
a YAGEO company

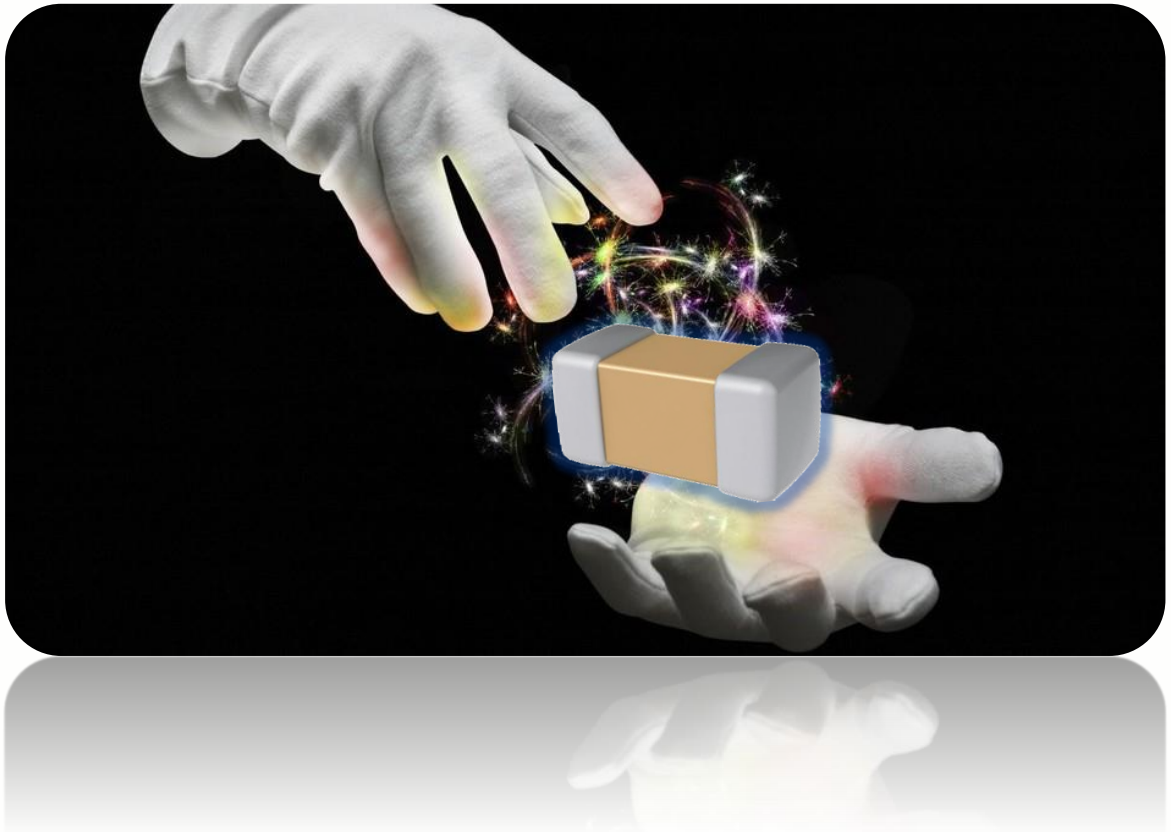
# Taking the Mystery Out of RF Ceramic Capacitors

August 2021

# Taking the Mystery Out of RF Ceramic Capacitors

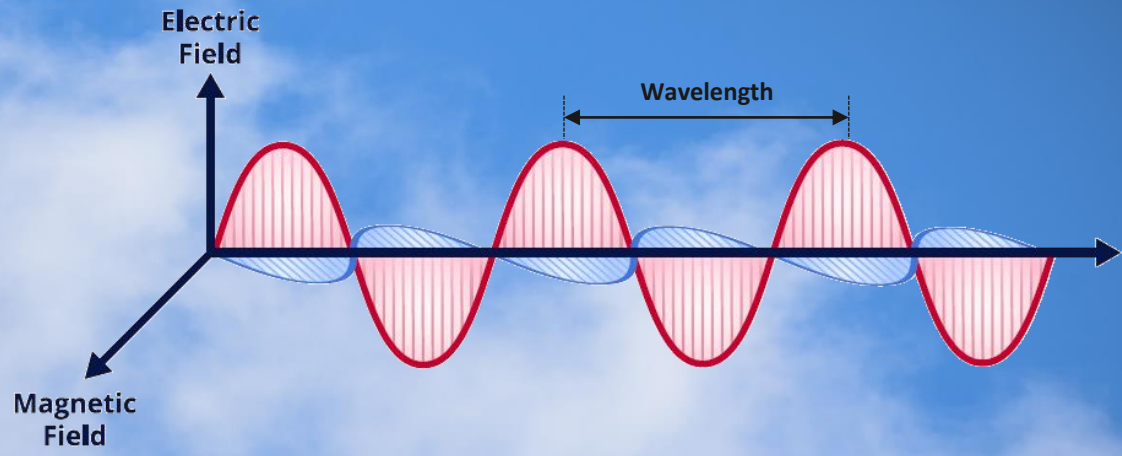
## Agenda

- What is RF?
- RF Applications
- Ceramic Capacitor Basics
- What are RF Capacitors?
- KEMET HiQ-CBR Series
- Characterization and E2Di
- CBR Roadmap and Summary



# What is RF?

## Radio Frequency




$$frequency = \frac{C = Speed\ of\ Light}{\lambda = Wavelength}$$

**10s MHz – 300GHz**

**“High Frequency”**

# RF Frequency Spectrum



RF "High Frequency" Range

Microwave Band

mmWave

Marine Navigation, Wireless Heart Rate Monitors

Navigation, RFID

AM Radio, Amateur Radio

Shortwave Radio, Aviation Communication, NVIS

VHF Television, FM Radio, Weather Radio, Line-of-Sight Communications

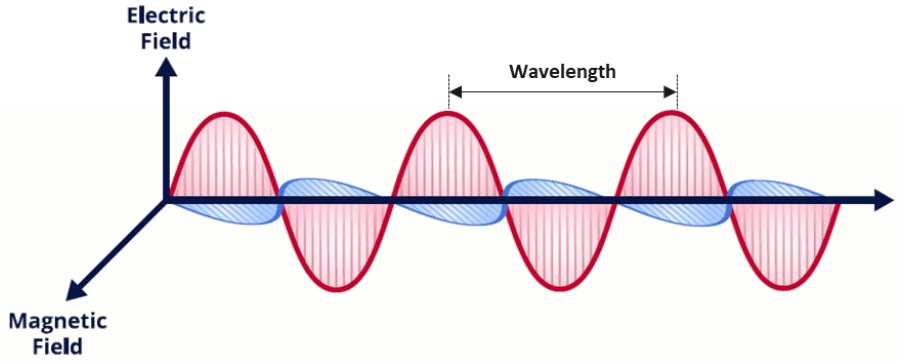
GPS, 4G Mobile Phones, Satellite Radio, Remote Control Systems

5G Mobile, Satellite Communications, WiFi

Radio Astronomy, Millimeter Wave Scanner

| Designation | VLF | LF | MF | HF | VHF | UHF | SHF | EHF |
|---|---|---|---|---|---|---|---|---|
| Wavelength | 100 km | 10 km | 1 km | 100 m | 10 m | 1 m | 10 cm | 1 cm | 1 mm |
| Frequency | 3 kHz | 30 kHz | 300 kHz | 3 MHz | 30 MHz | 300 MHz | 3 GHz | 30 GHz | 300 GHz |

4G 5G




Advantages of Higher Frequencies

- More use of the frequency spectrum
- High capacity (bandwidth) / sending more data in less time

Disadvantages of Higher Frequencies

- Shorter range
- Signals may be blocked by dense objects
- If outside, weather conditions have an impact

