricity experimenters could atually generate." [19]

"First solution to storing electricity." — The discovery of the Leyden jar allowed scientists to store elecricity for the first time. [42] —

2.2 Misc

In 1872, the standard unit of measurement of a capacitor's capcitance was set to be the Farad. [16]

In the 1950s, Bell labs began to popularize the transistor, which allowed circuits to become smaller and deal with lower voltages. This also lead to the development of smaller capacitors. [9, f. 12]

Birth of some capacitors:

Name	Date	
Leyden Jar	1745	
Mica	1874	
Paper	1876	[9, f. 19-25]
Ceramic	1900	
Electrolytic	1922	
Glass Tub	1904	
Solid Electrolytic	1956	

Glass tubular capacitors (Moscicki tubes) were the only option available to Marconi in his early wireless experiments.[9, f. 49-41]

— In the 1950s, Bell labs began to popularize the transistor, which allowed circuits to become smaller and deal with lower voltages. This also lead to the development of smaller capacitors. [9, f. 12]

2.3 Ceramic Capacitors

2.3.1 Basic Ceramic Dielectric Materials

[6, Ch 3 Sec IV] Materials:

1. Porcelein and Steatite [6, Ch 3 Sec IV.A]

    (a) Early ceramic dielectrics.

    (b) alkaline oxide-free compositions?

    (c) $\epsilon_r = [5, 7]$

    (d) positive tempco

[6, Ch 3 Sec IV]

2.3.2 Varieties of Ceramic Capacitors

[6, Ch 3 Sec VII]

1. Film

    (a) Thin-Film

   (b) Thick-Film

2. Single-Layer discrete Capcitors

3. Multilayer Capacitors

4. Barrier Layer Capacitors

5. Multilayer GBBL Capacitors

2.3.3 Misc

- First one was the Leyden jar
- 1926 – titanium dioxide (rutile) became available.
- 1941 – barium titanate became available (eps = 1000)
- 1970-80s – MLCC processes expanded ceramic capacitors [14]

Ceramic capacitors have several advantages, some of which include a high capacitances per unit volume, and a low ESL. NPO ceramic capacitors have one of the most predictable temperature coefficients on the market. [21]

In light of mica supply chain problems and the emergence of ceramic capcitors during WW2, mica capacitors fell from prominence to a niche market after the second great war.[6, Ch 3, Sec II]

Ceramic capacitors have several advantages, some of which include a high capacitances per unit volume, and a low ESL. NPO ceramic capacitors have one of the most predictable temperature coefficients on the market. [21]

" pros:

1. high ϵ
2. low ESR
3. good for SMD packaging

Cons:

1. low breakdown voltage

” [1]

2.3.4 Characteristics

Film Capacitors:

- Large swing in available energy storage
- high reactive power
- modest energy density
- high power density
- bipolar
- stable capacitance with frequency and voltage
- low ESR
- low ESL
- very low DF
- suitable for high voltage applications (¡=100kV)

Typical Uses:

- moderate to large value capacitances
- dc and ac applications
- high power elctronics
- high frequency filtering
- continuous ac operation
- solid state switch snubbers
- SCR communication circuits
- PF correction

- motor start and run capacitors

[35]

Typical Uses:

- surface mount
- low voltage dc control circuits
- blocking
- buffering
- bypass
- coupling
- low frequency filtering
- tuning
- timing (¡=GHzs)

[35]

CDL Characteristics:

- high energy density
- low power density
- small dc working voltage

Typical Uses:

- energy storage for hybrid vehicles
- reservoir caps for SMPS
- regenerative breaking

[35]

2.3.5 Classes

2.3.6 Class 1

- Low capacitance
- low dielectric loss
- low tempco of capacitance – 0 to +/- 75000 ppm/^oC
- most common tempco is 0 to +/- 30ppm/^oC
- low rate of aging
- temprange $[-55^oC, 85^oC]$
- $\epsilon - r <= 100$

[6, Ch 3 Sec VI]

Class 1 ceramics, (TCC caps), have very good temperature coefficients, and are used when you need to have a precisely valued capacitance over wide operating temperatures. [10]

Class 1:

- K = 5-100s
- DF <<.01
- Linear tempco 0-1000s ppm/^oC [11]

Early Types:

- porcelain
- steatite
- mica
- misc silicates

Modern Types:

First Marking		Second Marking		Third Marking	
Symbol	Signifcant Digit (ppm/^oC)	Symbol	Multiplier	Symbol	Tolerance (ppm/^oC)
C	0.0	0	-1	G	+/-30
B	0.3	1	-10	H	+/-60
L	0.8	2	-100	J	+/-120
A	0.9	3	-1000	K	+/-250
M	1.0	5	+1	L	+/-500
P	1.5	6	+10	M	+/-1000
R	2.2	7	+100	N	+/-2500
S	3.3	8	+1000		
T	4.7				
V	5.6				
U	7.5				

Table 1: EIA Specification Codes for Class 1 Dielectrics

[11]

- rutile
- perovskite titanates [11]

2.3.7 Class 2

- $\epsilon_r <= 15,000$
- The mostly ferroelectric barium titanate – causes concerns with:
  - voltage coefficient of capacitance
  - voltage coefficient of series resistance
  - voltage coefficient of dissipation factor
  - rate of capacitance decrease upon aging.
- Mostly Chosen for:
  - tempco of capacitance
  - temperature range

[6, Ch 3 Sec VI]

Class 2 ceramics have slightly worse characteristics, but have a much higher volumetric efficiency. [10]

Class 2: K = 1000 - 20,000 ferroelectric ceramics DF = .01-.03 mod-high temperature dependence [11]

2.3.8 Class 3

- Very high capacitance
- Low working voltage

[6, Ch 3 Sec VI]

Class 3: barrier layers very high capacitance $<$ 25V working voltage [11]

2.3.9 Misc

Ceramic capacitors are completely inert; which means that they will not deteriorate under normal operating conditions.[9, f. 45-46]

2.3.10 Glass (Porcelain)

The first glass dielectric capacitor was, in fact, the Leyden jar. While this early capacitor was used mainly for scientific experiments, commercial glass capacitors came later.

Glass tubular capacitors appeared in 1904 and were used in Marconi's experiments in wireless transmission. They were know as Moscicki tubes. They continued to be used in wireless communication until about WWI. [9, p. 102]

2.3.11 Steatite

Germany 1920 – steatite ceramics that used alkaline earth oxide fluxes instead of alkaline oxide (feldspare) [6, Ch 3 Sec II]

"Steatite, of which the principle constituent is magnesium silicate ($MgSiO_2$) has a high resistivity and a temperature coefficient close to that of mica." [18]

Magnesium silicate is known as talc. Talc existing in nature in large quantities is known as steatite. [12]

2.3.12 Rutile

1. First blended with Steatite
2. x10 ϵ_r
3. lower +tempco or -tempco
4. earliest know properties were single-crystal rutile in 1902.
5. best ceramic mixture, steatite-$Ti0_2$:
   (a) near zero tempco
   (b) $\epsilon_r = [15, 20]$
6. DF = [2,5]X low-loss steatite, but can be blended with steatite to get closer.[6, Ch 3 Sec IV.B]

1926 – titanium dioxide (rutile) became available.[14]

2.4 Barium-Titanate Capacitors

2.4.1 History

A ceramic composition wth barium titanate (BaTiO3) was first discovered in 1941. Barium titanate was quickly found to be able to exhibit a dielectric constant over 1000; an order of magnitude greater the best at this time (rutile - Ti02). It was not until 1947, that barium titanate appeared in its first commercial device, phonograph pickups.[17]

"Barium titanate ceramics were discovered by E. Wainer and N. Saloman in the USA in 1942., by T. Ogawa in Japan in 1944, and by B. M. Vul in the soviet Union in 1944. All discoveries were and independently with no communication between the researchers because of World War II."[11]

2.4.2 Ferroelectricity

"The discovery of ferroelectricty in barium titanate in the 1940s made available for ceramic capacitor design dielectric constants up to 2 orders of magnitude greater than previously known." [6, Ch 3 Sec III]

Preexisting dipoles can be accurately predicted in ferroelectric materials' crystal structure. They create regions of uniform polarization called domains. The crystal symmetry of the dielectric determines the relative orientation between domains.

These domains can be forced into a particular orientation by an externally applied electric field. "The effect of which is to increase the component of polarization in the field direction."

Increasing DC bias represses domain reversibility and consequently decreases the low-signal ac dielectric constant.

