Chapter 5 Passive microwave components

5.9 Mixers

application, operating principle, characteristics, double-balanced mixer

5.10 Cavity resonators

series RLC resonator, parallel RLC resonator, Q factor, half-power fractional bandwidth, transmission line resonator, cavity resonator, application

5.11 Filters

characteristics, YIG filter, SAW filter

5.12 T-sections

E-plane T, H-plane T, magic T, application

5.13 Flanges/joints

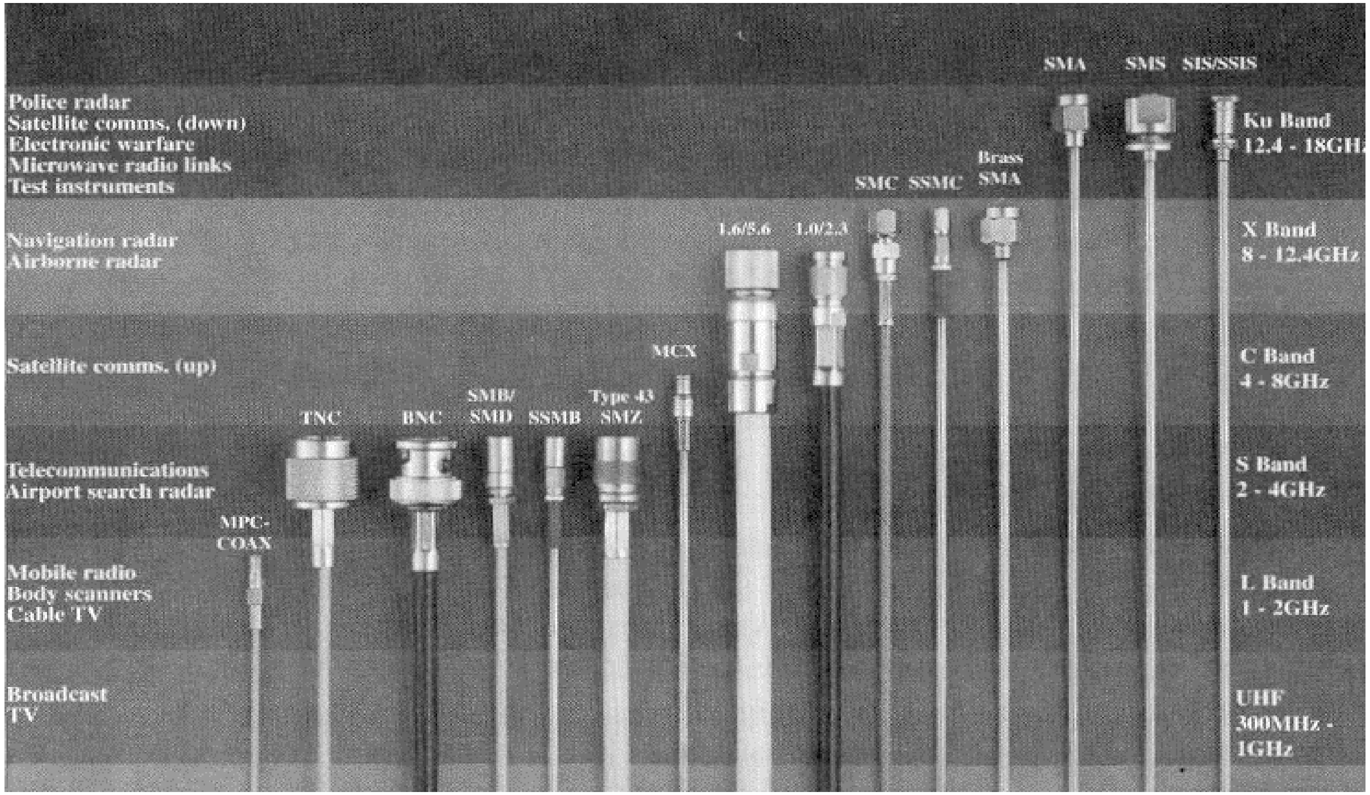
5.1 Introduction

1. Passive components (without DC bias): connector, coupler, attenuator, terminator, isolator, circulator, mixer, resonator, filer, duplexer, detector, phase shifter, tuner, antenna, ….
2. Active components (with DC bias): amplifier, oscillator, switch, mixer, frequency multiplier, active antenna, active filter,….
3. In general, input/output matching is inherently required for microwave components over the operating band.