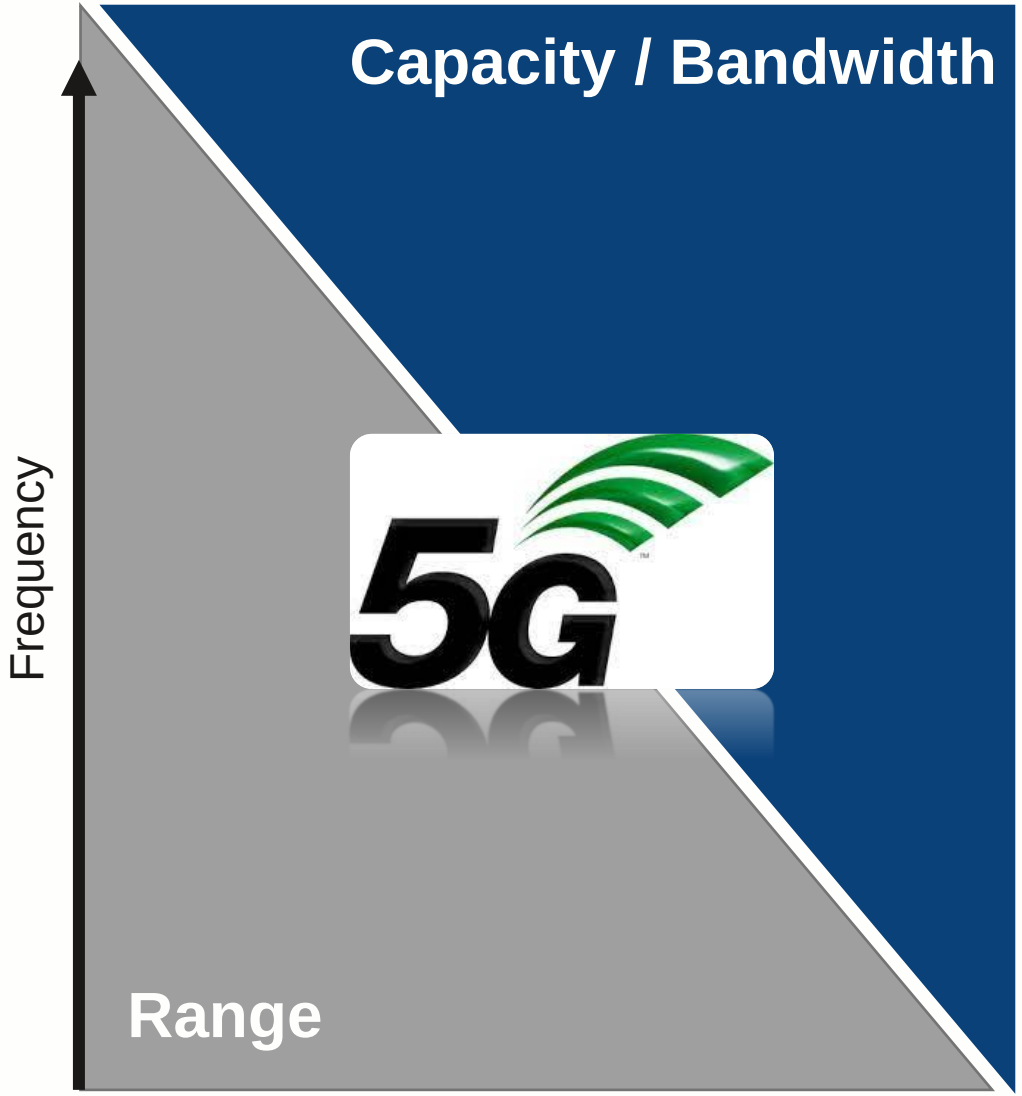
# 5G Technology

## Capacity / Bandwidth vs Range

**5G mmWave**
- >24GHz

**5G Mid Band**
- 1GHz - 6GHz

**5G Low Band**
- <1GHz

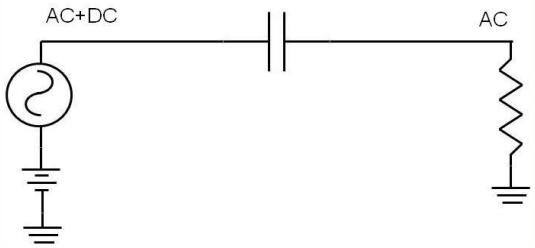



**Urban Areas**
Dense Population

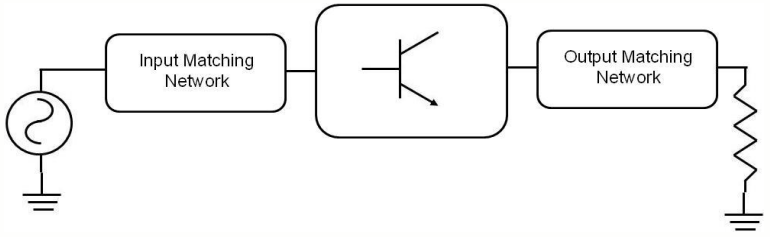
**Rural Areas**
Light Population

# RF Capacitor Applications and Functions

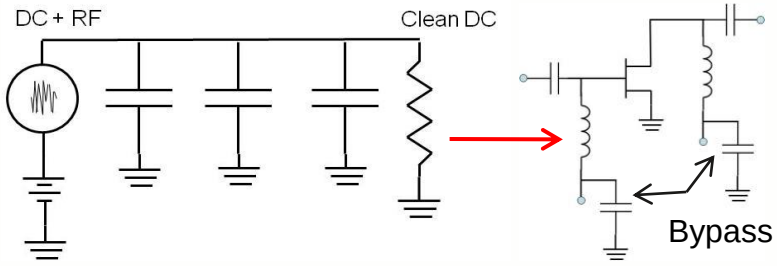
## DC BLOCKING




## MATCHING




## BYPASS/FILTERING



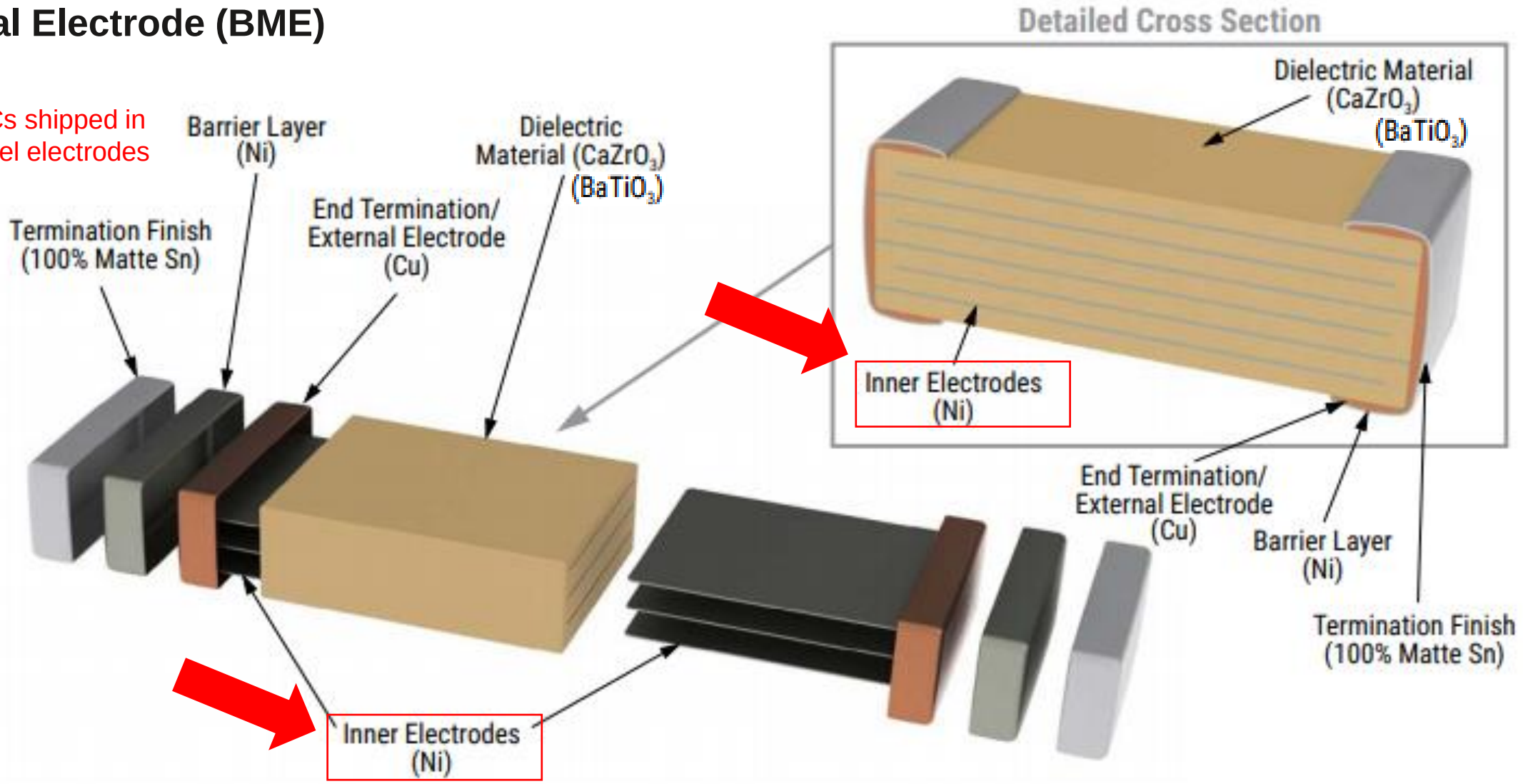
# Ceramic Capacitor Basics

# Ceramic Capacitor Basics

## MLCC Construction

### Base Metal Electrode (BME)

>99.9% of all MLCCs shipped in the world used Nickel electrodes



# Ceramic Capacitor Basics

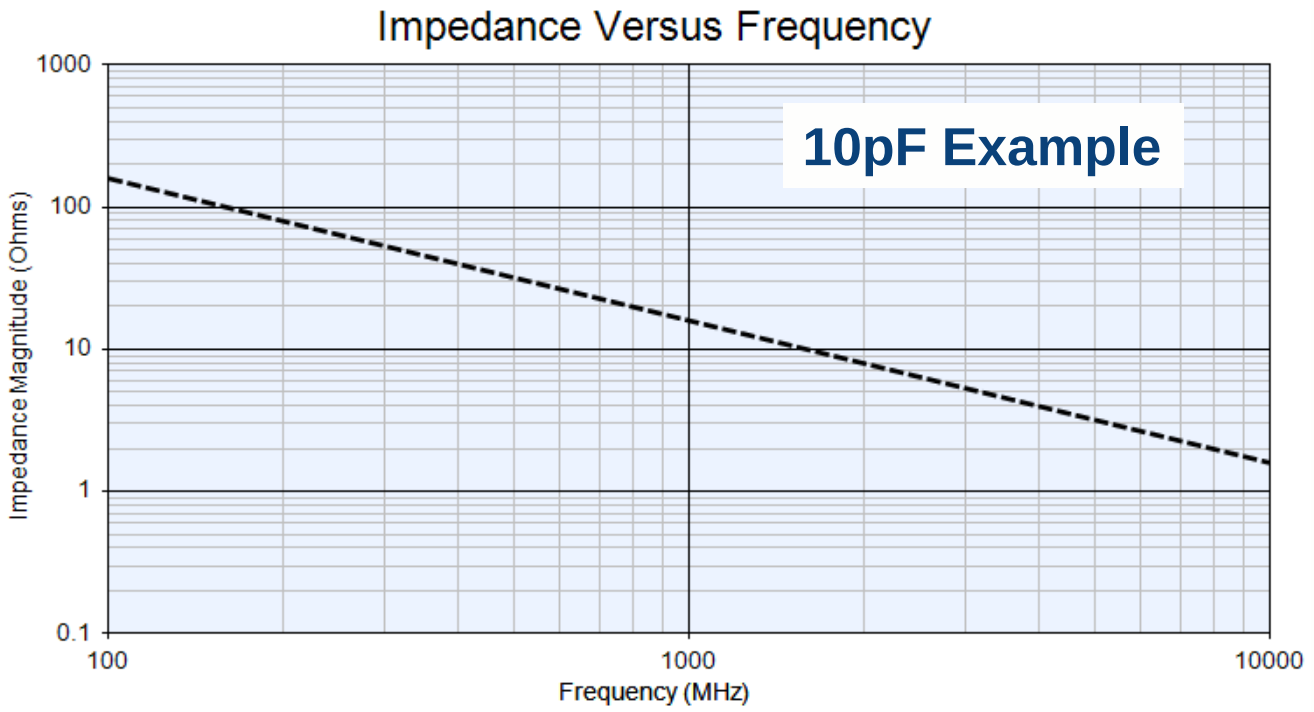
## Ideal Capacitor

- Ideal Capacitor
  - Pure Capacitance
  - No resistance (ESR)
  - No Inductance (ESL)

### Ideal Model

$$Z = \frac{1}{2\pi * Freq * Capacitance}$$

$$Z = Total\ Impedance$$



# Ceramic Capacitor Basics

## Real Capacitor

- Real Capacitor
  - C - Nominal capacitance
  - ESR – Equivalent Series resistance
  - ESL - Equivalent Series inductance

