LECTURE 020 – DISCRETE CIRCUIT TECHNOLOGY

(References: [7,8,9])

Objective

The objective of this presentation is:

1.) Characterize the various discrete components for frequency synthesizers

2.) Examine the performance capabilities and limitations of each type of discrete component

Outline

- Resistors
- Capacitors
- Inductors
- Transformers
- Miniaturization of discrete technology

RESISTORS

Resistance

Definition:

The resistance of the conductor shown is given as

$$R = \frac{L}{\sigma A} = \frac{\rho L}{A}$$

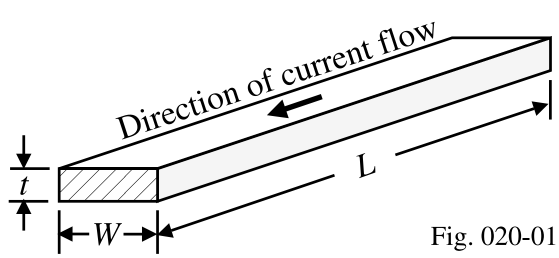


Fig. 020-01

where

$A = W \cdot t$

and

σ = conductivity (mhos/meter)

ρ = resistivity (ohms-meter)

Ohms Law:

$v = Ri$

Symbol:

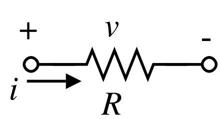


Fig. 020-02

Sheet resistivity:

$$R = \frac{\rho_S L}{W} \quad \rightarrow \quad \rho_S = \frac{\rho}{t} \text{ (ohms/square)}$$

Characterization of Resistors

- Range of resistance is the value of resistance available for that type of resistance.
- Power rating is the maximum power that can be dissipated in a resistor in watts.
- Absolute tolerance is the deviation of the resistance from a nominal value in ±%.
- Relative tolerance is the matching of the value between two similar resistors in ±%.
- Temperature coefficient is the first-order dependence of the resistance upon temperature in units of (%/°C) or (ppm/°C). [%/°C = 10^4(ppm/°C)]
- Voltage coefficient is the first-order dependence of the resistance upon the voltage across the resistance in units of (%/°C) or (ppm/°C).

Definition of Temperature and Voltage Coefficients

In general a variable y which is a function of x, $y = f(x)$, can be expressed as a Taylor series,

$$y(x = x_0) \approx y(x_0) + a_1(x- x_0) + a_2(x- x_0)^2 + a_1(x- x_0)^3 + \cdots$$

where the coefficients, a_i, are defined as,

$$a_1 = \frac{df(x)}{dx}\bigg|_{x=x_0},\ a_2 = \frac{1}{2}\frac{d^2f(x)}{dx^2}\bigg|_{x=x_0},\ \ldots.$$

The coefficients, a_i, are called the first-order, second-order, …. temperature or voltage coefficients depending on whether x is temperature or voltage.

Generally, only the first-order coefficients are of interest.

In the characterization of temperature dependence, it is common practice to use a term called *fractional temperature coefficient*, TC_F, which is defined as,

$$TC_F(T{=}T_0) = \frac{1}{f(T{=}T_0)}\frac{df(T)}{dT}\bigg|_{T=T_0} \text{ parts per million/°C (ppm/°C)}$$

or more simply,

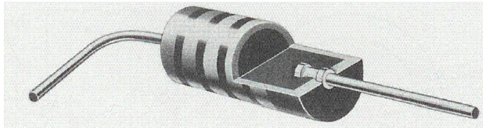
$$TC_F = \frac{1}{f(T)}\frac{df(T)}{dT} \text{ parts per million/°C (ppm/°C)}$$

A similar definition holds for fractional voltage coefficient.

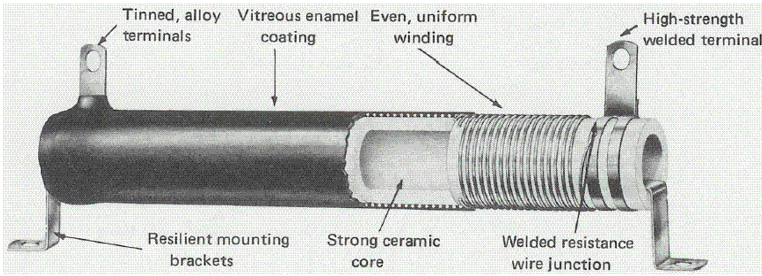
Fixed Resistors

The various types of resistors are

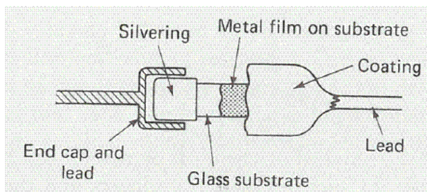
1.) Carbon composition – hot-pressed carbon granules mixed with varying amounts of filler to achieve a large range of resistance values.