Increasing frequency decreases the dielectric constant through a 'relaxation' "centered in the GHz range." At this point the DF is maximal. [6, Ch 3 Sec III]

2.4.3 MISC

1. Barium Titanate ($BaTi0_3$) [6, Ch 3 Sec IV.C]
2. Most modern ceramic capacitor dielectric. In common use now.
3. First published on in the US in 1942.
4. Took over a decade before the industry put the material into active development.
5. It is usually blended with other materials to get the desired effect.
6. 1941 – barium titanate became available (eps = 1000) [14]

Capacitor Range	1nF to 1uF
Capacitor Tolerance	+/-15%
Maximum Voltage Ratings	upto 2kV
Power Factor	0.005 to 0.01 (@1kHz)
Temperature co-efficient	100 to 200 ppm/^oC

Table 2: Impregnated Paper Capacitor Characteristics
[32, ch. 8.2.1.1]

2.5 Paper Capacitors

2.5.1 Misc

Paper capacitors use waxed paper as a dielectric. They are primarily used in high voltage applications. But they are not preferred for much due to their high leakage and tolerances.[21]

1876 – wax impregnated paper dielectric with foil electrodes [14] -¿ power supply filtering in radios

WWI spurred the development of radio. ”It might be considered that this period (the early 1920s) saw the birth of the components industry.... Paper-dielectric capacitors were mainly tubular types enclosed in plain bakalizied cardboard tubes, with bitman or similar material sealing the ends.” [9, ch3]

Paper capacitors were first patented in 1876 by Fitzgerald. [9, ch. 11]

During WW2, ”waxed tubular paper-dielectric capacitors were replaced by metal-cased tubular types with rubber end seals. Metalized paper-dielectric capacitors were developed. [9, ch. 3]

Kraft paper capacitors typically had a dielectric constant of about 2-6 [32, ch. 8.1]

2.5.2 Impregnated Paper Capacitor

Paper is used as the dielectric. The paper is soaked with mineral oil to provide extra stability. The paper is interleaved with metal foil and then rolled to make the capacitor. [32, ch. 8.2.1.1]

” ”

Capacitor Range	1nF to 1uF
Capacitor Tolerance	+/-25%
Maximum Voltage Ratings	upto 1.5kV
Power Factor	0.02 (@1kHz)
Temperature co-efficient	150 to 200 ppm/^oC
Temperature range	-40^oC to 80^oC

Table 3: Metalized Paper Capacitor Characteristics
[32, ch. 8.2.1.1]

2.5.3 Metalized Paper Capacitor

"The metalized paper capacitor is very similar to the impregnated paper capacitor. The exception is that instead of using a metal foil, one side of the paper dielectric is sprayed with metal." [11] " "

2.6 Lead Zirconate Capacitors

The discover of Lead Zirconate came directly from the study of Barium-Titanate.

2.7 Tantalum Capacitors

Tantalum capacitors are typically electrolytic and mostly have much better characteristics than aluminum electrolytic caps. There downside is a lower "maximum capacitance and and lower maximum working voltage."[21]

1956 - Tantalum solid electrolytic capacitor Transistors - spurred need for solid electrolytic capacitor (coupling or bypass) [9, f. 56-64]

Tantalum capacitors began to be commercially produced in the 1950s with the onset of the transistor. Bell labs patented the first solid-tantalum capacitor with Sprague pantenting the first comercially vaiable design in 1960. The solid tantalum capacitor presented a component which had a much higher capacitance per unit volume and greater reliablity than the market offerings at that time. [33]

Sprague released the first surface mount tantalum capacitor in the 1970s.[37]

Tantalum was designed to be a replacement for alumunim electrolytic capcitors in certain circumstances. It had a greater dielectric constant and was much more stable than aluminum. And with solid tantalum capacitors, the detriments of a liquid electrolyte went away. One of the historical main draw backs with tantalum capacitors has been the volatility in the supply chain. Short price spikes have repeatedly occurred in the market. When one such spike occurred around 1980, finer grain tantalum powders were created to acheive greater capacitance, in a smaller package with less overall tantalum. [15, ch 3.1]

2.8 Titanium Capacitors

2.9 Old Intro

1. glass (porcelein)

2. Steatite ceramics

   Contained feldspar and were not as high loss as porcelein ceramics

3. paper and mica

   Were primarily used in first radio circuits on the early 1900s. They had very good loss characteristics, and could be manufactured into units with thin sheets (high capacitance, despite having a modest dielectric constant).

4. Germany 1920 – steatite ceramics that used alkaline earth oxide fluxes instead of alkaline oxide (feldspare)

   This gave them a low-loss characteristic.