### Simplified Real Model

**C ESR ESL**

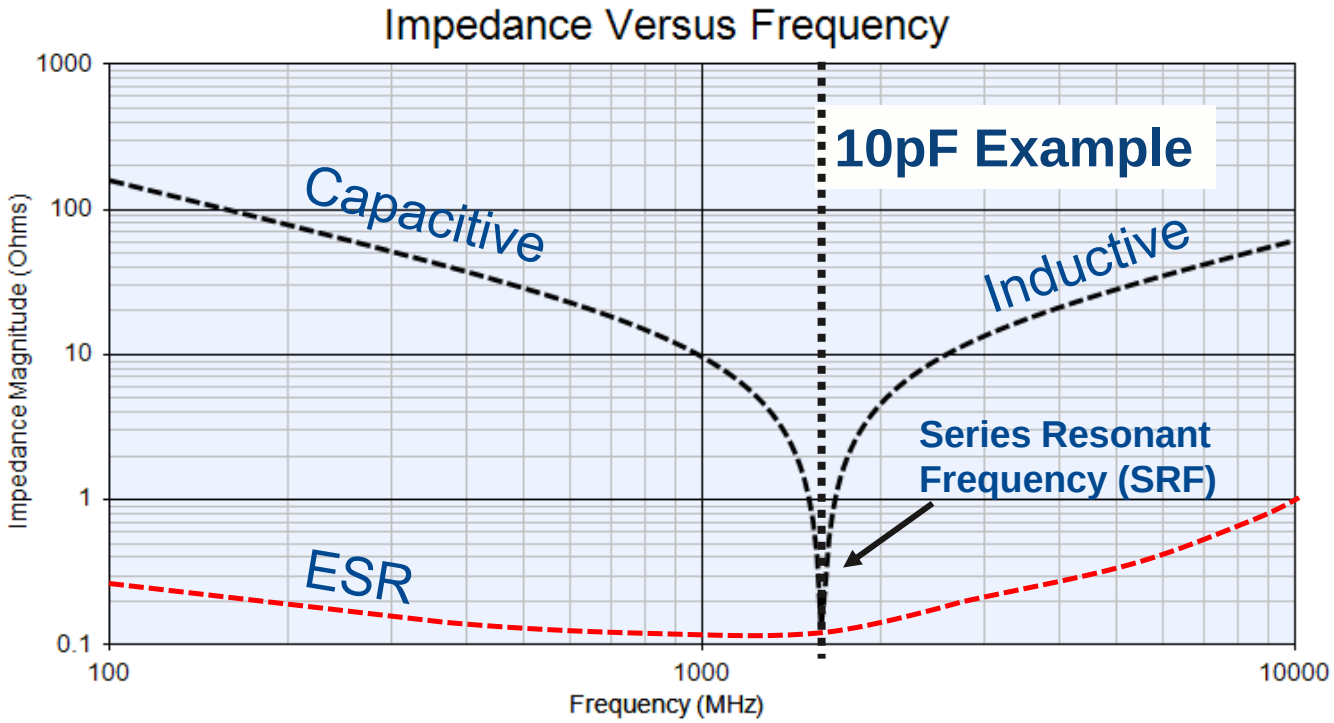
$$Z = \sqrt{ESR^2 + (X_L - X_C)^2}$$

$Z = Total\ Impedance$

$ESR = Equivalent\ Series\ Resistance$

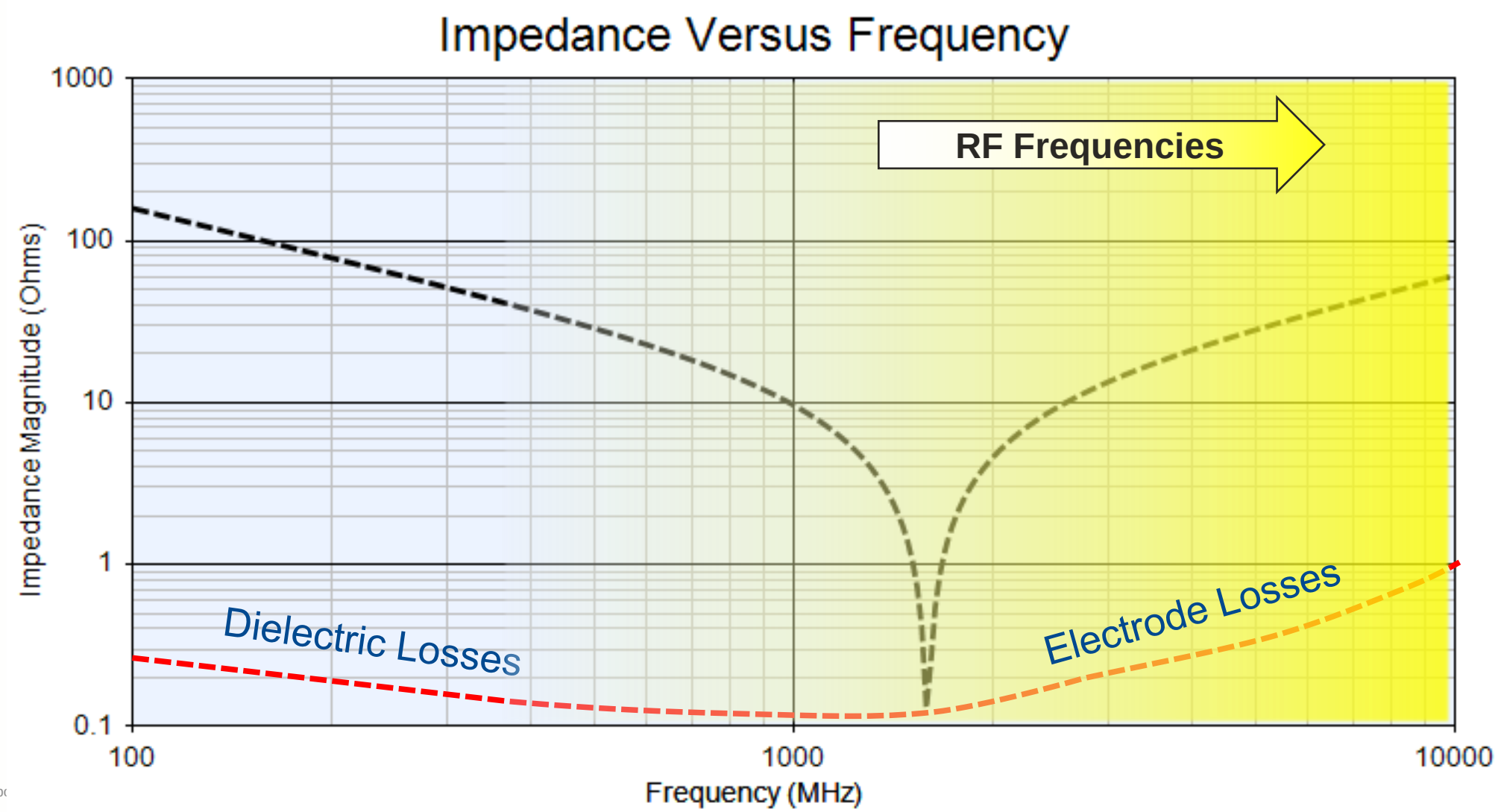
$X_C = Capacitive\ Reactance$

$X_L = Inductive\ Reactance$



# Ceramic Capacitor Basics

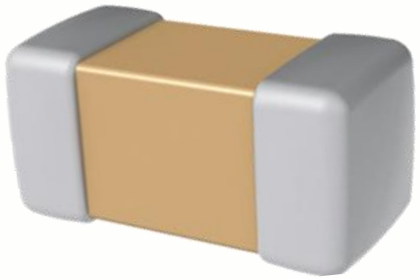
## Closer Look at ESR



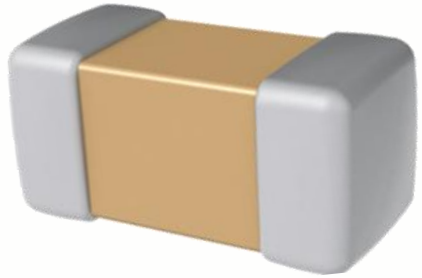
# RF Capacitors

## What's the Difference?

**"Standard" Ceramic Capacitor**



**RF Ceramic Capacitor**



# Key Characteristics for Capacitors in RF Applications

## What's Important for Design Engineers?

Most Important

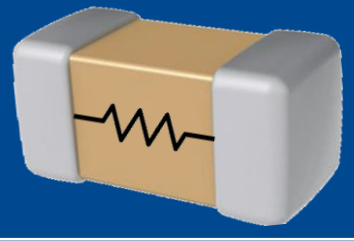
### ESR @High Frequencies

Low

Equivalent Series Resistance

$$Power\ Dissipation = i^2 * ESR$$

$$ESR \rightarrow Waste\ as\ Heat$$



### Q @High Frequencies

High

Quality Factor "Efficiency"

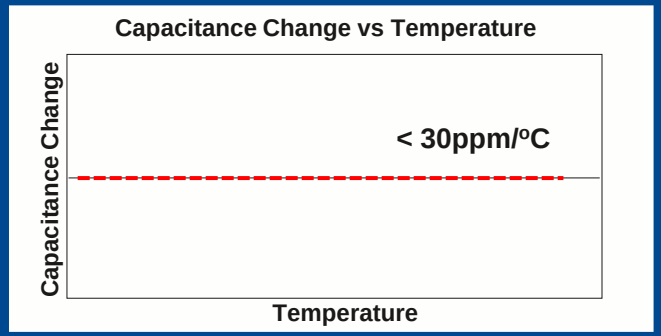
$$Q = \frac{X}{ESR}$$

$$\boldsymbol{Low\ ESR \rightarrow High\ Q}$$

### TCC

Low

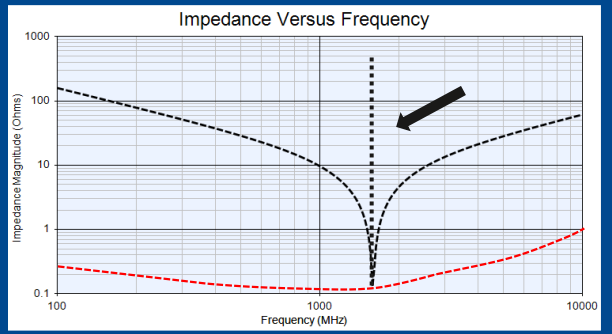
Capacitance Change with Temperature




### SRF

High

Series Resonant Frequency



# So, What is an RF Capacitor?

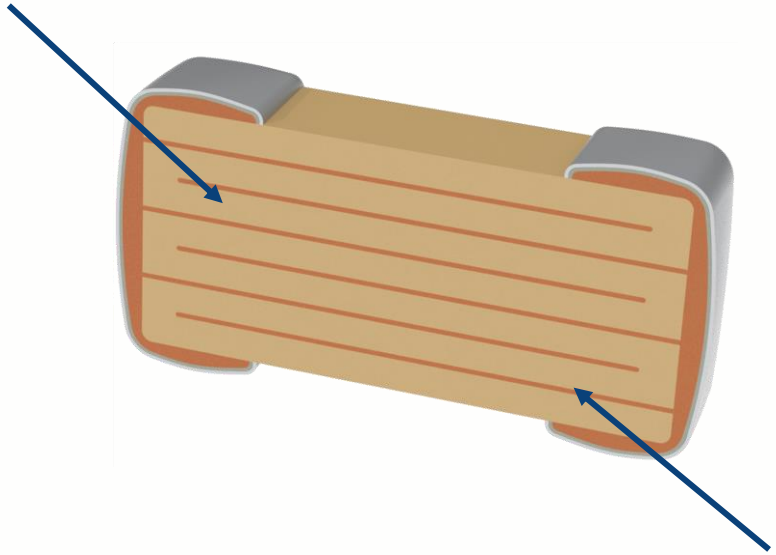
**An RF capacitor is a capacitor whose "characteristics" are optimal at RF frequencies**