2.) Wirewound – consist of lengths of wire wound on an insulating clyindrical core.



3.) Metal and carbon film – very thin metal and carbon films are deposited on insulating materials to provide very high resistance paths.

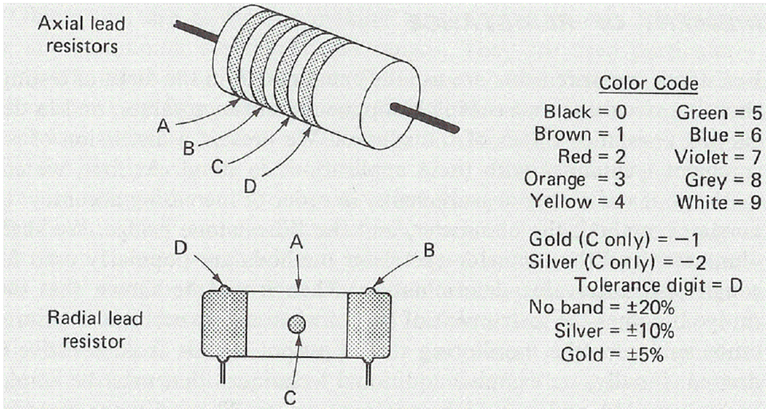


Characteristics of Fixed Resistors

Type	Range (Ω)	Absolute Accuracy (±%)	Temperature Coefficient (%/°C)	Maximum Power (W)	Advantages
Carbon composition	1 to 22M	±5 to ±20%	0.1	2	Inexpensive, reliable, remarkably free of stray capacitance and inductance
Wirewound	1-100k	≥ 0.0005	0.0005	200	Can be very precise and stable. Can dissipate high power
Metal Film	$0.1\text{-}10^{10}$	≥ 0.005	0.0001	1	Very high values, work at high frequencies
Carbon Film	10-100M	≥ 0.5	-0.015 to 0.05	2	Works at high frequencies

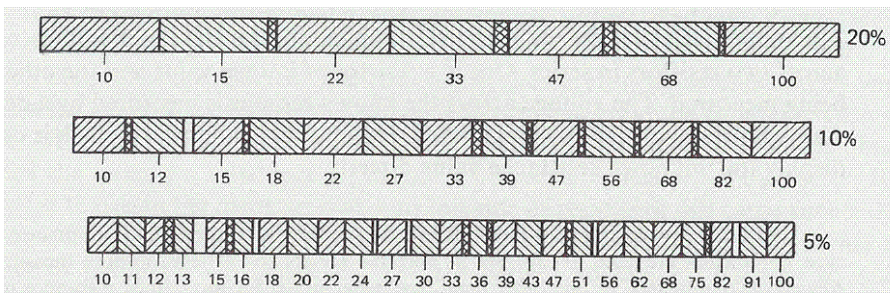
Resistor Color Code

Carbon composition color code:



Value = $A.B\mathrm{x}10^{C} \pm D$

Nominal values and tolerance ranges for resistors:



Variable Resistors

A variable resistor or a potentiometer is a three terminal resistor with one or more adjustable sliding contacts that function as an adjustable voltage divider.

The potentiometer can have 1 or multiple turns.

The potentiometer can be graded – i.e. the resistance per angle of turn increases or decreases.

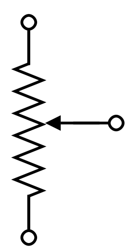


Fig. 020-03

CAPACITORS

Capacitance

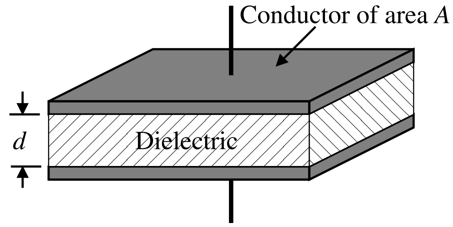
Definition:

The ratio of the charge between two bodies and the voltage between them is called capacitance.

$$C = \frac{q}{v} \text{ (Farads)}$$

Parallel plate capacitor:

$$C = \frac{\varepsilon A}{d}$$



where

ε = dielectric constant of the material separating the plates

A = area of the plates

d = distance between the plates

Symbol:

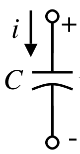


Fig. 020-05

$$q = Cv \rightarrow \quad \frac{dq}{dt} = \frac{d}{dt}(Cv) = v\frac{dC}{dt} + C\frac{dv}{dt} = 0 + C\frac{dv}{dt}$$

$$i = C\frac{dv}{dt}$$

Characterization of Capacitors

- Range of capacitance is the value of the capacitor available for that type of capacitance.
- Maximum voltage rating is the voltage across the capacitor where appreciable leakage current begins to flow known as breakdown given in volts.
- Absolute tolerance is the deviation of the capacitance from a nominal value in ±%.
- Relative tolerance is the matching of the value between two similar capacitors in ±%.
- The dissipation factor, D, is a measure of the resistance associated with the capacitor at a given frequency. D is defined below. R_s is sometimes called the equivalent series resistance (ESR).

