RF INDUCTORS IN HIGH-FREQUENCY DESIGN: SELECTION, TRENDS, AND CHALLENGES

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WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

THE WORLD OF RF INDUCTORS!!

"Tiny coils, massive impact"

From 5G smartphones to IoT sensors, inductors silently shape the signals that connect our world.

RF INDUCTORS IN HIGH-FREQUENCY DESIGN

- RF inductors are critical for high-frequency circuits in wireless, IoT, 5G/6G, GPS and Radar.
- Their performance directly impacts system efficiency and signal integrity.
- Market trends show growing demand for miniaturized, high-Q inductors.
- Key challenges: balancing size, cost, and performance.

AGENDA

What We'll Cover Today

- Inductor: What is it and how does it work?
- What makes RF field special: What happens at high frequencies?
- Key selection parameters: It is more than just inductance!
- WE RF inductors: What does WE offer?
- Emerging trends in RF inductors: Keeping pace with a wireless world.
- Design challenges: The hurdles that we must overcome!
- Conclusions & key takeaways.

WHAT IS AN INDUCTOR?

How does it work?

An inductor is a passive two-terminal electrical component that **stores energy in a magnetic field** when electric current flows through it.

It's built by winding a wire (often copper) around a core material (which can be air, iron, ferrite, or ceramic).

The Key Principle: Electromagnetism. When current flows through a wire, it generates a magnetic field around it.

By coiling the wire, this magnetic field is concentrated and strengthened. This stored magnetic field is the source of the inductor's properties.

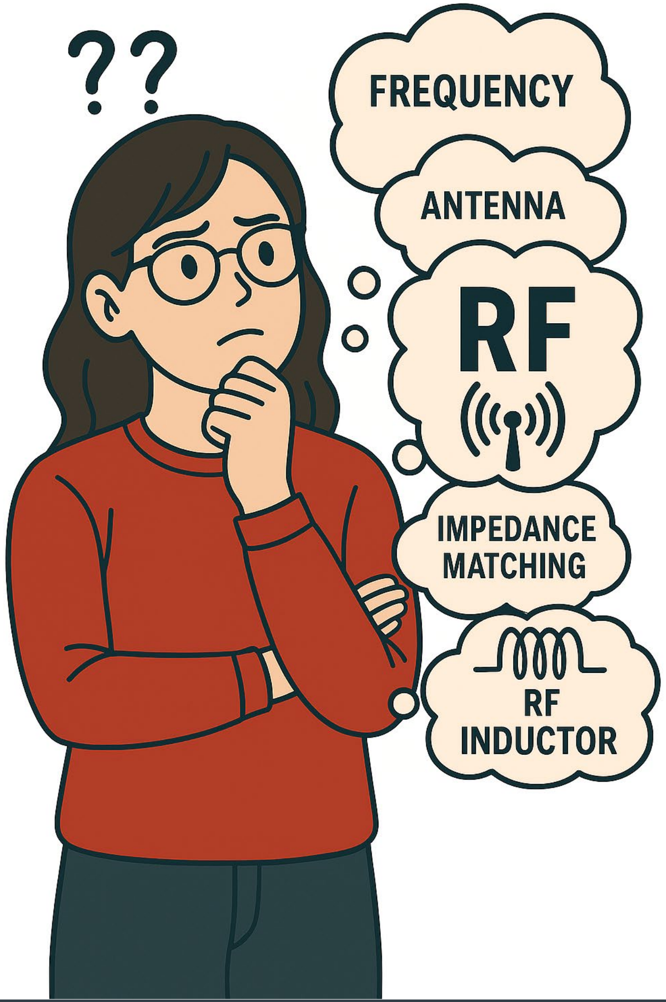
IS AN RF INDUCTOR DIFFERENT?

From Energy Storage to Frequency Control: A Fundamental Shift in Purpose.

- All inductors follow the same basic physics.
- However, when we move from low frequencies to radio frequencies, "hidden" properties become dominant, and the design priorities shift completely.
- “ **Inductance** is just the beginning of the story for high-frequency design.” (How?..We will see this in a while).

WHAT MAKES RF SO SPECIAL?

From Waves to Wonders



ITU (INTERNATIONAL TELECOMMUNICATION UNION)