| Key Characteristic | RF Capacitor Requirements |
|---|---|
| ESR (Equivalent Series Resistance) | Lowest possible ESR at RF frequencies |
| Q (Quality Factor) | High Q at RF frequencies |
| SRF (Series Resonant Frequencies) | High SRF as high as possible |
| TCC (Temperature Coefficient of Capacitance) | Minimal capacitance shift across temperature |

So, for RF capacitors, materials are chosen, and designs are optimized so that the capacitor's characteristics are optimal at the higher frequencies.

# Optimizing MLCCs for RF Applications

| Design | Design Goal | How? |
|---|---|---|
| Dielectric | • Low ESR / High Q<br>• Temperature and Voltage Stability | Typically, High Q class 1 dielectrics such as C0G or NPO |



| Design | Design Goal | How? |
|---|---|---|
| Electrodes | • Low ESR / High Q<br>• Low Inductance | • Non-ferrous materials<br>• No Nickel electrodes<br>• Copper (BME) |

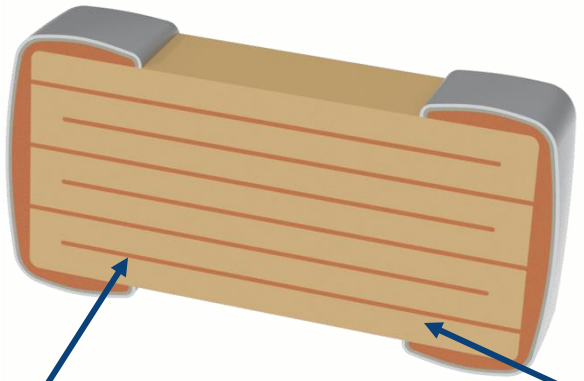
# KEMET HiQ-CBR Series

# KEMET HiQ-CBR Series RF & Microwave

## Commercial and Automotive Grade

- RF Power Amplifiers, Base Stations, Radios, Wearables, etc.
  V2X, Automotive Communication Systems
- AEC-Q200 Qualified (Automotive Grade Only)
- RF, Microwave, mmWave Bands
  1 MHz to 50 GHz
- Ultra-Low ESR, High Q
- 0201 – 0805 EIA Case Sizes
- 0.1pF – 100pF
- 6.3 – 500 Vdc