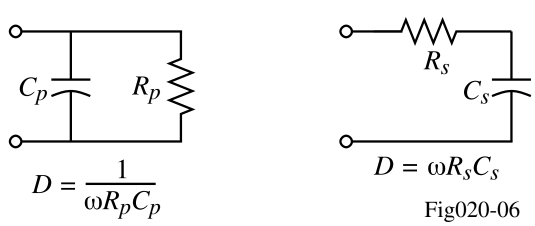


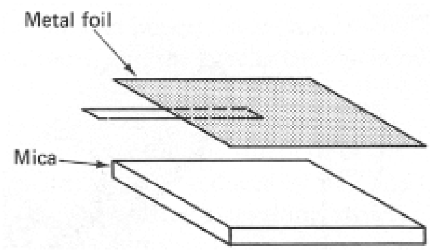
Fig020-06

- Temperature coefficient is the first-order dependence of the capacitance upon temperature in units of (%/°C) or (ppm/°C). [%/°C = 10^{-4}(ppm/°C)]
- Voltage coefficient is the first-order dependence of the capacitance upon the voltage across the resistance in units of (%/°C) or (ppm/°C).

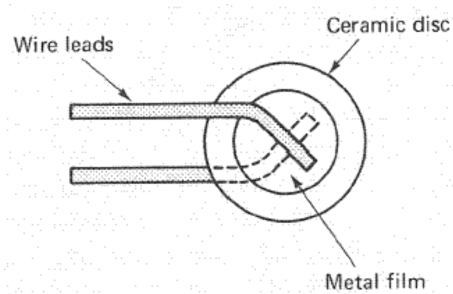
Fixed Capacitors

The various types of fixed capacitors are:

1.) Mica capacitors – constructed by sandwiching layers of metal foil and mica. Sometimes metal is deposited on the mica in lieu of the metal foil. The resulting stack of metal and mica sheets is firmly clamped and encapsulated in a plastic package.

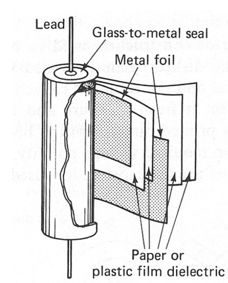


2.) Ceramic capacitors – a thin ceramic disk is coated with metal on both sides with lead attached and encapsulated in plastic or ceramic.

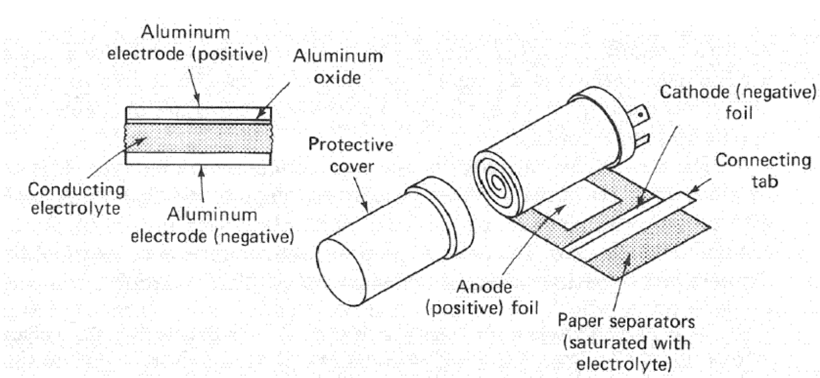


Fixed Capacitors – Continued

3.) Paper or plastic-film capacitors – are cylindrical in shape because they are made by rolling a sandwich of metal and impregnated paper or plastic sheets into a tube. Axial leads are attached to each metal sheet and the tube is encapsulated in waxed paper or plastic.



4.) Electrolytic capacitors – the structure consists of two aluminum foils with a thin oxide grown on one of the foils. Between the foils is an electrolytic solution soaked into paper. This electrolytic is a conductor and serves as the connection between the non-oxidized foil and the thin oxide. The two oppositely charged plates are separated by a very thin oxide film which has a very high dielectric constant. The electrolytic capacitor is *polarity sensitive* and must be connected properly.