5.2 Connectors

1. Application: connect transmission line to microwave components, or adapt to different types of connections (coaxial, waveguide, microstrip,…)
2. Coaxial connector material
   metal: beryllium copper, phosphor bronze, brass, or stainless steel
   with gold plate, silver plate, or passivated treatment
   dielectric: teflon (ε_r=2.08, tanδ=0.0004), air, polystyrene (PE, ε_r=2.54, tanδ=0.00033), polyethylene (ε_r=2.25, tanδ=0.0002),...

3. Types of coaxial connector



mechanical consideration: size, thread and sex match, mechanical strength, repeatability

electrical consideration: low loss, low VSWR (<1.1), Z_0, higher-order-mode-free operation at a high frequency

4. Coaxial connector performance

APC-2.4 (Amphenol precision connector): inside diameter 2.4mm, air dielectric

APC-3.5: inside diameter 3.5mm, compatible with SMA (Subminiature A) and type-K connector

APC-7: inside diameter 7mm, “sexless”

BNC (Bayonet Navy connector)

TNC (Threaded Navy connector)

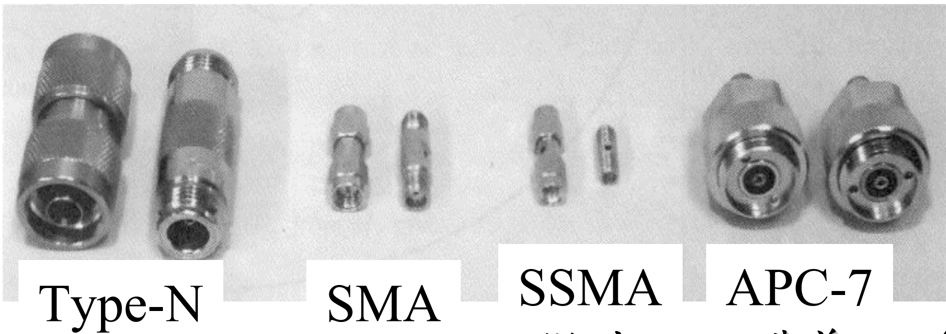
SMC (Subminiature C)