RoHS | REACH COMPLIANT | Lead-free



**Copper Electrodes**

- Low ESR
- High Q
- High SRF

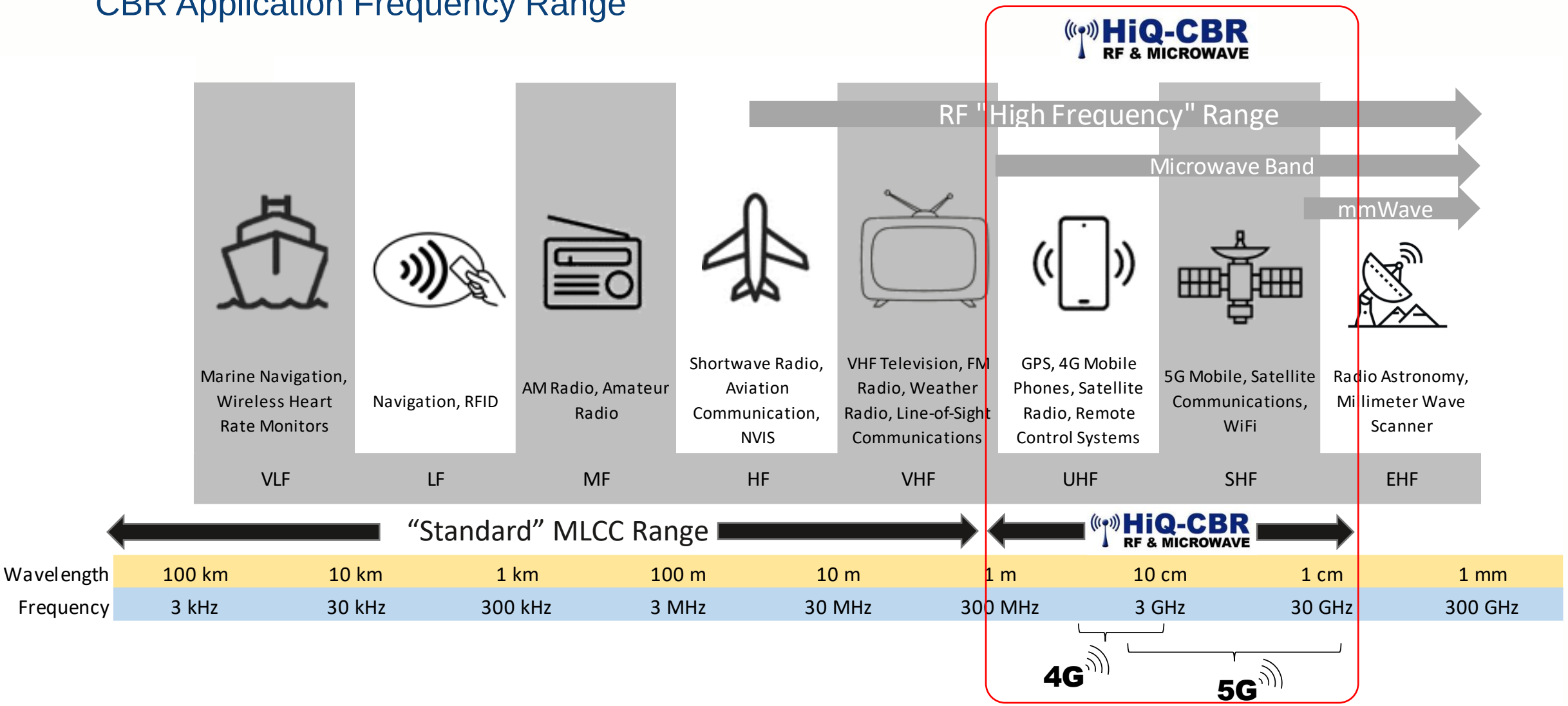
**High Q BME Class 1 Dielectric**

- Low ESR
- High Q
- Low TCC

Downloadable S-Parameters Available
Advanced Modelithics™ Models

# KEMET HiQ-CBR Series

## CBR Application Frequency Range



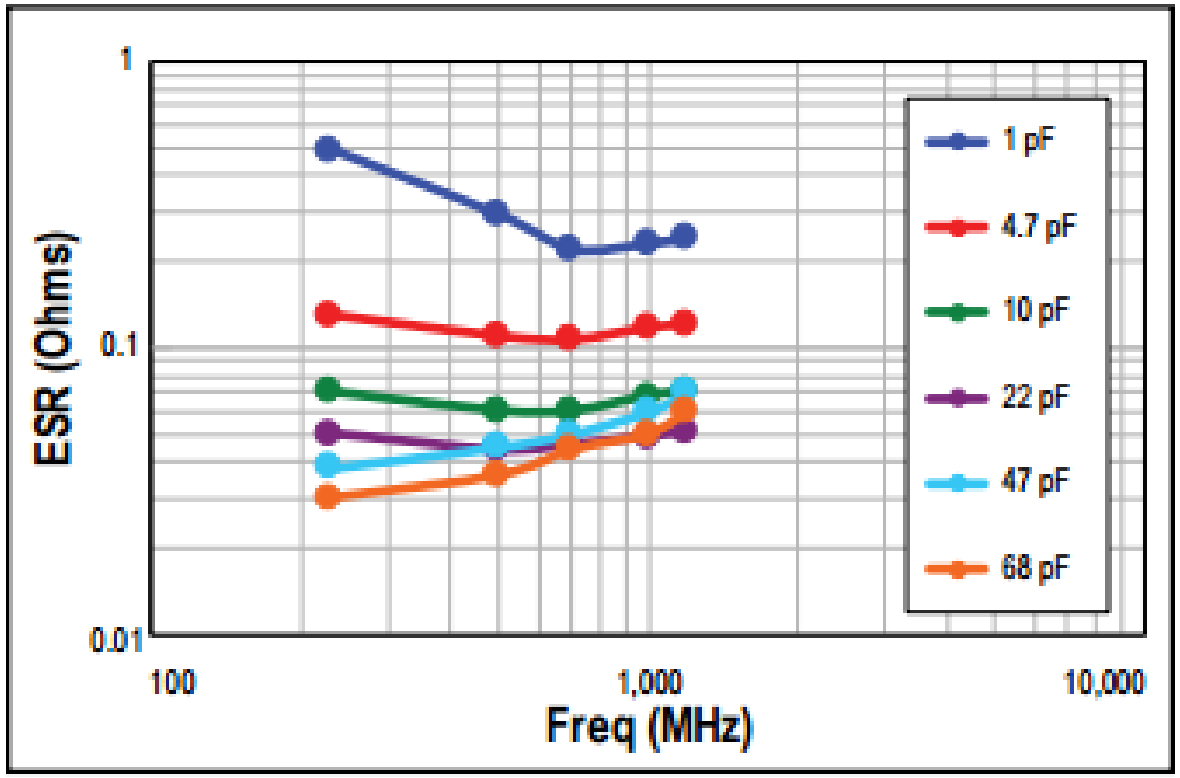
# KEMET CBR Characterization and E2Di

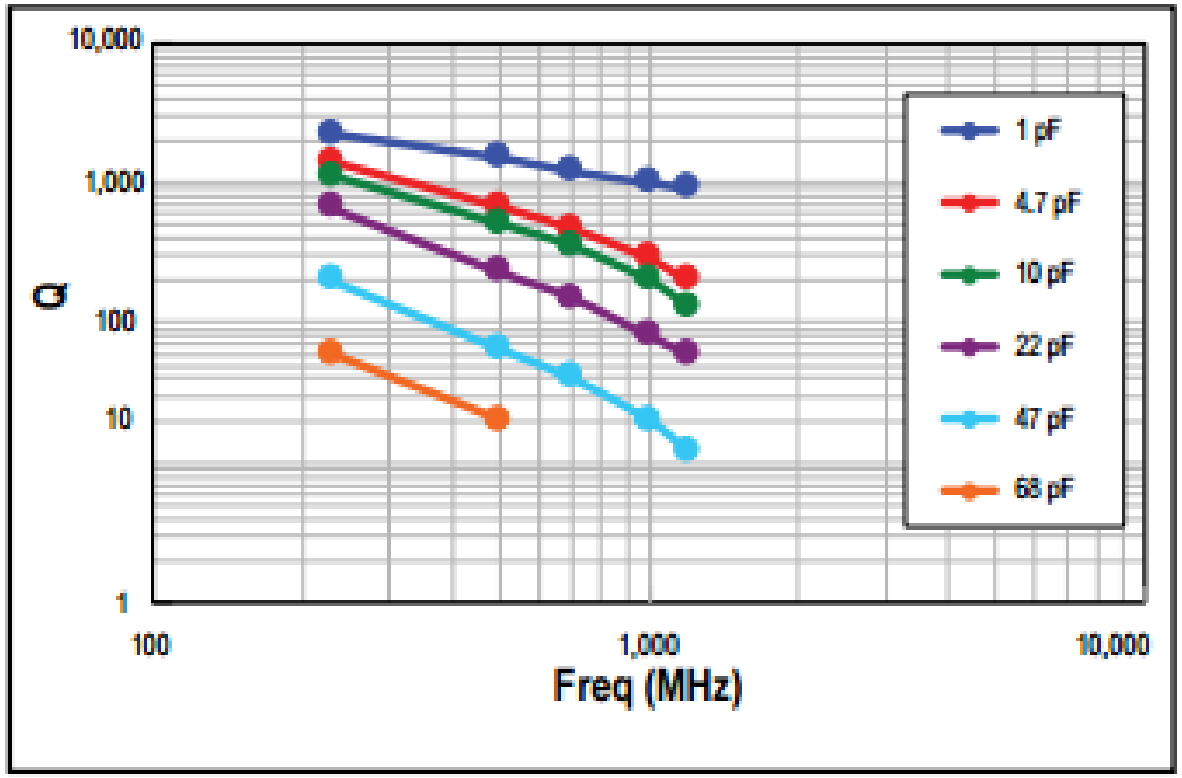
*“Why is KEMET’s CBR Series not in the KSIM tool?”*

# ESR and Q

HiQ-CBR
RF & MICROWAVE

KEMET
a YAGEO company



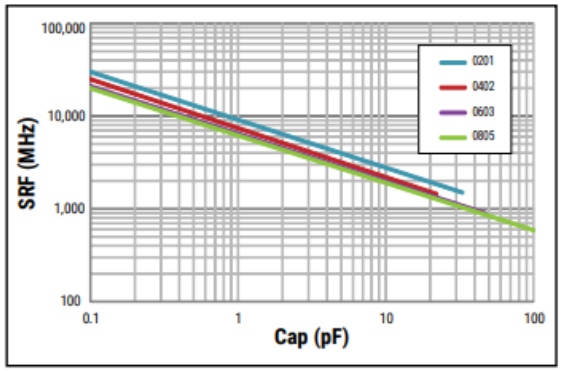




Boonton 34a – ESR and Q Measurements

# ESR, Q, and SRF
## Datasheet Availability

E2Di EASY TO DESIGN IN

SRF (MHz) vs. Cap (pF)




RF and Microwave

Ultra HiQ-CBR Squared, C0G Dielectric, 250 VDC
HiQ-CBR, C0G Dielectric, Low ESR, 6.3 - 500 VDC

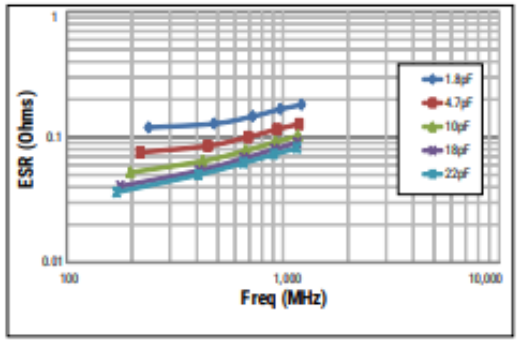
*https://www.kemet.com/en/us/capacitors/ceramic.html#tab-datasheets*



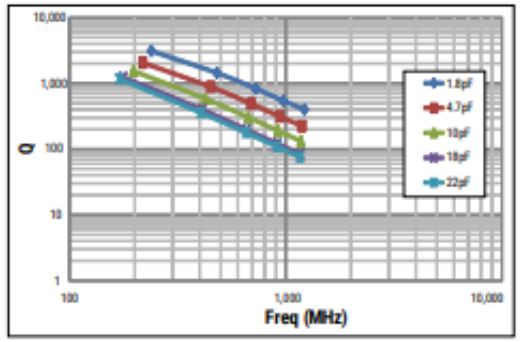


**Electrical Characteristics cont.**

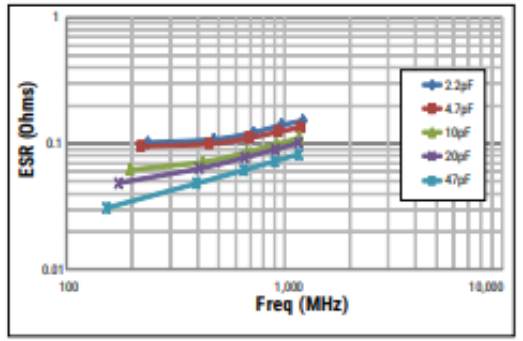
ESR vs. Frequency 0402



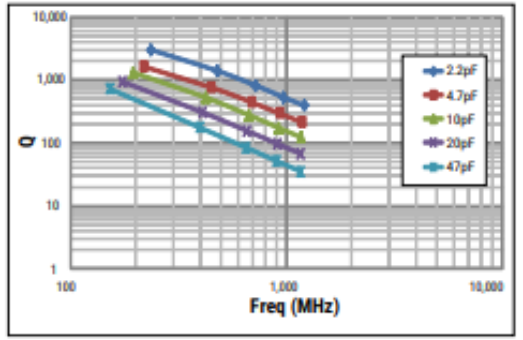

Q vs. Frequency 0402



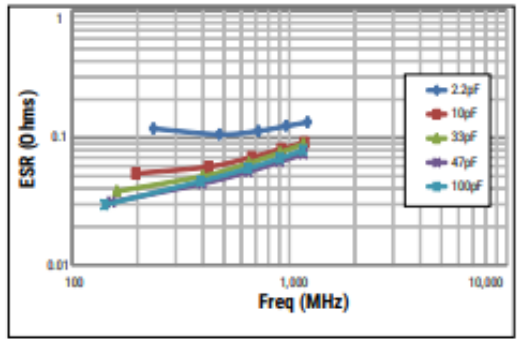

ESR vs. Frequency 0603



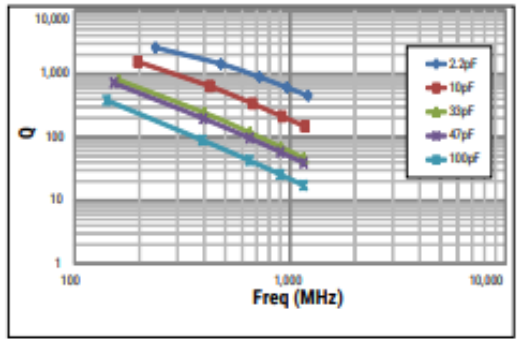

Q vs. Frequency 0603




ESR vs. Frequency 0805



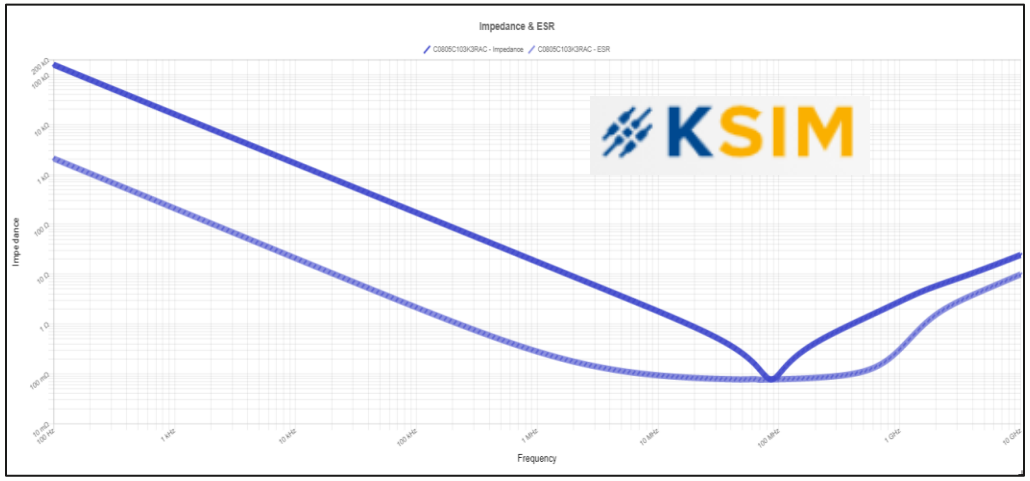

Q vs. Frequency 0805

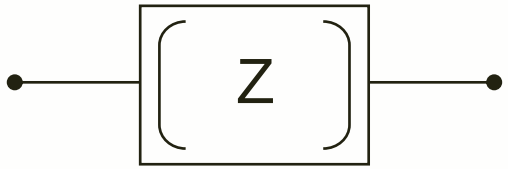


# S-Parameters

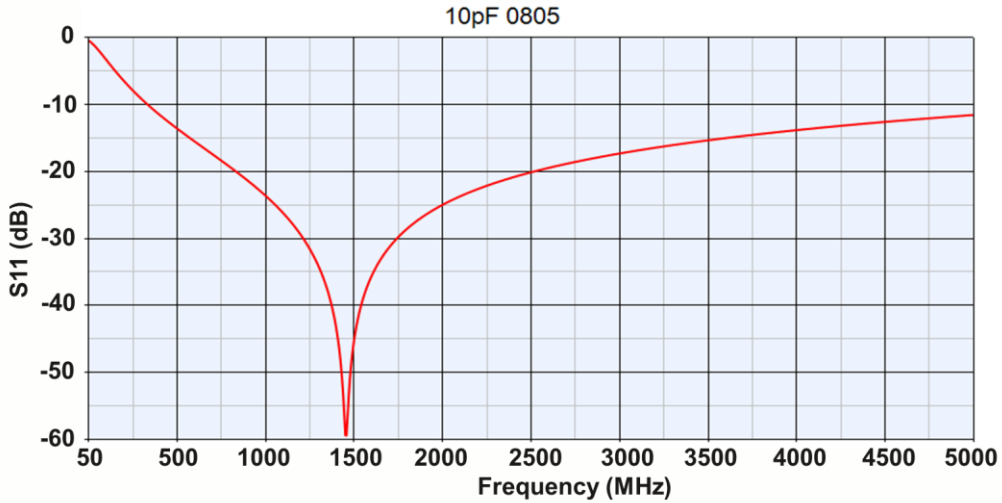
## Low Frequency Design vs High Frequency “RF” Design