5. Extruded tubular steatite ceramic capacitors arrived and replaced mica

[6, Ch 3 Sec II]

2.10 General Classifications

As of 1998: there are 5 basic capacitor technologies: "

1. ceramic

2. aluminum electrolytics

3. tantalum electrolytics

4. film (polymeric)
5. film (mica and paper)

” [35]

3 basic technologies: ”

1. electrolytic
2. film
3. ceramic

” [35]

distinctions ”

aluminum - liquid impregnant tantalum - dry impregnant

polymeric and mica – synthetic film paper film – natural film ” [35]

Evolving technologies:

CDL (Chemical double layer)

- very high capacitances
- 1-3V working
- fuly bipolar

nanostructure mulitlayer

- inorganic high dielectric constant coatings
- interleaved layers
- 100-10,000 layers

[35]

2.11 Electrolytic Capacitors

Characteristics:

- moderate energy
- moderate power density
- relatively high losses
  - high ESR
  - high DF
- polarity dependent
- primarily used in dc circuits

Typical Uses:

- large value capacitors (1-100,000 uF)
- DC applications
  - filtering
  - rectified circuits
  - pulsing circuits
    * strobe lights
    * SCR communication circuits
    * fractional horsepower motor starting

[35]

Karol Pollak discovered the principle of the electrolytic capacitor in 1886 while he was researching the anodization of metals. In 1897, he received a patent for the borax-solution aluminum electrolytic capacitor. In 1926, Julius Lilienfeld patented an electrolytic capacitor containing electrolyte soaked paper. Ralph D. Mershon developed the first practical, commercially available radio electrolytic capacitor. After the start of WW2, increased funding and effort was applied to the cause of electrolytic capacitors and technics such as "etching and preanodizing" greatly increased their reliability. [40]

In 1897, Charles Pollak received a patent for the borax electrolyte aluminum electrolytic capacitor. In 1936 Cornell-Dubilier opened a factory to produce aluminum electrolytic capacitors. EL caps became more reliable after WW2 after people threw resources at them. [14]

An electrolyte is an "ionic conducting fluid." [30] Mclean and Power developed the tantalum solid electrolytic capacitor in 1956. [30]

2.12 Cornell-Dublier

William Dublier invented the first pratical mica capacitor in 1909. He went on to found the Dublier Condensor Company in 1915, which became the modern Cornell-budilier in 1933.[14]

2.13 Capacitor Markets

- motors
- lighting
- power supplies
- electronic circuits

[35]

2.14 Mica Capacitors

During WWI, mica capacitors began to be produced in large quantities. This was mainly due to it being able to survive shock from weapons better than its glass counterpart. Also, it allowed the capacitors to be shrunk to achieve the same purpose. [9, f. 37-41]

In light of mica supply chain problems and the emergence of ceramic capacitors during WW2, mica capacitors fell from prominence to a niche market after the second great war.[6, Ch 3, Sec II]

Mica capacitors were originally made as a "clamped" style capacitor and used through the 1920s[41].

The mica capacitor was invented by M. Bauer in Germany in 1874.

Mica capacitors are used as an extremely reliable and efficient option due to mica's inherent inertness and stability. [38] – "Mica is very stable electrically, mechanically, and chemically. ϵ = [5-7].[20]"

Mica capacitors have a very low tempco, change little with voltage, high Q, low ELS, and vary little with frequency. Used in RF a lot. On the downside, they are large. (You can used ceramics as a replacement). Most mica capacitors have low values (in the nF range).[20]

[26][ch 1.13 pg 22]

Mica capacitors tend to provide very good results. They provide a choice which has high accuracy, a low temco, low variations of capacitance with voltage, and high Q. There main drawback is that they tend to be available only in lower capacitance ranges. They are know to jump in value on some occasions???? [31]

The mica dielectric "was also one of the first dielectric materials to be used for capacitors in the early days of wireless because of its combination of stability and general physical and mechanical stability." Mica capacitors age slowly due to mica's natural inertness (it reacts with very little).[31]

2.14.1 Silver Mica Capacitors

Tight tolerance (¡=1%),really good tempco and stability, but low capacitance values and expensive. Used in high frequency circuits a lot.[21]

2.15 Aluminum Capacitors

Aluminum capacitors typically come in up to 50mF, but have high leakage currents, large tolerances, and large temperature coefficients. [21]

2.16 Polyester Capacitors

Polyester capacitors provide an option for a cheap, high capacitance per unit volume option. On the downside, they have a high temperature coefficient. [21]

2.17 Polypropylne Capacitors

Polypropylene capacitors can come up to a high working voltage of up to at least 3kV. They also can be used as a replacement to polyester capacitors due to their tight (1%) tolerances.[21]

2.18 Polystyrene Capacitors

Polystyrene capacitors have a high isolation resistance, but they also have a high ESL and exhibit a permanent value change if they get above 70C. [21]

2.19 Polycarbonate Capcitors

Polycarbonate capcitors have descent temperature coeficients, but bad tolerance. [21]

2.20 Film

"Traditional film capacitors were only available in modest sizes, ¡10uF."