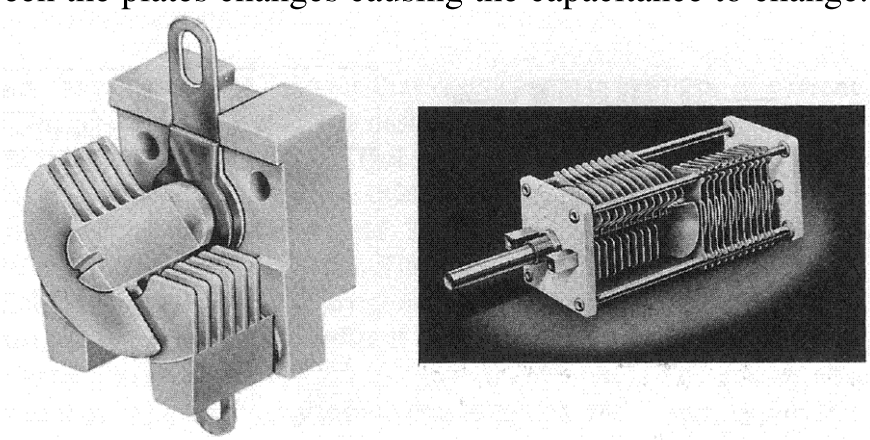
Characteristics of Fixed Capacitors

Type of Capacitor	Range of Values (F)	Absolute Tolerance (±%)	Leakage Resistance† (MΩ)	Maximum Voltage Range (V)	Useful Frequency Range (F)
Mica	1-f to 0.1µ	±1 to ±20	1000	500-75k	10^3-10^{10}
Ceramic (low loss)	1p to 0.0001µ	±5 to ±20	1000	6000	10^3-10^{10}
Ceramic (high-*K*)	100p to 0.1µ	+100 to –20	30-100	≤ 100	10^3-10^8
Paper (oil soaked)	1000p to 50µ	±10 to ±20	100	100 to 100k	100-10^8
Polystyrene	500p to 10µ	±0.5	10,000	≤ 1000	0-10^{10}
Mylar	5000p to 10µ	±20	10,000	100 to 600	100-10^8
Electrolytic	1µ to 0.5	+100 to –20	1	≤ 500	10-10^4

† Generally the dissipation factor, *D*, is sufficiently large so that the leakage resistance is a better measure of the loss.

Variable Capacitors

1.) Air capacitors – a set of metal plates are mounted on a shaft and as the shaft is rotated, the area between the plates changes causing the capacitance to change.



Range = 10pF to 500pF, Tolerance = ±0.1%, Maximum voltage = 500V

2.) Trimmer capacitors – a mica capacitor that has a screw which clamps the metal-mica sheets. When the screw is tightened, the separation between the plates is reduced and the capacitance increased. Range is about 15-500pF.

INDUCTORS

Inductance

Definition:

Inductance, L, is the ratio of flux-linkages to the current creating that the flux.

$$L = \frac{\psi}{i} \text{ (Henrys)}$$

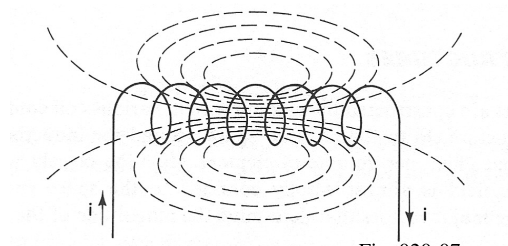


Fig. 020-07

This inductance is better termed self-inductance.

Inductance Structures:

Factors –

1.) Number of coil turns

2.) The type and shape of the core material

3.) The diameter and spacing of turns.

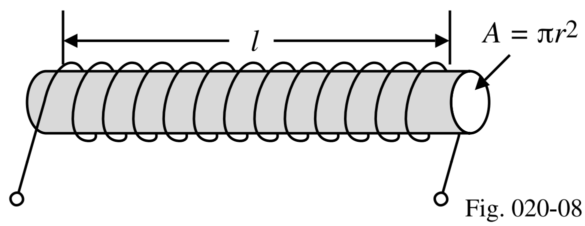


Fig. 020-08

$$L = \frac{\mu_r N^2 A}{l}$$

N = number of turns

μ_r = relative permeability of the cylindrical core

Symbol:

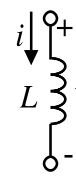


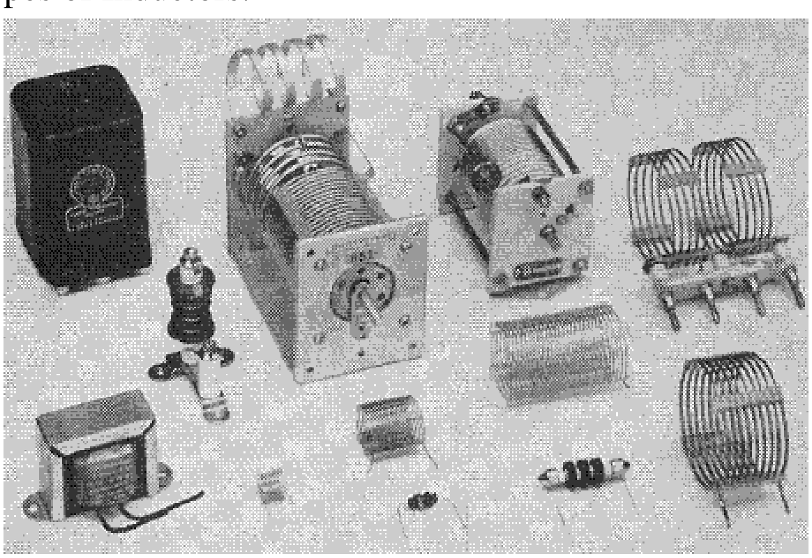
Fig. 020-09

$$\psi = Li \quad \rightarrow \quad \frac{d\psi}{dt} = \frac{d}{dt}(Li) = i\frac{dL}{dt} + L\frac{di}{dt} = 0 + L\frac{di}{dt} \quad \rightarrow \quad v = L\frac{di}{dt}$$

Characterization of Inductors

- Range of inductance
- Maximum current rating
- Absolute and relative tolerance
- Quality factor, Q, which is a measure of the losses in the inductor
- Temperature and voltage coefficients

Types of Inductors:



Two iron-core coils at the left are "chokes" for power-supply filters.

The mounted air-core coils at the top center are adjustable inductors for tank circuits.

The pre-wound coils at the left and in the foreground are rf chokes.

The remaining coils are typical of inductors used in rf tuned circuits.

The Quality Factor of an Inductor

The quality factor, Q, of an inductor is given as,

$$Q = \frac{\omega L}{R_s}$$

where

R_s = the series resistance of the inductor

This resistance includes:

1.) Ohmic series resistance

2.) Skin effect losses (current conducting only at the surface of the conductor)

3.) Any losses induced by the flux-linkages

Model:

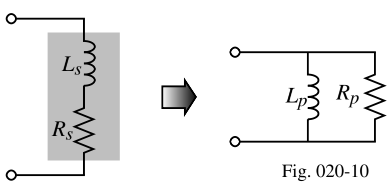


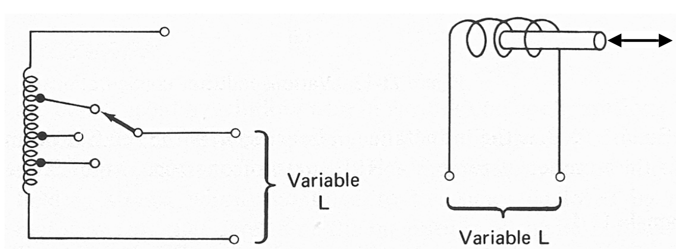
Fig. 020-10

$$Y(j\omega) = \frac{1}{R_p} + \frac{1}{j\omega L_p} = \frac{1}{R_p} - j\frac{1}{\omega L_p} = \frac{1}{R_s + j\omega L_s} = \frac{1}{R_s + j\omega L_s}\left(\frac{R_s - j\omega L_s}{R_s - j\omega L_s}\right) = \frac{R_s}{R_s^2 + (\omega L_s)^2} - \frac{j\omega L_s}{R_s^2 + (\omega L_s)^2}$$

$$\therefore \boxed{R_p = \frac{R_s^2 + (\omega L_s)^2}{R_s} = (1+Q^2)R_s} \quad \text{and} \quad \omega L_p = \frac{R_s^2 + (\omega L_s)^2}{\omega L_s} \quad \rightarrow \quad \boxed{L_p = L_s\left(1 + \frac{1}{Q^2}\right)}$$

Variable Inductors

1.) Tap switching.



Tap Switching Inductor Movable-Core Inductor

Fig. 020-11

2.) Movable core.

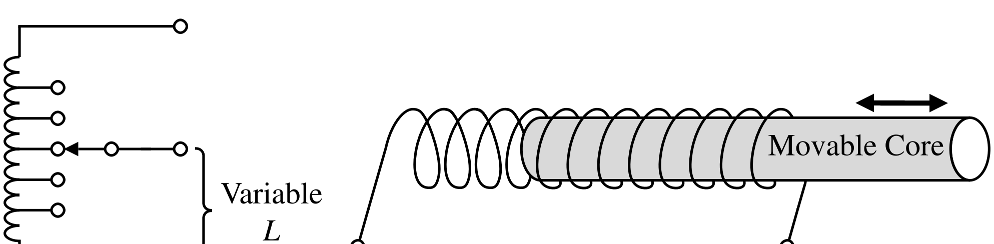


Fig. 020-11

When adjusting the movable core, the tool used to do the adjusting must not be metal.