„WE RF“

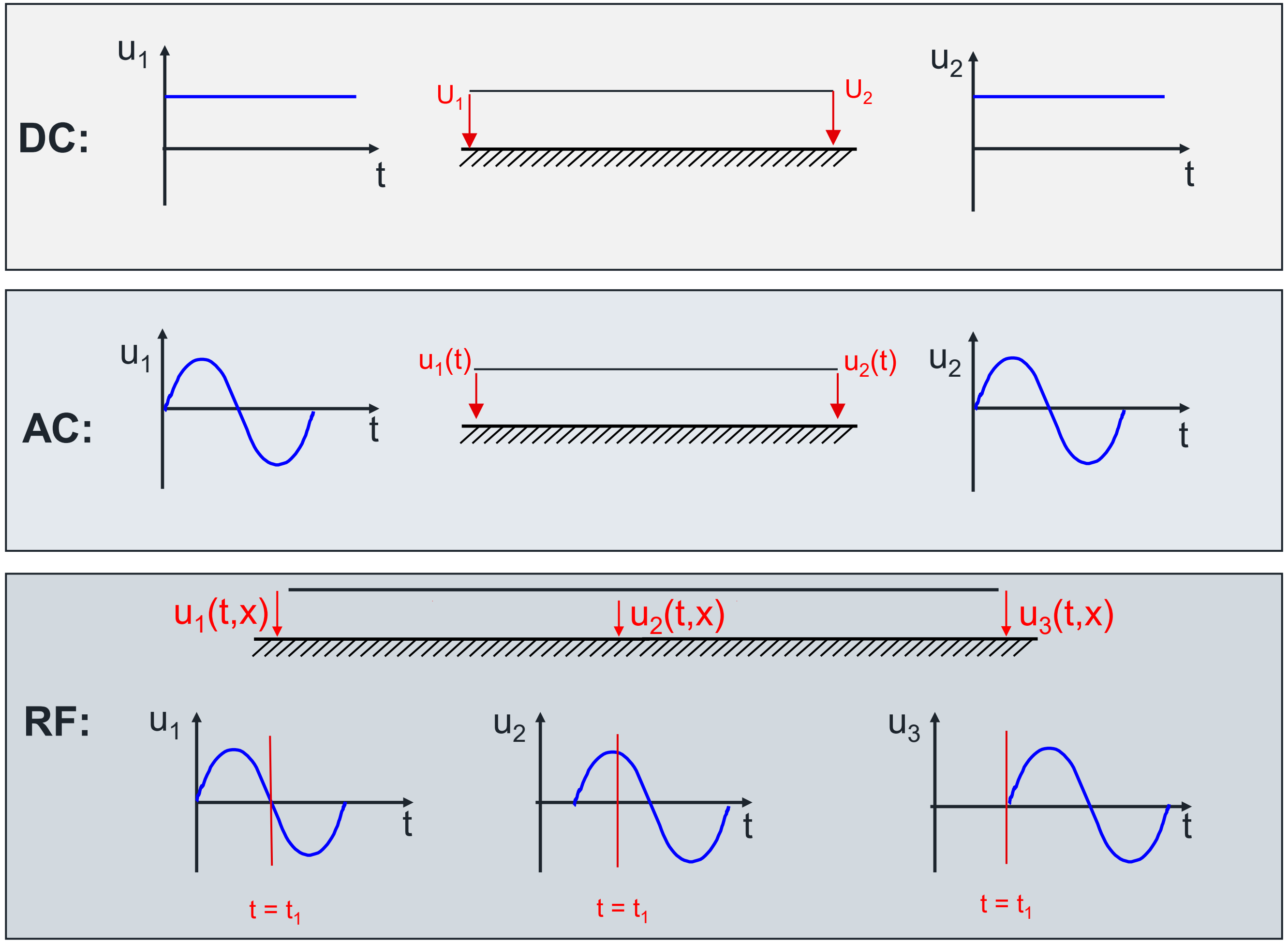
RF

Microwave

Radio Frequency Band	Frequency	Wavelength	Example uses
extremely low frequency (ELF)	3 - 30 Hz	100 - 10,000 km	Submarine communications
super low frequency (SLF)	30 - 300 Hz	10 - 1,000 km	Submarine communications
ultra low frequency (ULF)	300 - 3000 Hz	1000 - 100 km	Communication within mines
very low frequency (VLF)	3 - 30 kHz	100 - 10 km	Navigation, time signals, wireless heart rate monitors
low frequency (LF)	30 - 300 kHz	10 - 1 km	AM longwave broadcasting, RFID, amateur radio
medium frequency (MF)	300 - 3000 kHz	1000 - 100 m	AM (medium-wave) broadcasts, avalanche beacons
high frequency (HF)	3 - 30 MHz	100 - 10 m	Shortwave broadcasts, citizens band radio, RFID, marine and mobile radio telephony
very high frequency (VHF)	30 - 300 MHz	10 - 1 m	FM, television broadcastsland mobile and maritime mobile communications, weather radio
ultra high frequency (UHF)	300 - 3000 MHz	1000 - 100 mm	TV broadcasts, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS, satellite radio, Remote control Systems
super high frequency (SHF)	3 - 30 GHz	100 - 10 mm	WLAN, radars, communications satellites, cable and satellite TV broadcasting, DBS, satellite radio
extremely high frequency (EHF)	30 - 300 GHz	10 - 1 mm	Millimeter wave scanner, wireless LAN (802.11ad)
tremendously high frequency (THF)	0.3 - 3 THz	1 - 0.1 mm	Experimental medical imaging to replace X-rays

WHAT HAPPENS AT HIGH FREQUENCIES?

The wavelength is comparable to circuit dimensions



- At high frequencies, **Current and voltage depend on both time and location.**
- The size of cables, circuit boards, and even components can no longer be ignored.

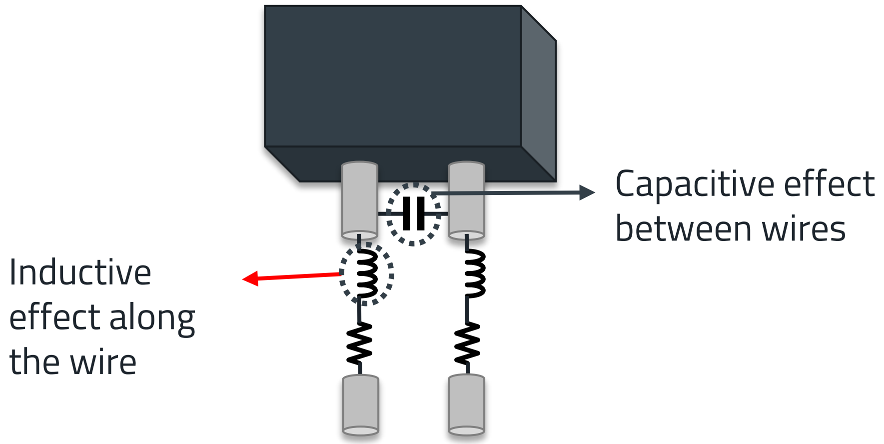
Wavelength and frequency:

$$\lambda = c \cdot T = \frac{c}{f}$$

WHAT HAPPENS AT HIGH FREQUENCIES?

Dominance of Parasitic Effects

- **Parasitic Inductance:** Every tiny piece of wire and every PCB trace has inductance. At RF, this tiny inductance can have a significant impedance.
- **Parasitic Capacitance:** There is capacitance between adjacent traces, between component leads, and within the components themselves. At RF, this tiny capacitance can provide a low-impedance path, shunting the signal to ground.



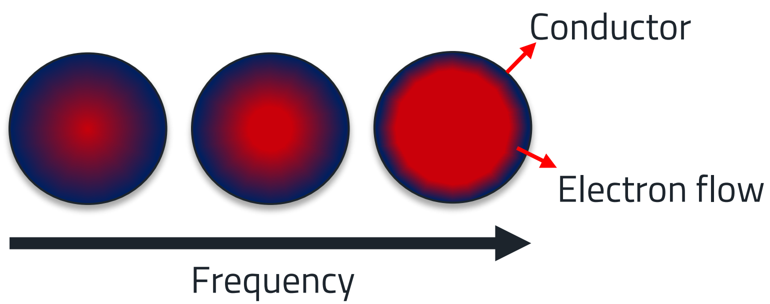
WHAT HAPPENS AT HIGH FREQUENCIES?