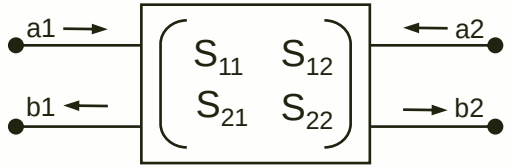
### Impedance / ESR Approach




### S-Parameter Network Approach

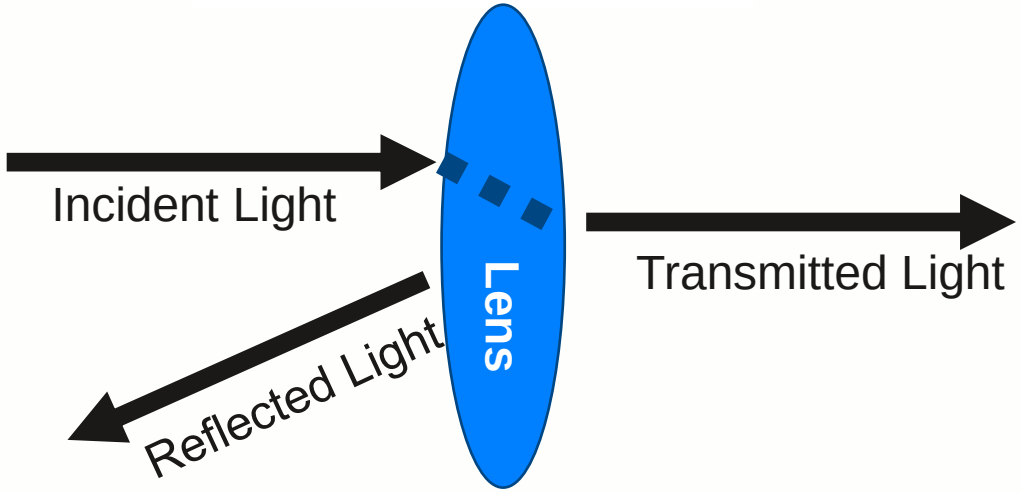


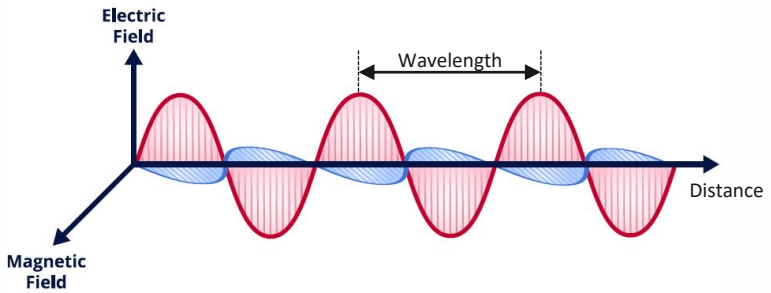
# S-Parameters (Scattering Parameters)

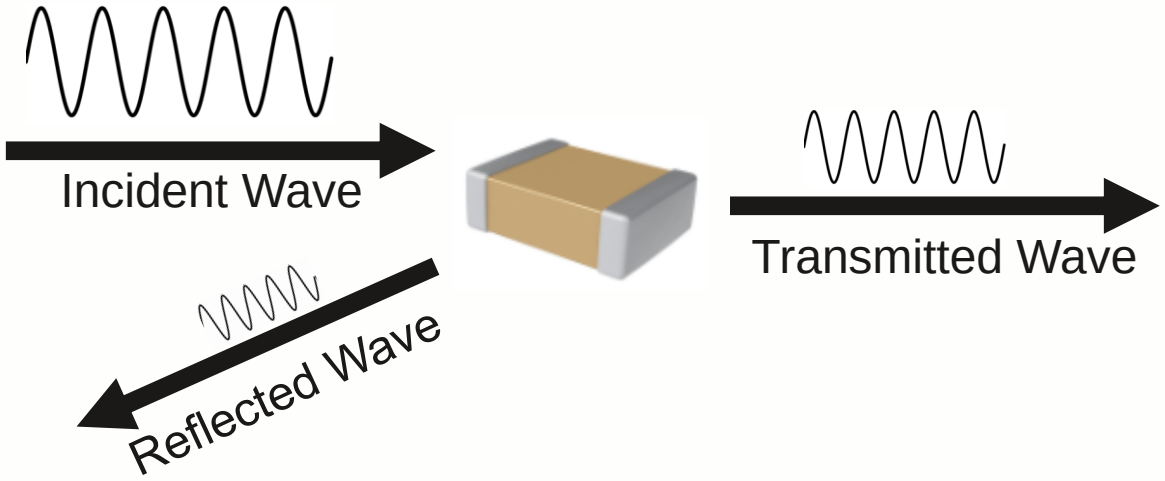
## What are they?

### Light Analogy




### RF Voltage Wave

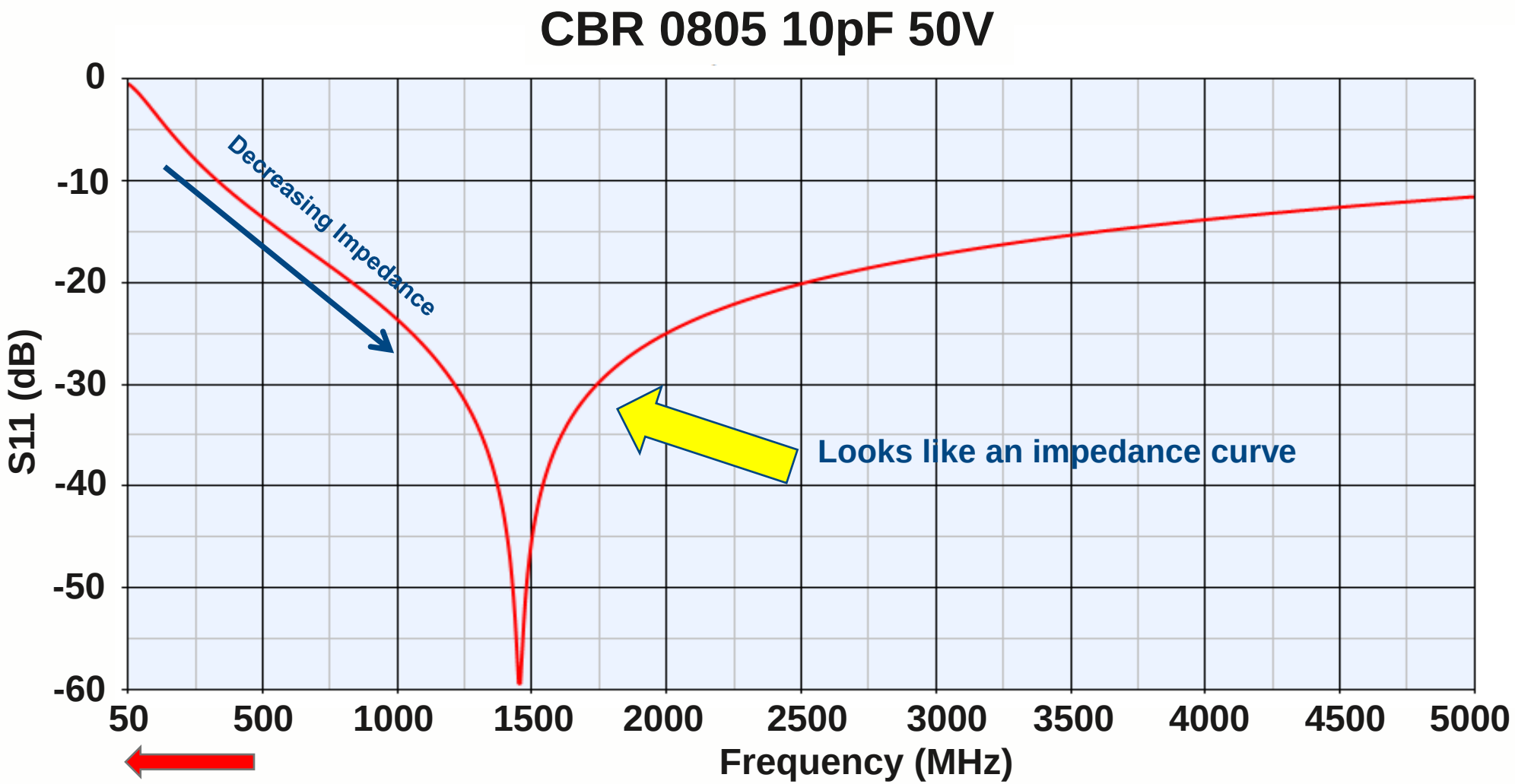



$$S_{11} = \frac{Reflected\ Wave}{Incident\ Wave} \qquad S_{21} = \frac{Transmitted\ Wave}{Incident\ Wave}$$