TRANSFORMERS

Transformer

The transformer consists of two or more coils wound around a common core of magnetic material. When current flows in one coil, it creates a magnetic field which links the second coil and creates a current in the second coil.

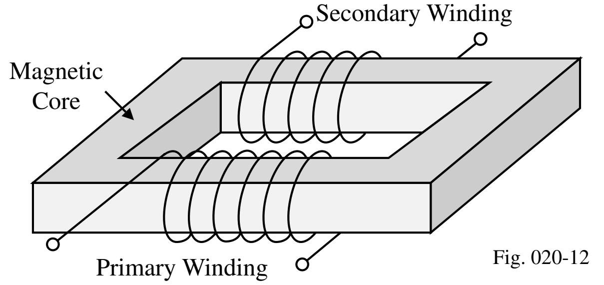


Fig. 020-12

Equations:

$V_1 = sL_1I_1 \pm sMI_2$ and $V_2 = \pm sMI_1 + sL_2I_2$

where

M = mutual inductance between the two windings = $k\sqrt{L_1L_2}$

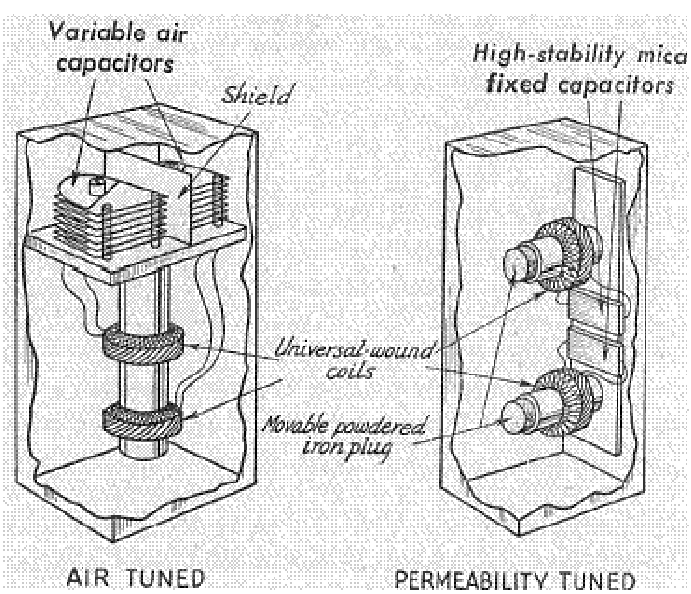
k = coefficient of coupling ≤ 1

Turns ratio:

$V_1 = \frac{N_1}{N_2} V_2$ and $I_1 = \frac{N_2}{N_1} I_2$

Types of Transformers

- Power transformers
- IF and RF transformers



MINIATURIZATION OF DISCRETE TECHNOLOGY[1,2]

An alternative to integrated circuit technology is the miniaturization of discrete components. This technology is sometimes called *hybrid technology*.

Hybrid technology involves attaching two or more components (both active and passive) on a single substrate.

Hybrid technology consists of:

1.) A substrate

2.) Passive and active components

3.) Connections between the components

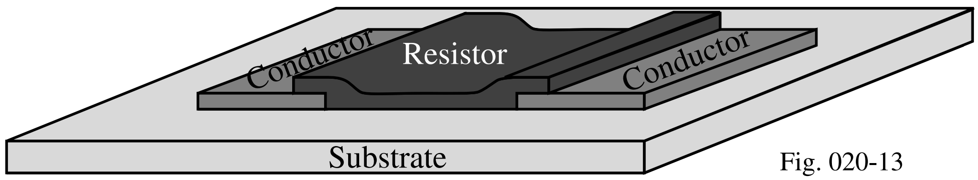


Fig. 020-13

Types of hybrid technology:

1.) Thin films (conductor thickness in the range of 50-500Å)

2.) Thick films (conductor thickness in the range of 20μm)