Type-N connector: outer radius of female connector D=0.625in

SMA (Subminiature A): D=0.25in

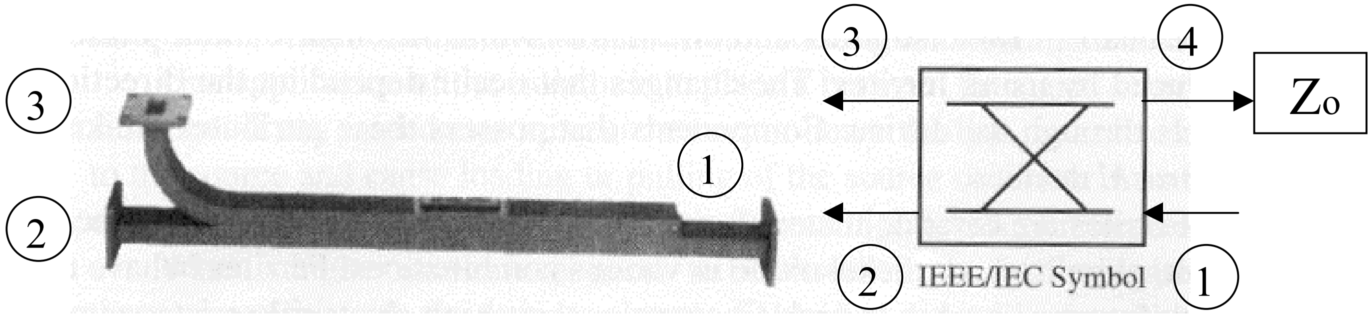
SSMA (scaled SMA): D=0.192in

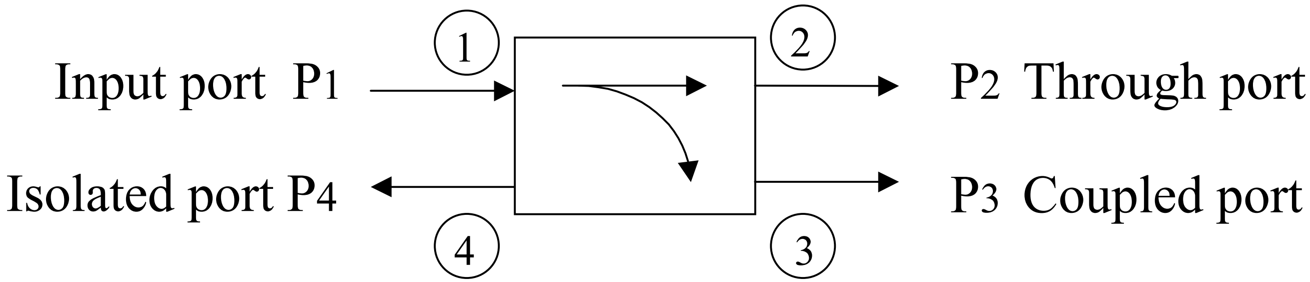
Connector Type	Maximum Frequency (GHz)
APC-2.4	50
APC-3.5	34
APC-7	18
1.85 mm	65
BNC	4
TNC	12
SMA	24
SMC	7
Type K	40
Type N	18



5.3 Directional couplers

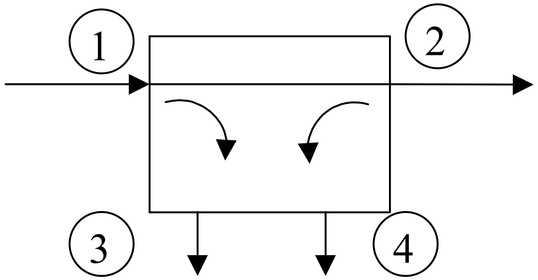
1. Configuration/symbol





2. Application: normally used as a power divider for sampling the input signal, but can also be a power combiner.

3. Port definition



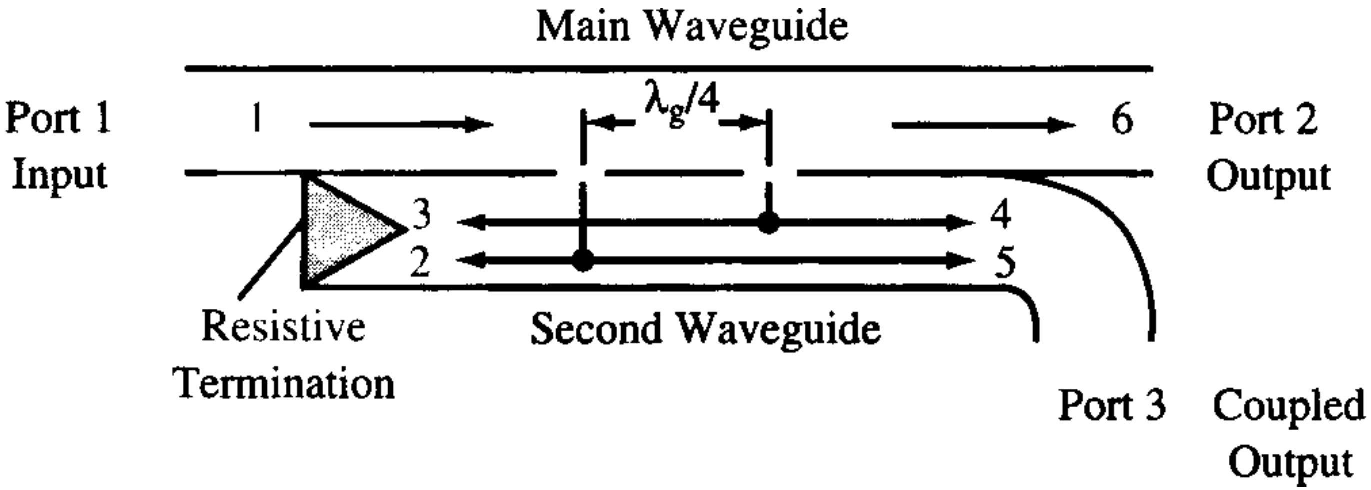
Coupling factor $C(dB) = -10\log\dfrac{P_3}{P_1}$