# S-Parameters

## Example of S11 Plot



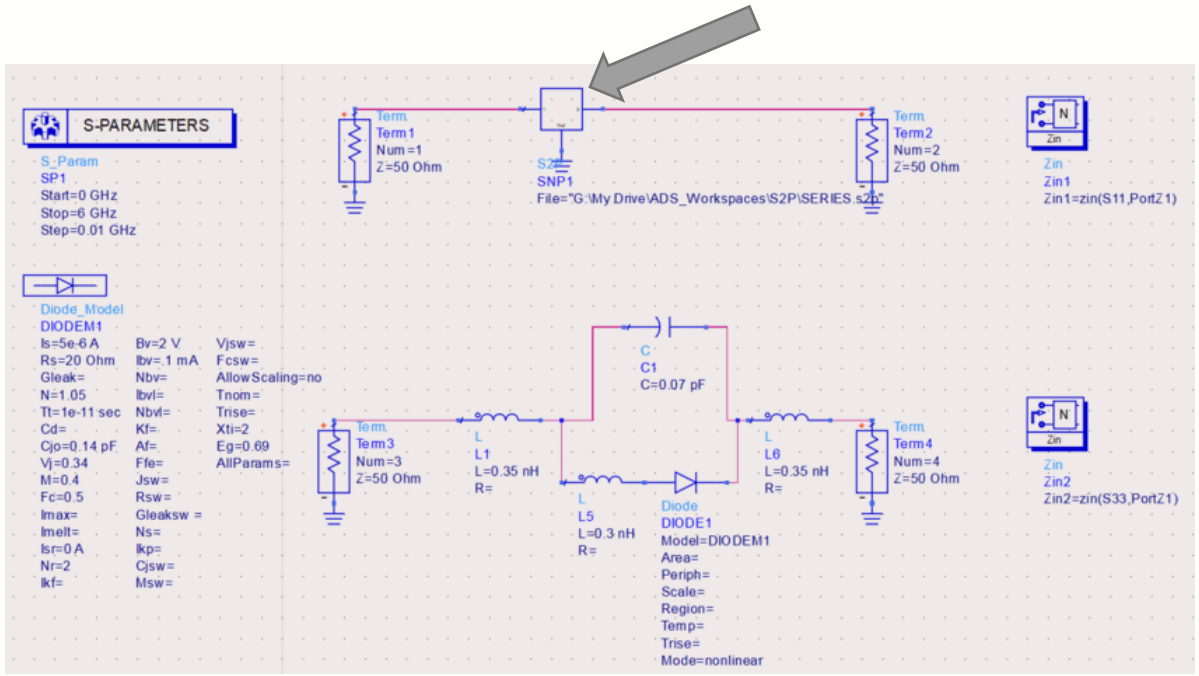

***KSIM Frequency Range***

# S-Parameters

## How Designers Use Them

### RF Simulation Tools

- Keysight's Advanced Design Systems (ADS)
- Keysight's PathWave RF Synthesis (Genesys)
- Cadence AWR's Microwave Office
- Other tools available



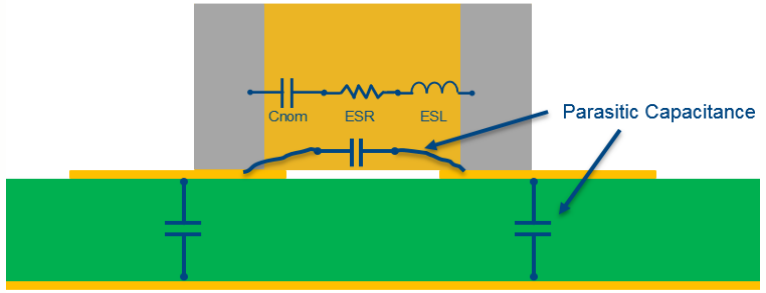

## ASCII text files - Touchtone Format

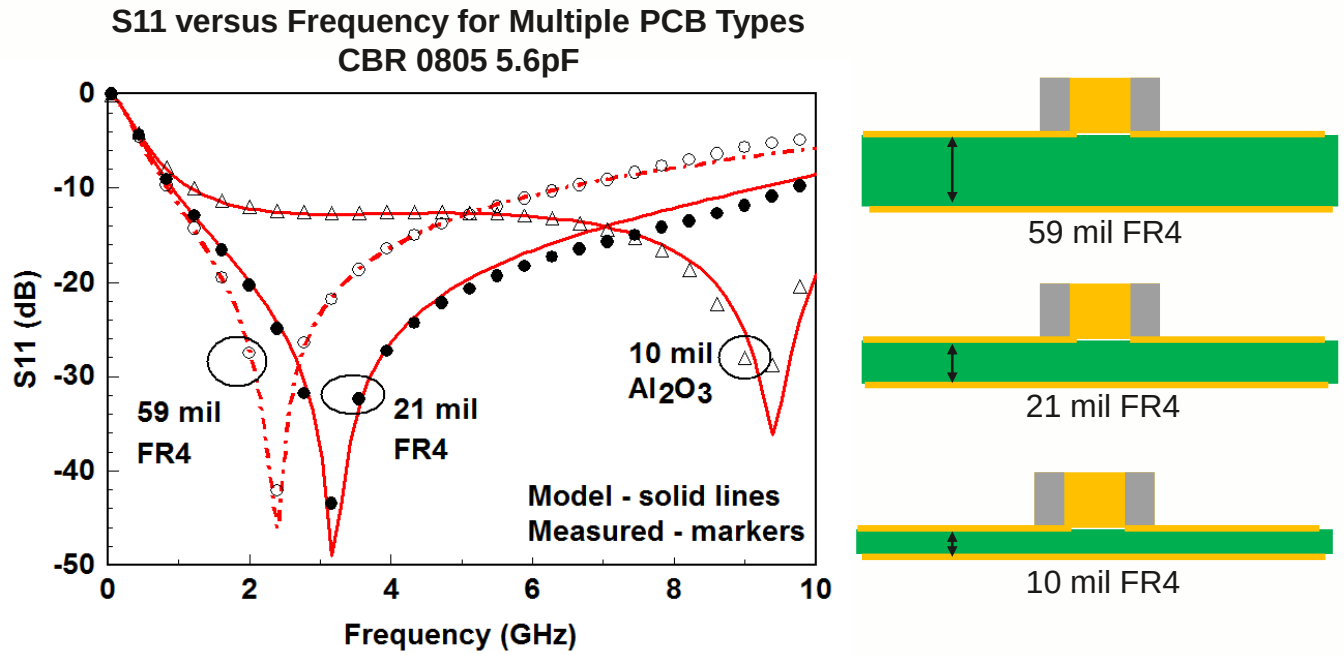
```
!Agilent Technologies,E5071C,MY46109480,A.09.54
!Date: Tue Oct 11 20:23:29 2011
!Data & Calibration Information:
!Freq    S11:SOLT2(ON)    S21:SOLT2(ON)    S12:SOLT2(ON)    S22:SOLT2(ON)
# Hz S dB R 50
50000000        -3.760025e-001  -1.745230e+001  -1.070520e+001  7.279950e+001   -1.070309e+001  7.281087e+001   -3.737441e
74937500        -8.168459e-001  -2.525207e+001  -7.644260e+000  6.481506e+001   -7.641570e+000  6.482366e+001   -8.142310e
99875000        -1.360752e+000  -3.223251e+001  -5.704231e+000  5.780029e+001   -5.702769e+000  5.781035e+001   -1.357891e
124812500       -1.973216e+000  -3.834190e+001  -4.391318e+000  5.161158e+001   -4.389353e+000  5.162188e+001   -1.970618e
149750000       -2.616565e+000  -4.365442e+001  -3.463572e+000  4.626452e+001   -3.460819e+000  4.627317e+001   -2.613514e
```

# Considering Effects of the PCB and Pad Dimensions

## PCB properties

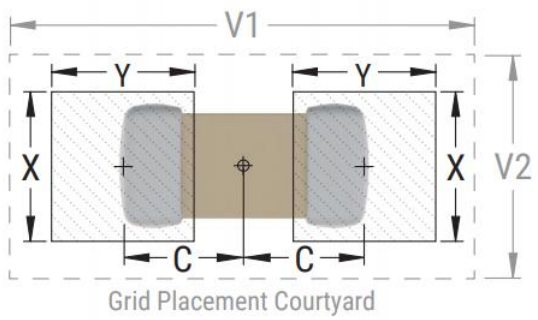
- Thickness
- Dielectric Constant
- Trace Thickness