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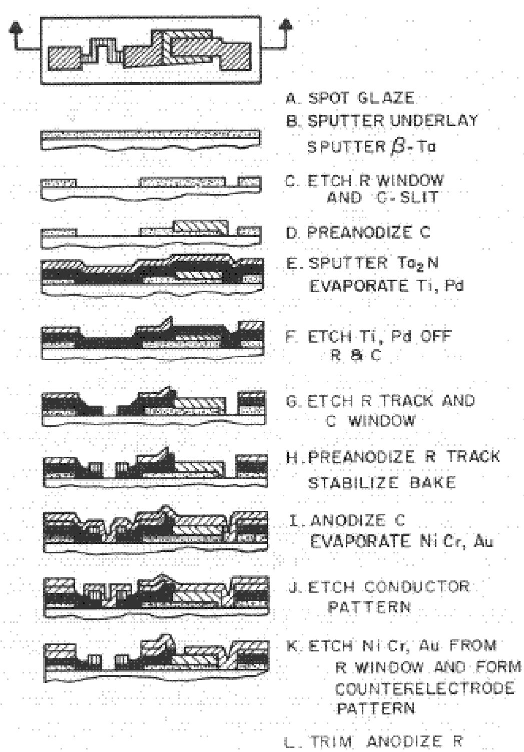
[1] A.B. Glaser and G.E. Subak-Sharpe, "Integrated Circuit Engineering," Addison-Wesley Publishing Co., Reading, MA, 1979.

[2] R.L. Geiger, P.E. Allen, and N.R. Strader, "VLSI Design Techniques for Analog and Digital Circuits," McGraw-Hill Book Co., NY, 1990.

Thin Film Technology

The processing steps are deposition of films and etching of unwanted depositions.

Example of a thin-film circuit containing resistors and capacitors on a single substrate:



Thick Films

Thick film technology uses a screening process to apply layers of different material upon a substrate. The material can be conducting or insulating.

The screening process involves the following steps:

1.) A paste or ink is forced through small holes in a tightly stretched piece of fabric called a screen. The grid is very regular and the size of the holes can be varied.

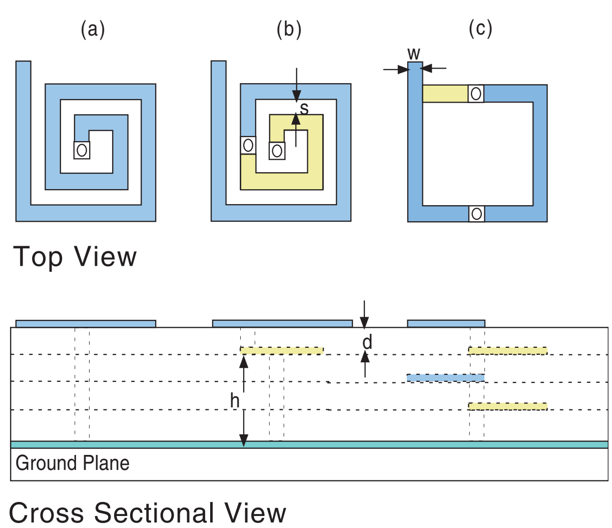
2.) Where the paste or ink is not desired, the holes in the screen are plugged by a mask.

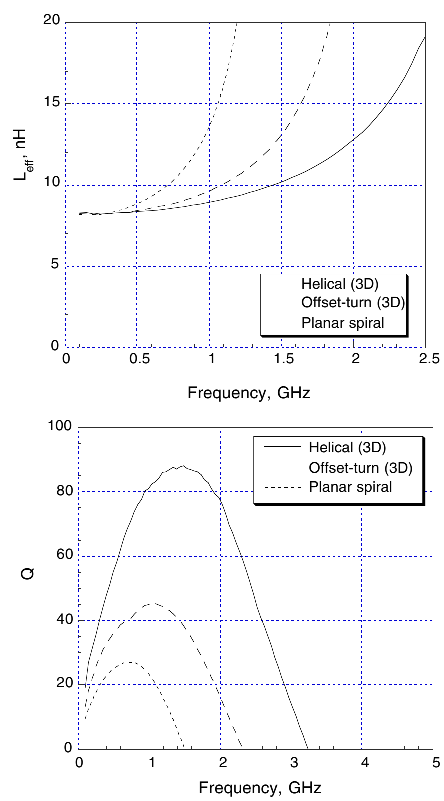
3.) A squeegee is used to force the ink or past through the unrestricted areas.

4.) Following the screening, each layer is fired to harden it at a temperature of 500°C to 1000°C.

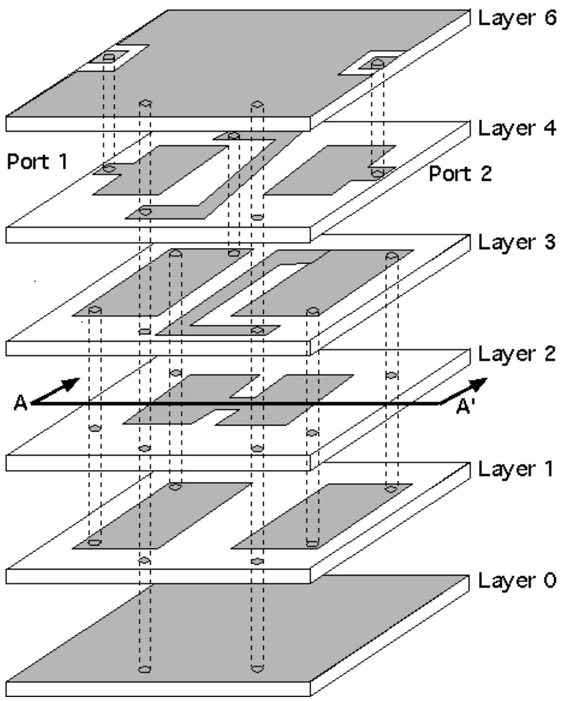
5.) Active components can be attached by soldering.