Directivity $D(dB) = 10\log\dfrac{P_3}{P_4}$

Isolation $I(dB) = 10\log\dfrac{P_1}{P_4} = C + D$

Normally, C: 10, 20, or 30dB, D: 30dB

4. Operating principle

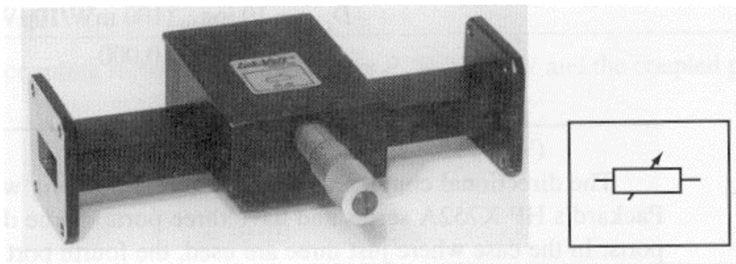


5. Ex.5.1 Input power 228mW, coupled power 228uW→C=30dB
Ex.5.2 Input power -20dBm, coupled power -40dBm →C=20dB
Ex.5.3 In coupled arms with forward power 100mW and reverse power 10uW →D=40dB

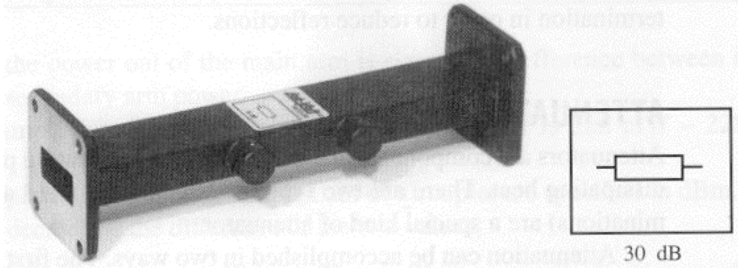
5.4 Attenuators

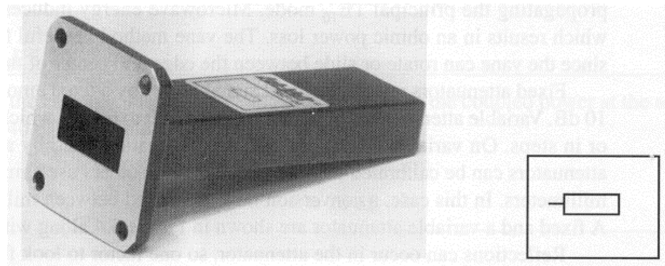
1. Configuration/symbol

variable attenuator



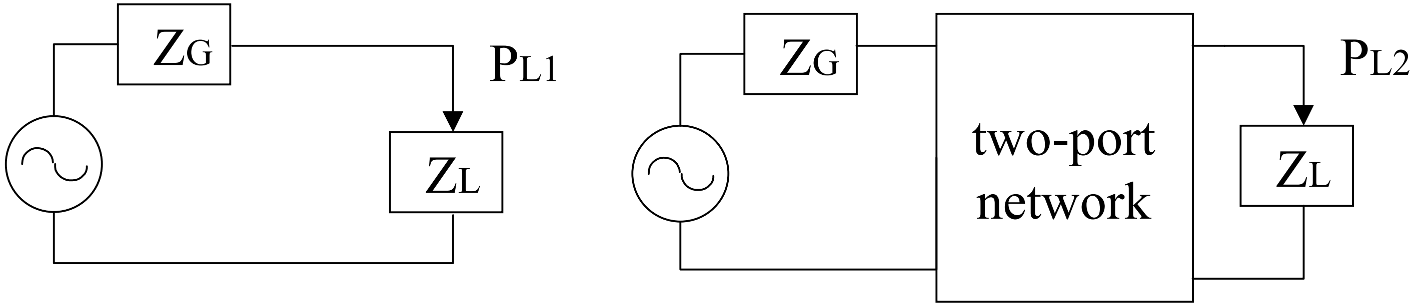
fixed attenuator





terminator
“dummy” load

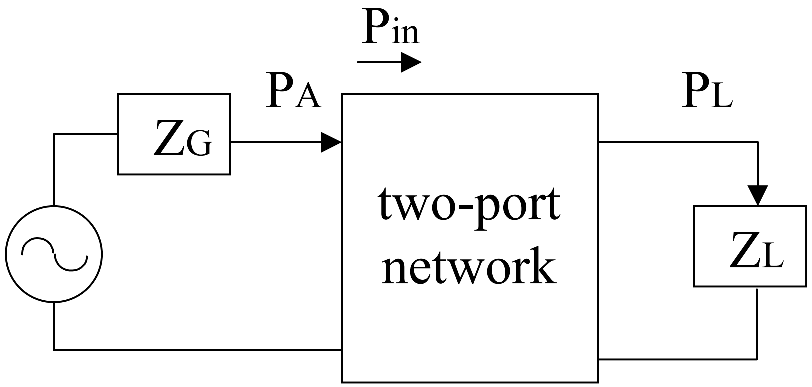
2. Application: provide protection, reduce power, extend the dynamic range of the test equipment, improve matching