## Pad Dimensions

- Length
- Width
- Spacing



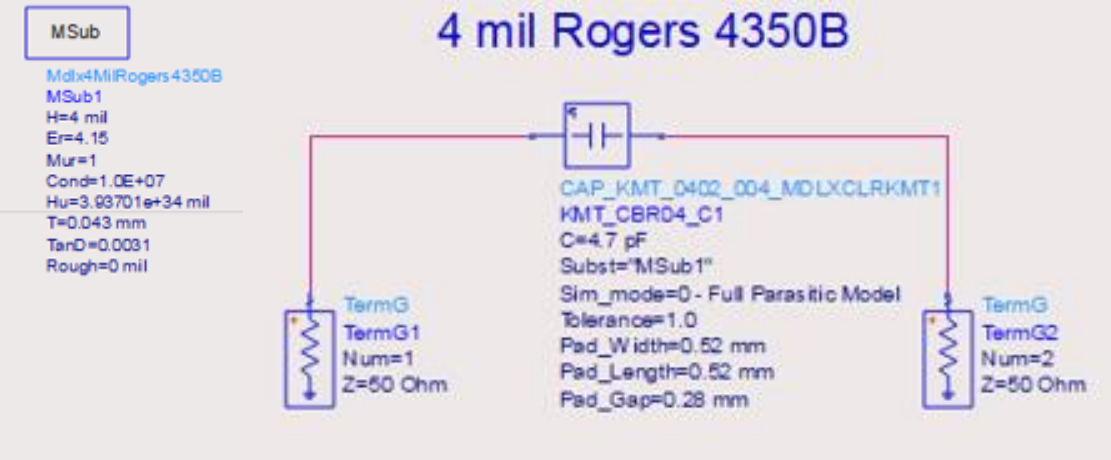
# Advanced CBR Modelithics Models

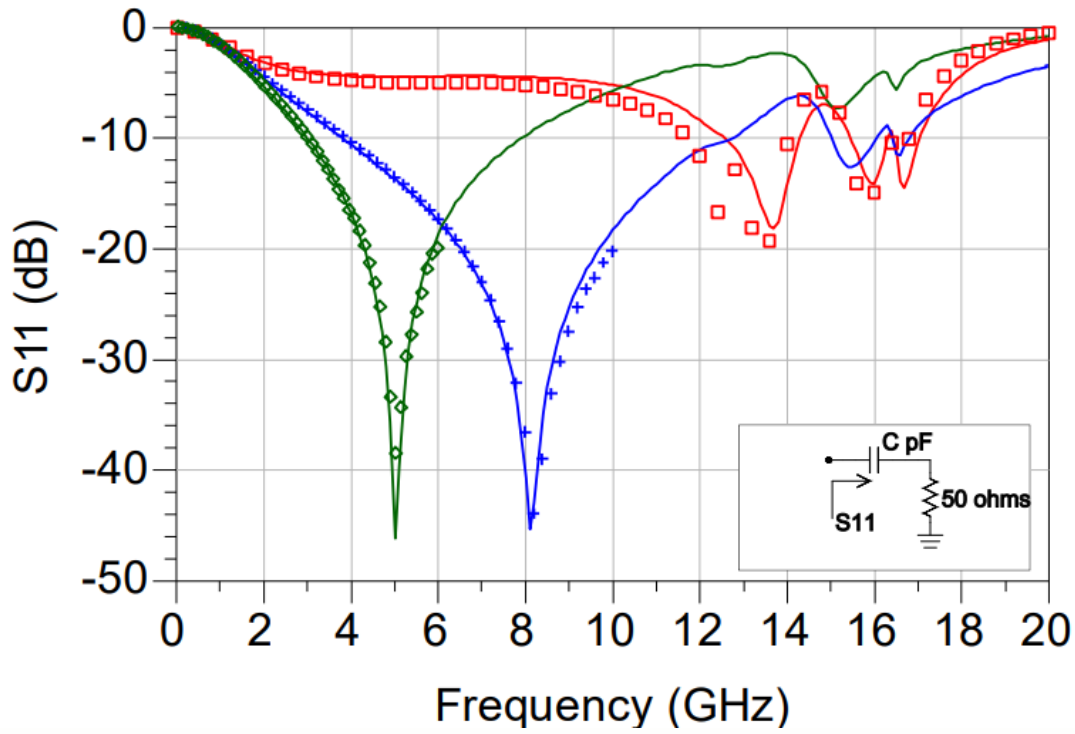
## Full Parasitic Models

Modelithics®

**Simulating Real World Parasitics**

- Capacitance and Tolerance
- PCB Properties
- Pad Dimensions




Lines – Model, Symbols – Measured Data

- 4 mil Rogers 4350B
- 20 mil Rogers 4003C
- 60 mil Rogers 4003C

**First Pass Design Success!!!**

# Advanced CBR Modelithics Models

## How Designers Access Models

E2Di EASY TO DESIGN IN

KEMET a YAGEO company

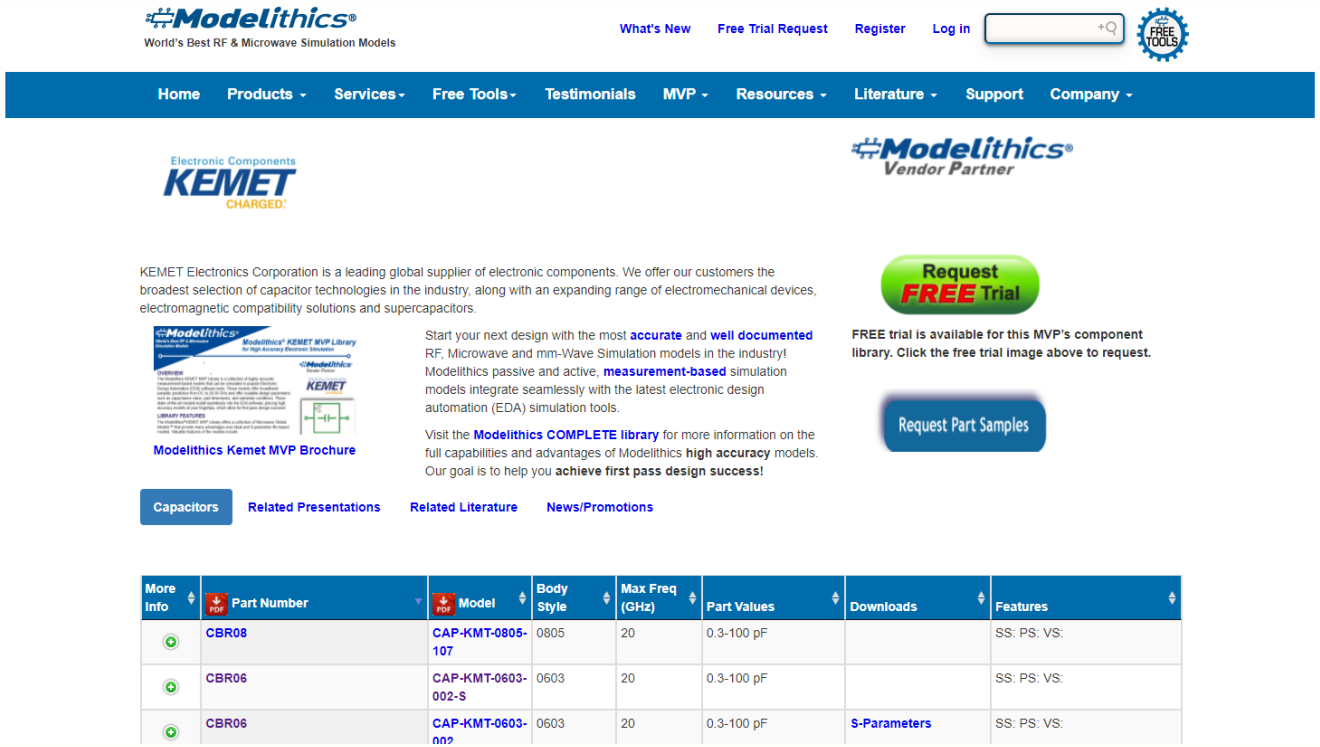
### RF Simulation Tools

- Keysight's Advanced Design Systems (ADS)
- Keysight's PathWave RF Synthesis (Genesys)
- Cadence AWR's Microwave Office

### Accessing Models

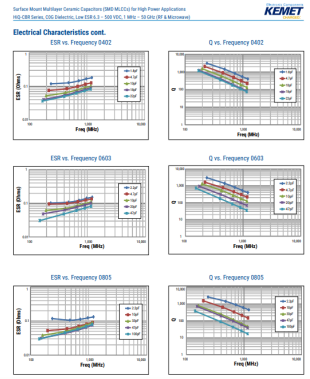
- Contact Product Management

https://www.modelithics.com/mvp/kemet

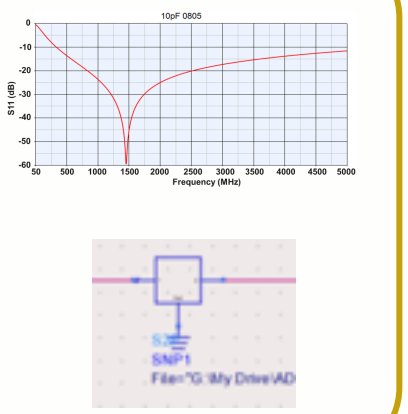


# KEMET HiQ CBR

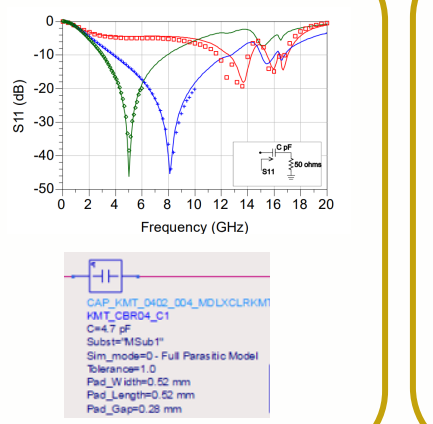
## Full E2Di Support



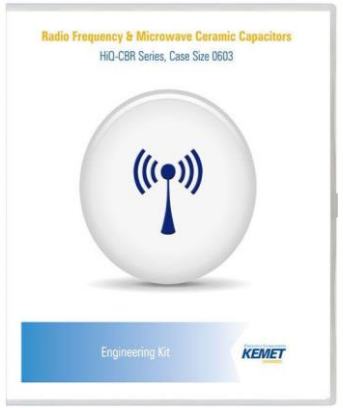

Datasheet Data
ESR / Q / SRF



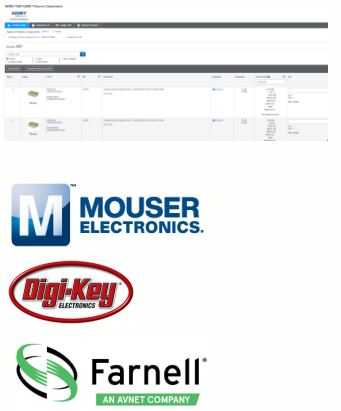

S-Parameters
Available




Advanced
Modelithics
Models




Engineering
Kits




Long Tail
Stocking
Package
0402/0603

HiQ-CBR RF & MICROWAVE

E2Di EASY TO DESIGN IN

# “Standard” Capacitor

Low Frequencies <100MHz

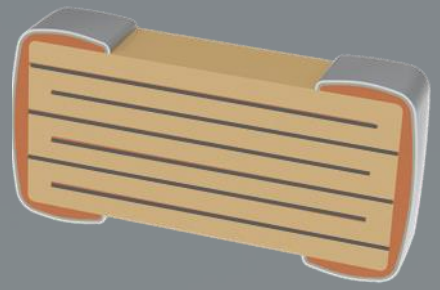
Nickel (BME)

Low ESR

Moderate Q-Factor

Class 1 or Class 2 Dielectrics

Standard E2Di Tools (KSIM)



# CBR RF Capacitor

Higher frequencies >100MHz

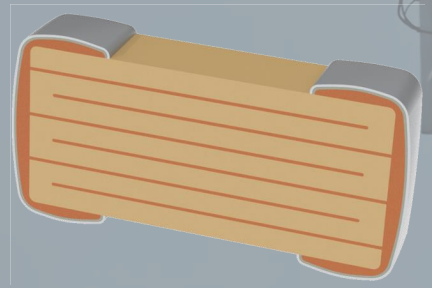
Copper (BME)

Very Low ESR

High Q-Factor

Class 1

Advanced Tools (S-Parameters, Modelithics Models)



# Key Takeaways

- An RF capacitor is a capacitor whose “characteristics” are optimal at RF frequencies
- Applications including RF Power Amplifiers, Base Stations, 5G, wearables, autonomous and connected vehicles
- KEMET continues to expand the CBR Hi-Q RF Series
  - 01005 case size
  - CBR Automotive
- CBR E2Di Tools
  - Datasheet graphs
  - S-Parameters
  - Advanced Modelithics Models
  - Engineering Kits
  - Long Tail Stocking package