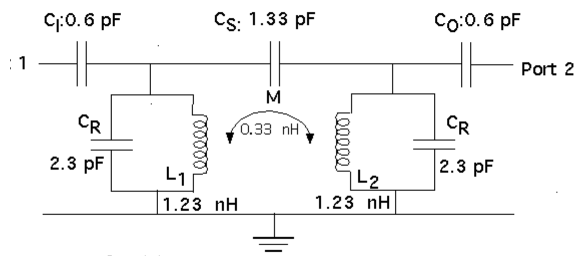
Multi-Layer Inductors in a Thick Film Process

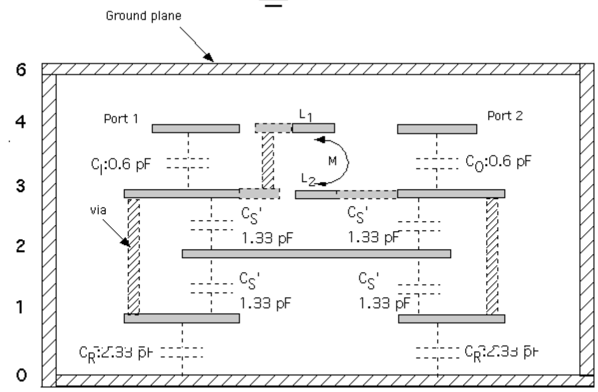




Three-Dimensional RF Filter

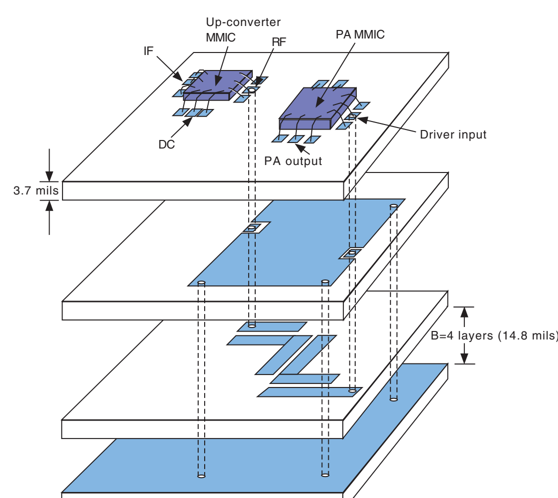


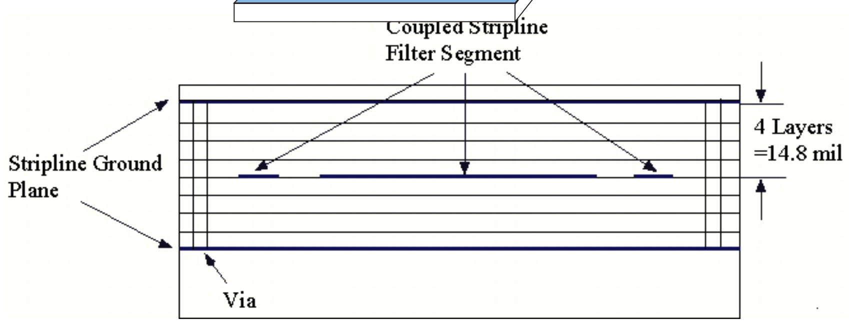




Ku-Band Transmitter Module

- **Two MMICs on a multi-layer LTCC substrate**
- **Stripline front-end bandpass filter**
  - **— Three coupled-line segments**
  - **— Folded structure**
- **LTCC 951 Dupont tape with 8 stacked layer**
  - **— Tape layer thickness : 3.7 mils**
- **Balanced stripline topology**





SUMMARY

Discrete components:

- Resistors
- Capacitors
- Inductors
- Transformers

Characterization of discrete components:

- Range of values
- Absolute and relative accuracy
- Maximum ratings (power, voltage and/or current)
- Temperature and voltage coefficient
- Losses – dissipation factor for capacitors and quality factor for inductors

Miniaturization of discrete components:

- Thin films
- Thick films