3. Insertion loss



Insertion loss $IL(dB) = 10\log\frac{P_{L1}}{P_{L2}}$

Usually $Z_G = Z_L = Z_o$.
Two-port passive component has IL>0.
For active component, one can define insertion gain = -IL.
Fixed attenuator: 3dB, 6dB, 10dB, 20dB, 30dB.
Variable attenuator: 0-10dB with 1dB step, 10-60dB with 10dB step

4. Transducer loss



P_{in}: incident power
P_d: dissipated power in the two-port network

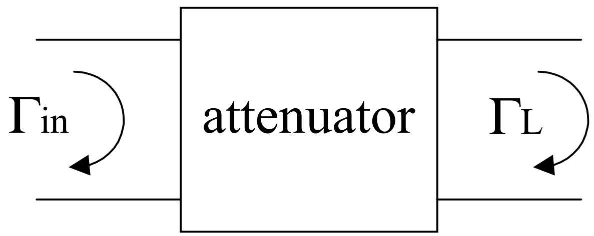
$$L_T(dB) \equiv 10\log\frac{P_A}{P_L} = 10\log\left(\frac{P_{in}}{P_{in}-P_d}\frac{1}{1-|\Gamma_{in}|^2}\right)$$

$P_A = \frac{V_G^2}{4R_G}$: available power from source, P_L : power delivered to the load

$P_{in} = (1-|\Gamma_{in}|^2)P_A, P_L = P_{in} - P_d$

As $Z_G = Z_L$, L_T = IL. For active component, one can define transducer gain $G_T = -L_T$.