Skin Effect Defines Performance

- At DC, current flows uniformly through the entire cross-section of a wire.
  At **RF**, alternating current is pushed to the outer "skin" of the conductor. This effectively reduces the cross-sectional area of the wire, increasing its **AC resistance**.

- **Consequence:** Conductors have higher losses at RF than their DC resistance would suggest.

Skin effect vs frequency



KEY PARAMETERS FOR RF INDUCTOR SELECTION

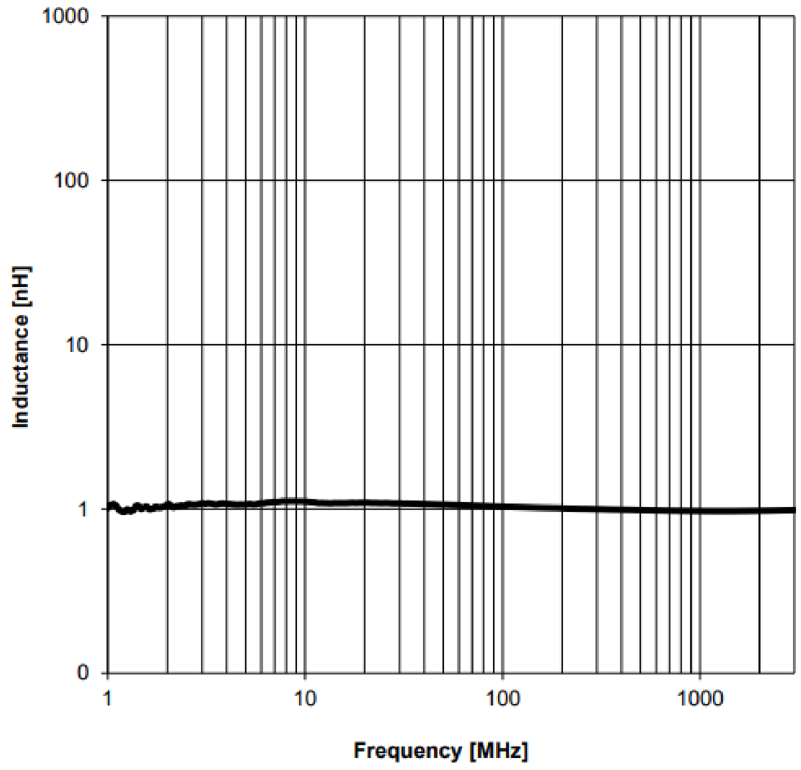
It is more than Inductance!!

- **Inductance Value (L):** Determines resonance and filtering characteristics.
- **Self-Resonant Frequency (SRF):** The frequency where the inductor behaves as a capacitor.
- **Quality Factor (Q):** Indicates efficiency – higher Q means lower losses.
- **DC Resistance (DCR):** Affects power loss and efficiency.
- **Current Rating:** The maximum current the inductor can handle without saturation.
- **Size and Integration:** Multilayer vs wire-wound vs thin-film

INDUCTANCE VALUE (L)

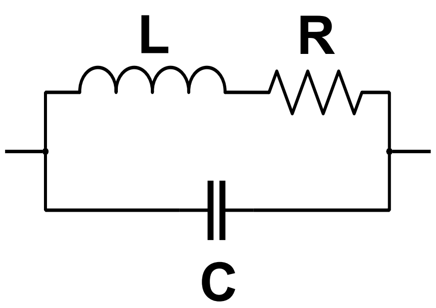
- The primary characteristic of an inductor, measured in **nanohenries (nH) or microhenries (µH)**.
- Determines the reactance ($X_L = 2\pi f L$) at a given frequency.
- Must be carefully chosen for **filters, tuning networks, and impedance matching circuits**.

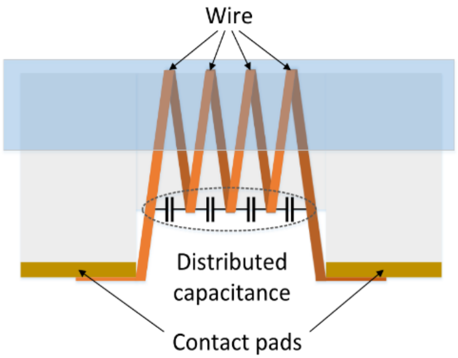
Typical Inductance vs. Frequency Characteristics:



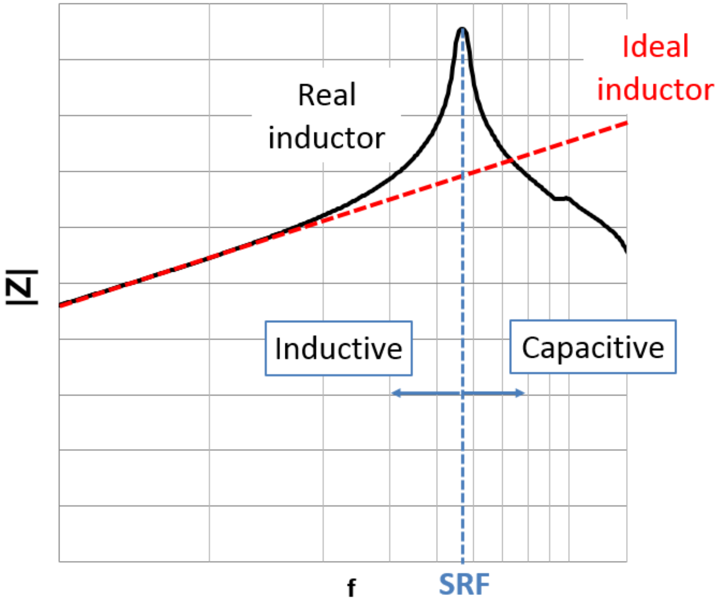
SELF RESONANT FREQUENCY (SRF)

- The **Self-Resonant Frequency (SRF)** is the frequency at which an inductor **naturally stops behaving like an inductor** and starts acting as a **capacitor** due to its internal parasitic capacitance.