Longer lifespans when compared to electrolytics.

Types:

- Film-foil – Good at high currents
- metalized filem – Good at self-healing

"

Pros:

1. low leakage
2. low aging

Cons

1. low K

" [1]

2.21 Applications

In 1907, Lee De Forest created the first? vaccum tube. [14] 1915 – coast to coast telephone 1927 – RCA Radiola 17 – first AC line powered radio

mica dielectrics – RF circuits

1909 – William Dublier – invented mica dielectric capacitors –¿ highly reliable

1897 – Charles Pollak got the patent for the first electrolytic capcitor (borax electrolyte aluminum)

WW2 – electrolytic capacitors became more reliable

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WW2 – electrolytic capacitors became more reliable

Metalized, self-clearing capacitors -Mansbridge patented in 1900 – frequent shorts -WW2 - reached maturity 1950 - used in the phone system

1954 - Bell labs took the metalied... and created the metalized polymer film capacitor

1941 - Polyethlyne tetrephtalate (PET) – Mylar – 1950s

1951 - semicrystalline polypropelyne

1970 - film-foil capacitors (no paper) - electric utility applications

1957 - Electric Double Layer Capcitors patented –1978 - ”supercapacitor” 5.5V 1F [14]

2.28 Current State of the Art

Current Important Types: [14]

1. impregnated foil-polymer film (high V,I)

2. metalized film
3. ceramic
4. electrolytic
5. electric double layer

2.29 Strengths and Weaknesses

Look here for more info. [14]

3 Modeling

3.1 Neumayer Complex Curve Fitting Paper

This section will contain notes on Neumayer's Paper on Complex curve fitting.[25]

This paper compares two methods for determining model parameters from frequency domain data. Method 1 is a "parametric complex curve fitting technique" and method 2 is a frequency-domain subspace identification algorithm."

He seems to be saying that Levy [22] is an iterative approach. One downside of many iterative approaches is that they require you to guess the initial values of the parameters. This can be difficult in high-order systems. He provides an alternative[39], which only require you to specify the model order. Although the focus of this paper is on the microwave band, it is my hope that I can apply these techniques to the RF and lower bands.

$$H(s) = \frac{A_0 + A_1 s + A_2 s^2 + ... + A_\epsilon s^\epsilon}{1 + b_1 s + b_2 s^2 + ... + b_\eta s^\eta} \tag{1}$$

Equation: (1) is used in both methods as the form of the model transfer function. You can use various techniques such as "Model-Based-Parameter-Estimatior or Vector Fitting" to solve for the coefficients. You can convert the systems to equivalent subcircuits if you cannot use differential equations.[24]

Terminology list:

1. Newton-Gauss
2. Levenberg-Marquardt
3. Jordan-Canonical Transformation
4. Staircase Algorithm

3.1.1 Frequency-Domain Subspace Identification

Methods of this type will start with Equation (2).[39]

$$H_R = \Gamma_i X_R + \Theta_i I^R \ [25][Eq.\ 5] \tag{2}$$

Γ_i is the extended observability matrix. Θ_i is the block Toeplitz matrix.

Terminology list:

1. Singular Value Decomposition (SVD)
2. Moore-Penroes Pseudo-inverse
3. Forsythe recursions [39]

$$\omega_{scale} = \frac{\omega_{min} + \omega_{max}}{2} \ [39] \tag{3}$$

"The frequency domain identification algorith" can be improved by normalizing the frequency via Equation: (3).

3.1.2 Passive Equivalent Circuit

Once the parameters of Equation: (1) are established, we will want to obtain a passive eletrical model. "This can be ensured by checking that the Hamiltonian matrix has no purely imaginary eigenvalues.[5][25]"

3.2 Neumayer Synthesis of Equivalent-Circuit Models...

This section will contain notes on Neumayer's Paper on fitting.[24]

This paper will show how to model systems using either Y,Z, or S parameters. It will show how to determine if the system is stable and passive. In order to prove passivity, we must show that "$ReY(s) or ReZ(s)$ must be positive definite (PD)." He gives sources for this. The author will provide an alternative in this paper which only requires the user to solve one Ricatti eqution.

In order to solve the coefficients for the transfer function, you can solve an easily defined matrix (his equation 7). The problem with this, and it is what I found with Levy's method, is that is becomes unusable for data sets with a wide bandwith.But the good news is that there are ways to circumvent this problem. Two simple methods are to either "normalize the frequency range, $w_i^* = \frac{w_i}{w_0}$ or split the freuency into several sub domains." Another way is to "replace the power series with orthogonal polynomials, such as Chebyshev polynomials.[4]

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