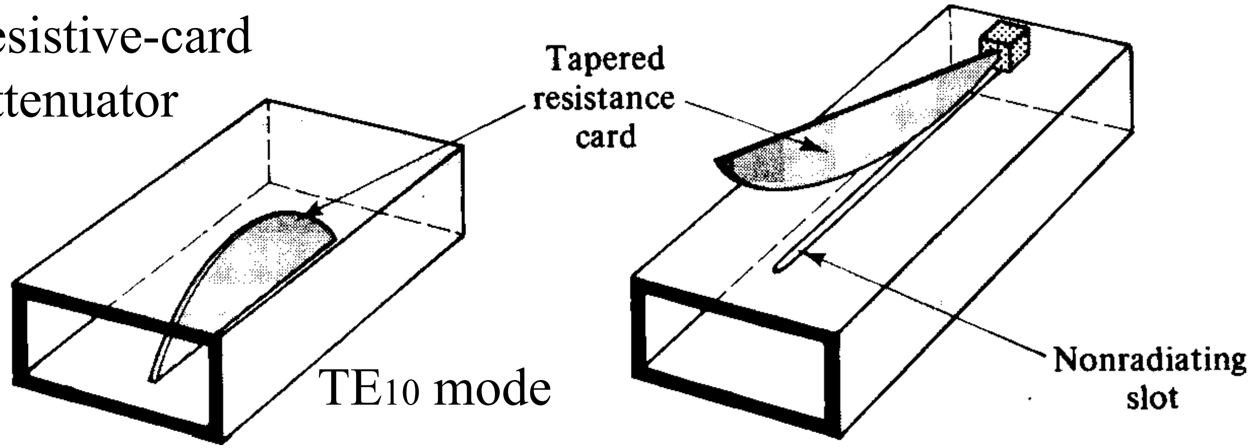
5. Matching improvement



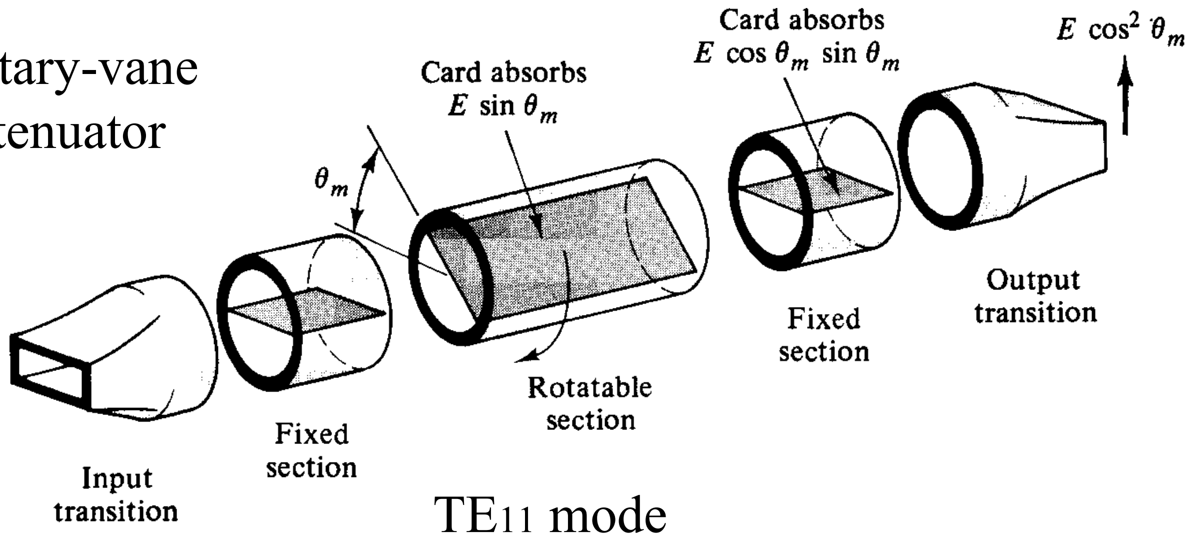
$$RL_{in}(dB) = 10\log\frac{P_{in}}{P_r} = 10\log\frac{P_{in}}{P_{in}|\alpha|^2|\Gamma_L|^2} = 10\log\frac{1}{|\alpha|^2|\Gamma_L|^2} = RL_L - IL$$