Equivalent Series Circuit of an Inductor considering the capacitive effect



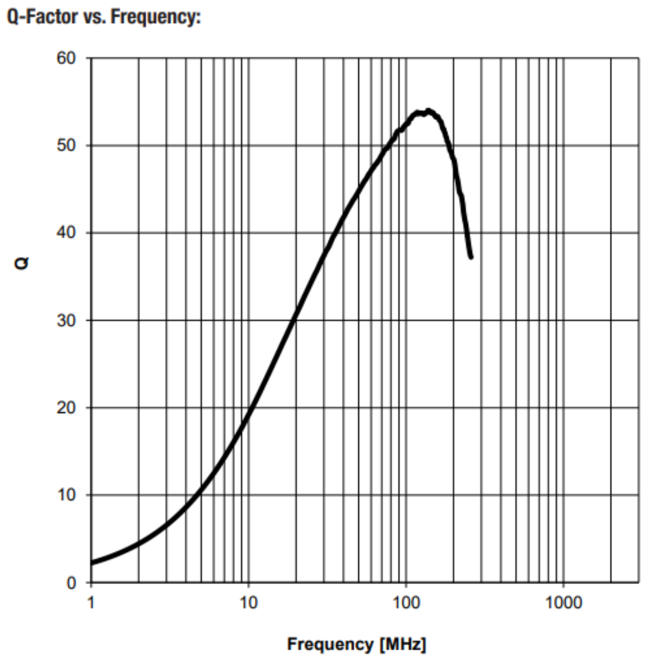
- At SRF, impedance peaks and then drops rapidly.
- Above SRF, the inductor behaves like a capacitor, disrupting circuit performance.
- **The golden rule in RF design is "**always select an inductor with a SRF, which is a decade higher than the operating frequency."

QUALITY FACTOR (Q)

- The **Quality Factor (Q)** of an RF inductor is a measure of its efficiency in storing energy relative to its losses.
- A **higher Q means lower energy loss**, which is crucial for **filters, impedance matching, oscillators, and tuning circuits** in RF design.

$$Q_L = \frac{X_L}{R_S} = \frac{\omega L}{R_S}$$

$$R_S = R_{DC} + R(f)$$



- Q **increases with frequency** (up to a limit).
- However, at **higher frequencies, skin effect and core losses increase**, reducing Q.
- The peak Q often occurs **before the self-resonant frequency (SRF)**

DC RESISTANCE (R_{DC})

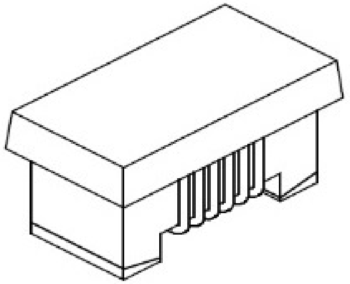
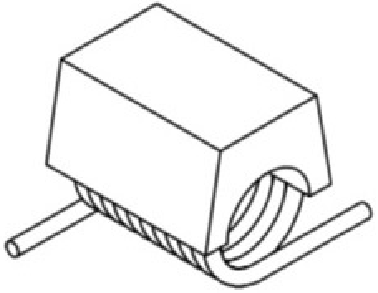
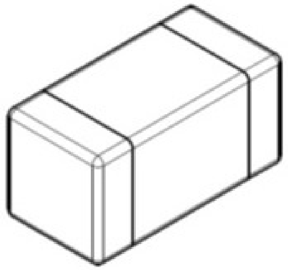
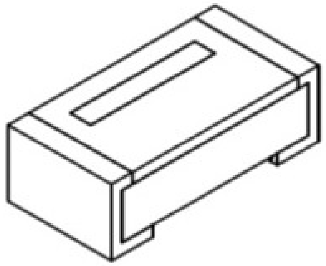
- The inductor's resistance to DC current, measured in ohms (Ω).
- Lower DCR means **lower power loss and higher efficiency**.
- Critical for applications where power efficiency is a concern.

CURRENT RATING

- The maximum current the inductor can handle without saturation.
- When the core saturates, the **inductance value drops dramatically**.

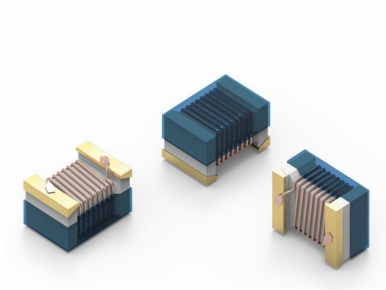
RF INDUCTOR

Technology Landscape

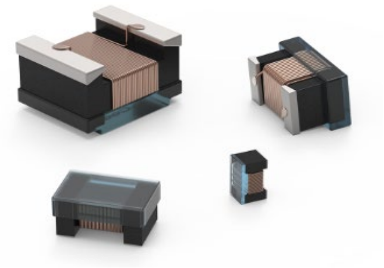
Wire wound inductors		Multilayer inductors	Thin film inductors
With core	Air core		
			
WE-KI / WE-KI HC / WE-RFI / WE-RFH	WE-CAIR / WE-AC HC	WE-MK	WE-TCI

WE RF INDUCTORS

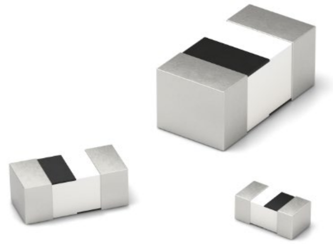
WE-KI
Wirewound Ceramic Inductor



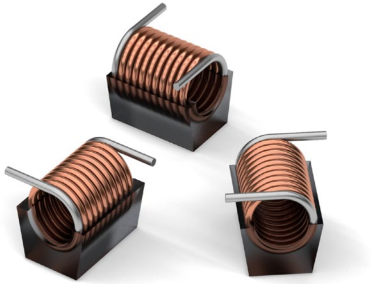
WE-RFI
Wirewound Ferrite Inductor



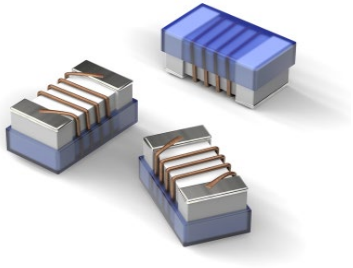
WE-MK
Multilayer Ceramic Inductor



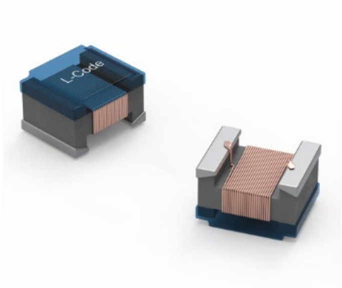
WE-CAIR
Air Coil Inductor



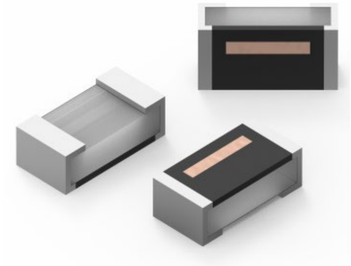
WE-KI HC
High Current Wire Wound Ceramic Inductor