6. Operating principle

resistive-card attenuator

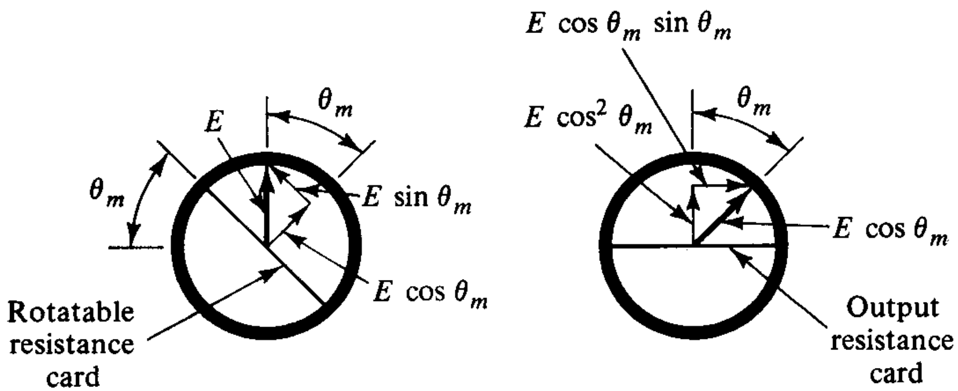


rotary-vane attenuator



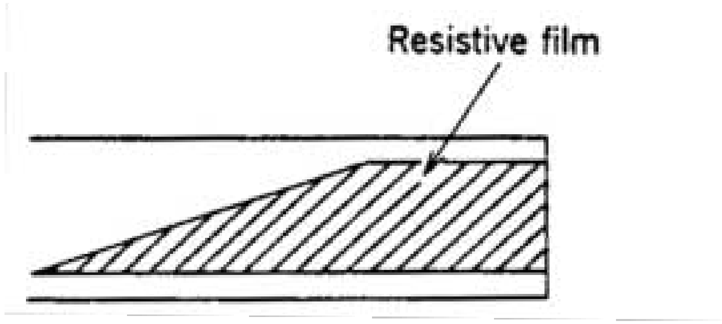
TE11 mode

TE10 mode

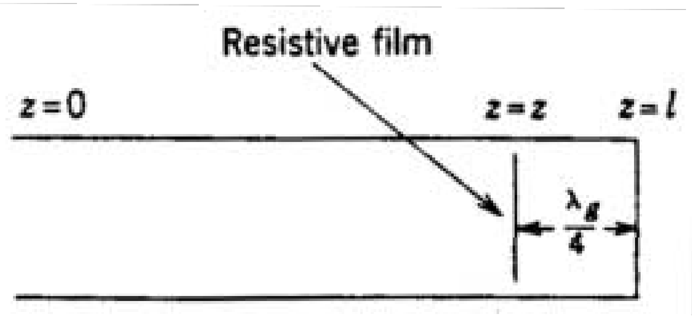


Wave components at the input to the rotatable section

Waveguide components at the input to the second fixed section



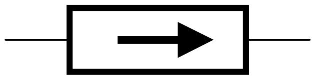
tapered terminator



$\lambda/4$ resistive-film terminator

5.5 Isolators

1. A nonreciprocal two-port component (using ferrite) permits transmission with low loss in one direction and absorbs the power in the other direction.



2. Application: improve loading effect, especially for oscillator and power amplifier output port.

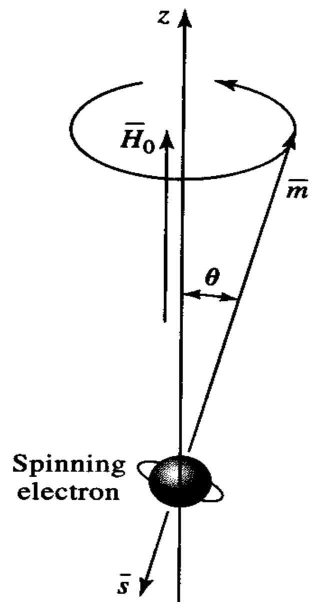
3. Operating principle (ref. Collin, Sec.6.7)

(1) gyromagnetic resonance

spinning electron has a magnetic dipole moment

$$\vec{m} = -\gamma\vec{p}, \text{or } m = \frac{q\hbar}{2m_e}, p = \frac{\hbar}{2}, \gamma = \frac{q}{m_e}$$