WE-RFH
Wirewound Ferrite Inductor



WE-TCI
Thin film Chip Inductor



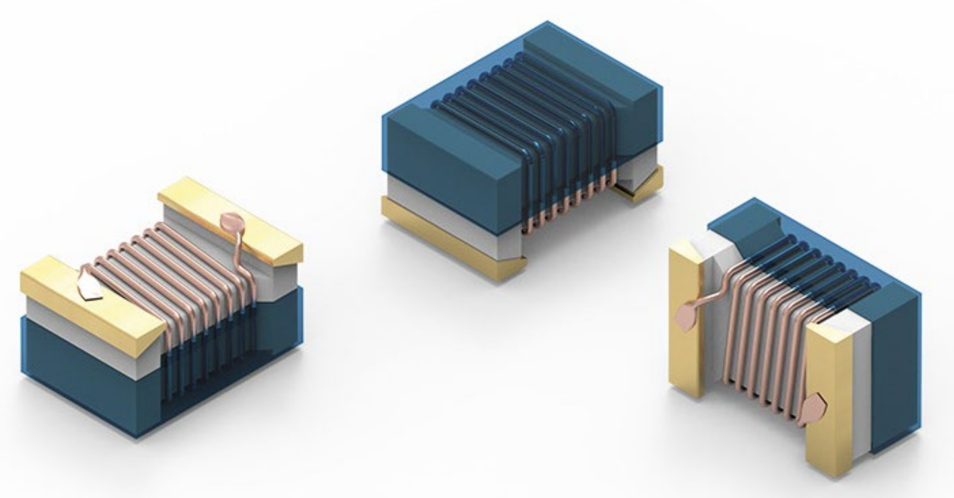
WE-AC HC
High Current Air Coil Inductor

WE-KI

Wirewound Ceramic Inductor

- It is formed by winding copper wire in a spiral shape around a ceramic core.

- Properties:
  - **Gold plated contacts**, ensuring high precision and reliability
  - High Q
  - High SRF
  - Low RDC
  - Large currents supported
  - Tol. ±2% - ±5%
  - Many different sizes: 0402 / 0603 / 0805 / 1008
  - WE-KI

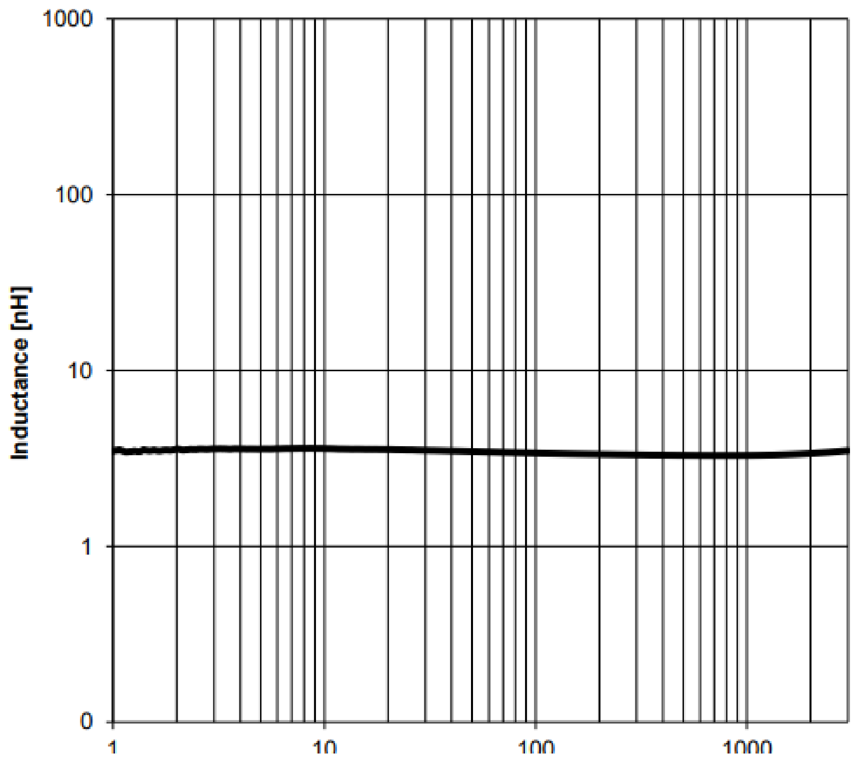


WE-KI

Ceramic Core

- Ceramic-core inductors are widely used in **RF and microwave circuits** due to their **high-Q factor, stability, and low losses.**

- **The core:**
  - Frequency, temperature and current independent
  - No magnetic properties (no saturation effect)
  - Low permeability (≈1)
  - Minimal core losses



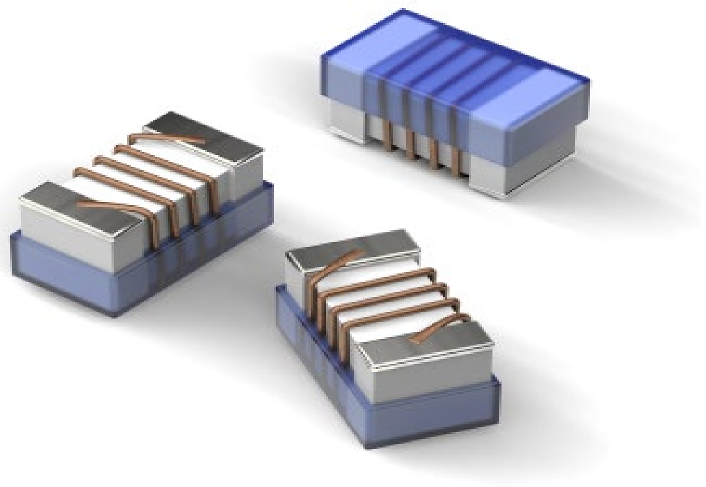
WE-KI HC

High Current Wirewound Ceramic Inductor

- WE-KI with thicker wire and thinner core ⟶ Improved charcteristics of WE-KI

- Properties:
  - High Q
  - High SRF
  - Very low R_{DC}
  - Very large currents supported
  - Tol. 2%
  - Sizes: 0402, 0603

- Applications:
  - Ideal for high current applications
  - Matching applications in antennas
  - Matching applications in PA circuits
  - WE-KI HC

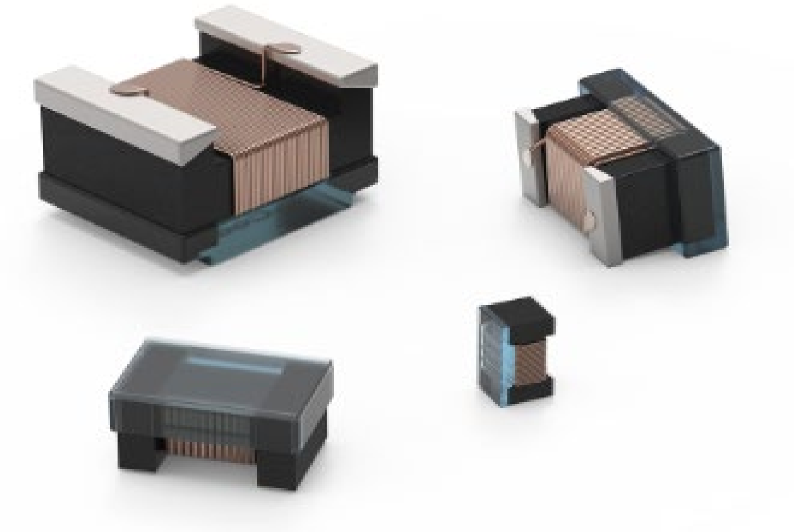


WE-RFI

Wirewound Ferrite Inductor

- It is formed by winding copper wire in a spiral shape around a ferrite core.
- Higher inductance in a small size but with core losses at high frequencies.

- Properties:
  - High Q
  - Very low SRF
  - Higher Inductance values (up to 47µH)
  - Tol. 5%
  - Sizes: 0402, 0603, 0805, 1008
  - WE-RFI



WE-RFI

Ferrite Core

- Ferrite core RF inductors are widely used in radio frequency (RF) circuits due to their high inductance values, excellent EMI suppression, and ability to operate at lower frequencies compared to air-core or ceramic-core inductors.

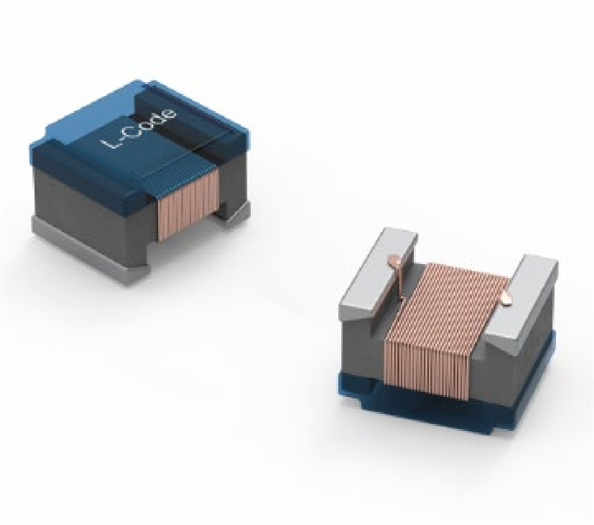
- **The core:**
  - Higher Permeability (μ)
  - Provides greater inductance in a smaller size.
  - Good Electromagnetic Interference (EMI) Suppression → Reduces unwanted noise.
  - Works Well at Lower RF Frequencies → Used in MHz to low-GHz applications.

WE-RFH

Wirewound Ferrite Inductor

- Larger current carrying capacity than RFI.

- Properties:
  - High Q
  - High thermal stabilty
  - Inductances: 0.47 – 10µH
  - Inductance Tol. ±5%
  - Sizes: 1008
  - WE-RFH

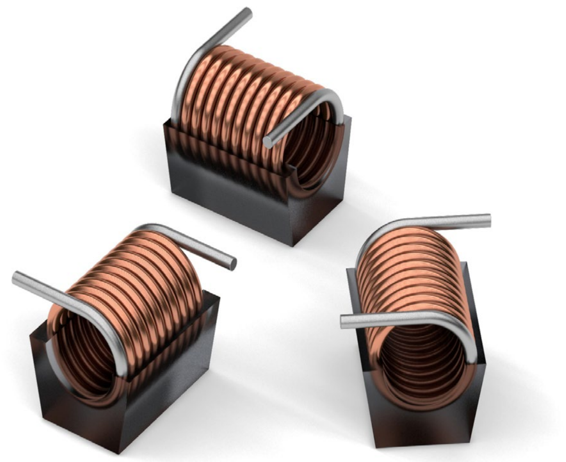


WE-CAIR

Air Coil Inductor

- Thick winding copper wire in a spiral shape with no core (air)

- Properties:
  - Extremly high Q (up to 140)
  - Very low R_{DC}
  - Very large currents supported
  - Tol. 2% and 5%
  - Sizes: 1322, 1340, 3136, 3168, 4248, 5910
  - WE-CAIR



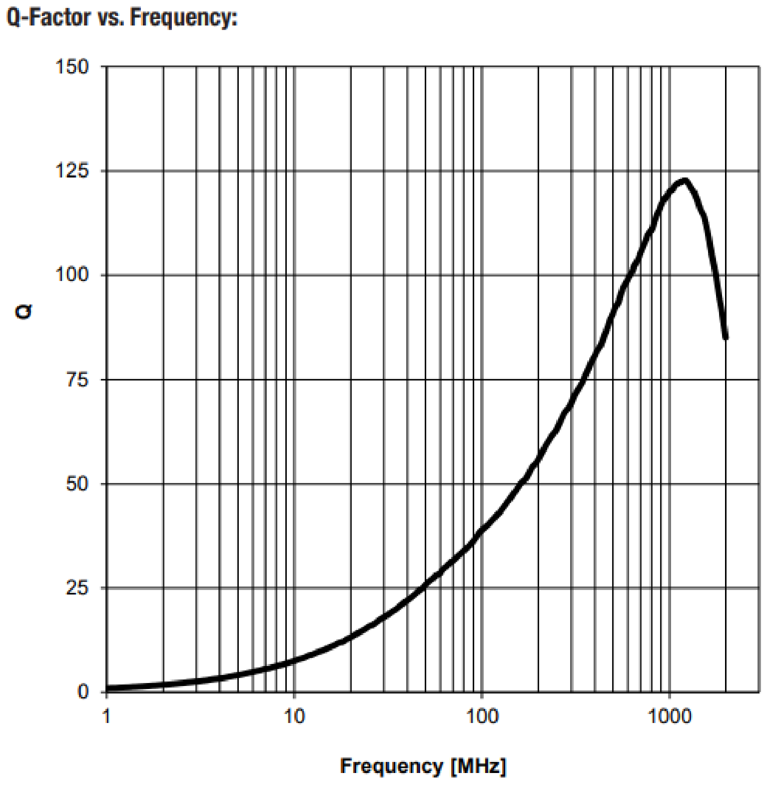
WE-CAIR

AIR CORE

- **Advantages**
  - No core Saturation
  - High efficiency at high frequency
  - High Q factor
  - Temperature stability

- **Disadvantages**
  - Larger Physical Size
  - Lower inductance per volume

- **Applications:**
  - Broadband I/O filtering
  - Frequency selection
  - Impedance matching



WE-ACHC

High Current Air Coil Inductor

- Air coil inductor with flat wire for high current and high frequency applications

- **Properties:**
  - Extremly large currents supported (up to 40A)
  - Extremly high Q
  - Very low R_{DC}
  - Tol. 20%
  - Sizes: 1010, 1212
  - WE-ACHC

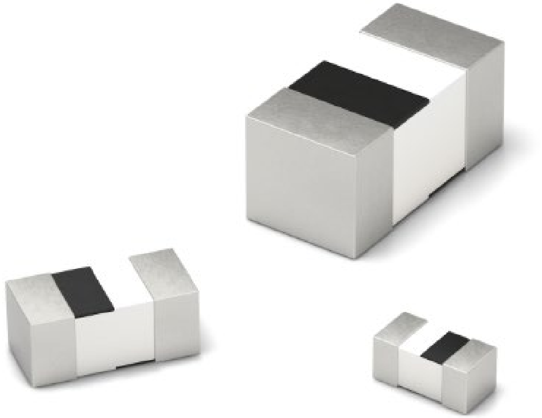
- **Applications:**
  - High power filter
  - High current applications
  - RF-Voltage regulator (in MRI, PA, ...)

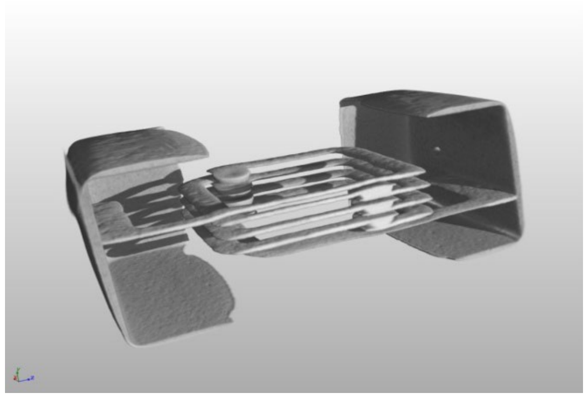
WE-MK

Multilayer Ceramic Inductor

- It is formed by layering ceramic materials and a coil conductor to create an integrated monolithic-type inductor

- Properties: Inductances: 1 – 470nH
  - High RDC
  - Low Q
  - High SRF
  - **Double Side Polarity Marking**
  - Tol. ±2% - ±5%
  - Many different sizes: 0201 / 0402 / 0603 / 0805
  - WE-MK





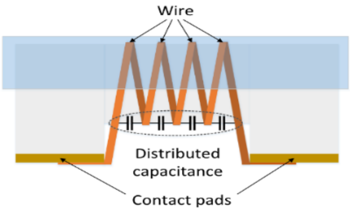
THE SRF TRADE-OFF: WIRE-WOUND VS MULTILAYER INDUCTORS

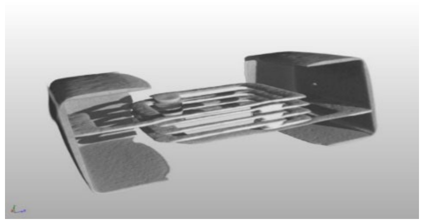
- The Self-Resonant Frequency (SRF) of an inductor is influenced by its construction and the parasitic capacitances associated with it.

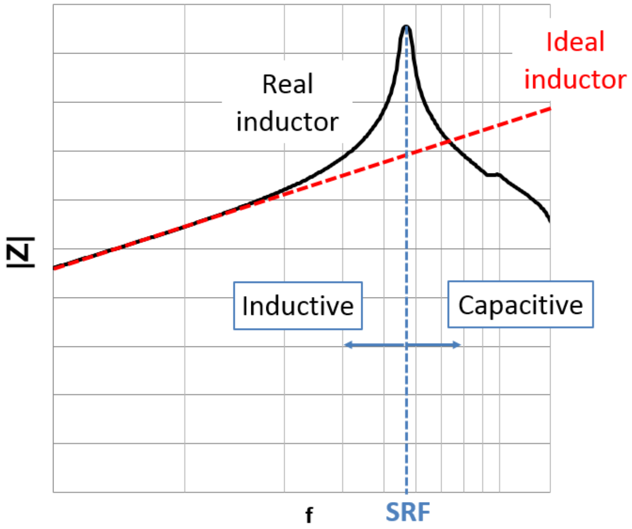
- Wire-wound inductors are made by winding a wire around a core. This winding process introduces parasitic capacitances between the turns of the wire.

$$SRF = \frac{1}{2\pi\sqrt{L \cdot C_p}}$$

- The parasitic capacitance in multilayer ceramic inductors is lower because the layers of ceramic act as a dielectric, reducing capacitive coupling between the layers.





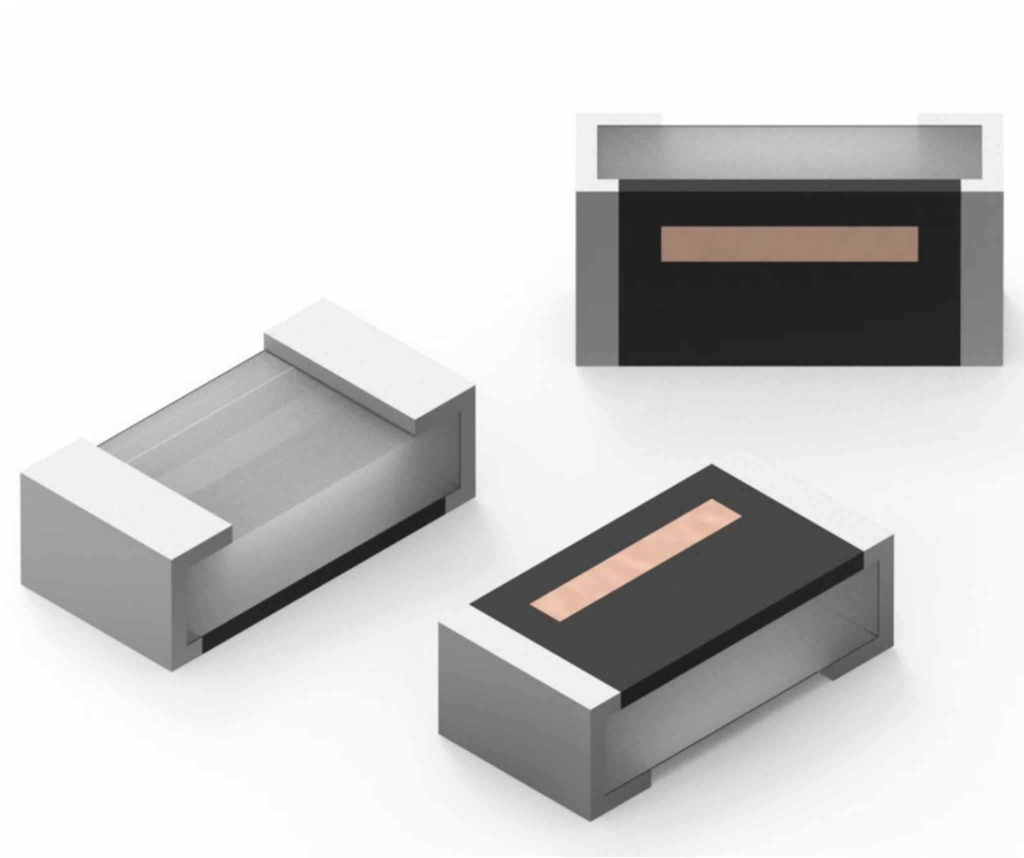


WE-TCI

Thin film Chip Inductor

- It is formed by photolithographic process

- Properties:
  - Inductances: 1 – 27nH
  - High precision (up to ±1% tolerance)
  - Extremely thin (max. 0.32mm)
  - Low inductance values
  - High SRF
  - Sizes: 0201 / 0402



RF INDUCTORS

OVERVIEW

Air-Core Inductors

- High Q, no core losses, suitable for high frequencies.

Ceramic Core Inductors

- High Q, stable performance, used in RF filters.

Ferrite Core Inductors

- Higher inductance in a small size but with core losses at high frequencies.

Multilayer Inductors

- Compact, SMD-friendly but lower Q than wire-wound.

THE FUNDAMENTAL ROLE OF RF INDUCTORS

- More Than Just a Coil: The RF Inductor's Jobs

Impedance Matching: Maximizing power transfer between circuit stages (e.g., between an amplifier and an antenna).

Filtering: Blocking unwanted frequencies (in LC tanks and bandpass/bandstop filters).

Biasing & Choking: Allowing DC current to pass while blocking/RF signals (RF chokes).

Resonance: Forming tuned circuits with capacitors for oscillators and filters.

EMERGING TRENDS IN RF INDUCTORS

Keeping Pace with a Wireless World

Miniaturization: Demand for smaller packages for 5G mm Wave modules, wearables, and IoT devices.

Higher Frequency Support: Components designed for >6 GHz, supporting 5G FR2, Wi-Fi 6E/7.

Advanced Materials: Use of low-loss, low-permittivity ceramics materials to boost Q and SRF.

Embedded Components: Inductors fabricated directly into the PCB substrate (Integrated Passive Devices - IPDs) for reduced size and improved parasitics.

Automated Tuning: AI and ML-driven systems for real-time tuning of matching networks using tunable inductors.

KEY DESIGN CHALLENGES

Overcoming the Hurdles

The Q-Factor Trade-off: Achieving high Q in an ultra-miniaturized package is extremely difficult.

Parasitics are Paramount: At mmWave frequencies, every picohenry and femtofarad counts. PCB pads and via effects can dominate component behavior.

Current Handling in Small Sizes: Preventing saturation in power-dense designs is a major challenge.

Modeling Accuracy: Simulation models must be exceptionally accurate to predict performance at high frequencies.

Manufacturing Variability: Tighter tolerances are harder to achieve with smaller components, impacting yield and performance consistency.

CONCLUSION AND KEY TAKEAWAYS

Summary

- **Critical Component:** RF inductors are indispensable for impedance matching, filtering, and biasing in all wireless systems.
- **SRF and Q are King:** Always operate below the SRF and strive for the highest possible Q at your target frequency.
- **Selection is a Balancing Act:** It requires juggling electrical specs (L, Q, SRF), physical size, and cost.
- **Trends Point to Miniaturization & Higher Frequencies:** Designers must adapt to smaller components.
- **Challenges are Significant:** Overcoming parasitics, loss, and modeling complexities is key to successful high-frequency design.

ADDITONAL INFORMATION

- Application notes:
  - Introduction to RF Inductors
  - RF Gain Block Amplifier
  - Inductive SMT Component in Comparison

REDEXPERT

- RF inductors

Product selection → Signal & Communication → RF Inductors

Easy Component Selection, Comparison and Evaluation for all product areas.
redexpert.we-online.com