$\vec{p}$: angular momentum, γ : gyromagnetic ratio

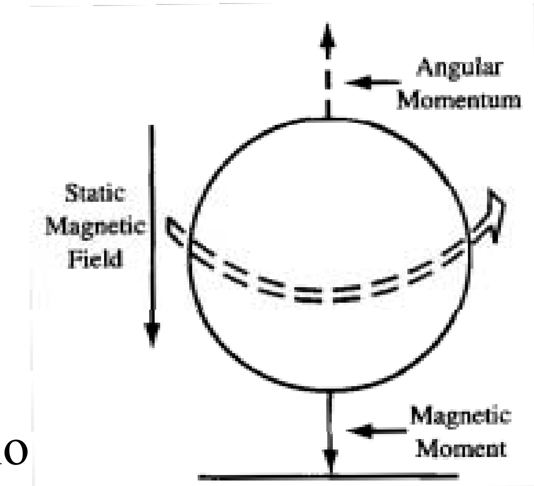


as a static magnetic field $\vec{H}_o$ is applied,

$\rightarrow$ a torque is exerted on the magnetic dipole

$$\vec{T} = \vec{m} \times \mu_o \vec{H}_o = \frac{d\vec{p}}{dt} = -\frac{1}{\gamma}\frac{d\vec{m}}{dt} = \vec{w}_o \times \vec{p}$$

$$\rightarrow \begin{cases} \dfrac{d^2 m_x}{dt} + w_o^2 m_x = 0 \\ \dfrac{d^2 m_y}{dt} + w_o^2 m_y = 0 \end{cases}, w_o = \gamma B_o : \text{Lamor frequency}$$



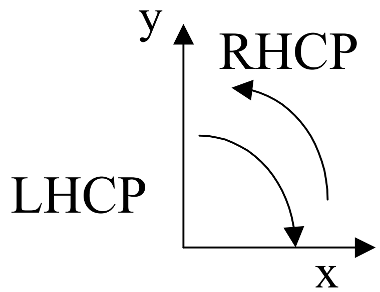
$\rightarrow$dipole moment precesses at w_o (ferrite natural frequency), then is damped out due to magnetic lo

(2) circular polarized wave

• LHCP

$$\vec{H}_1^L = \mathrm{Re}[H_1(\hat{x} + j\hat{y})e^{jwt}] = H_1(\cos wt\hat{x} - \sin wt\hat{y})$$

$\rightarrow$ field vector rotates at a rate $-w$ about z-axis



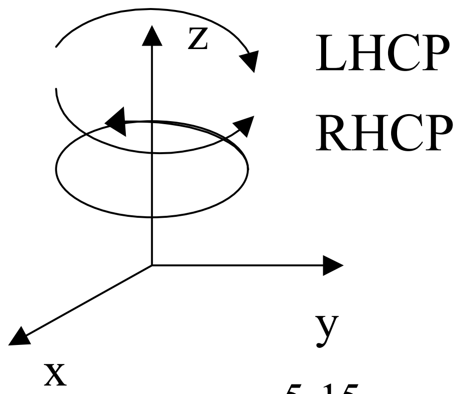
• RHCP

$$\vec{H}_1^R = \mathrm{Re}[H_1(\hat{x} - j\hat{y})e^{jwt}] = H_1(\cos wt\hat{x} + \sin wt\hat{y})$$

$\rightarrow$ field vector rotates at a rate w about z-axis

(3) interaction with microwaves

If a small time-harmonic field $\vec{H}_1$ is superimposed on $\vec{H}_o = H_o\hat{z}$, the magnetic dipole moment will undergo a forced precession.



(4) nonreciprocal permeability

For a uniform, isotropic magnetic material

$$\vec{B} = \mu\vec{H} = \mu_o(1+X_m)\vec{H} = \mu_o\vec{H} + \mu_o\vec{M}, \vec{M} = N\vec{m} : \text{magnetization}$$

For a ferrite material

$$LHCP\ \vec{B}^L = \mu_0(\vec{M}^L + \vec{H}^L) = \mu^L\vec{H}^L$$

$$RHCP\ \vec{B}^R = \mu_0(\vec{M}^R + \vec{H}^R) = \mu^R\vec{H}^R$$

$$\rightarrow \vec{B} = [\mu]\vec{H} = \mu_o([U] + [X_m])\vec{H}, [X_m] = \begin{bmatrix} X_{xx} & X_{xy} & 0 \\ X_{yx} & X_{yy} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

(5) resonant absorption isolator

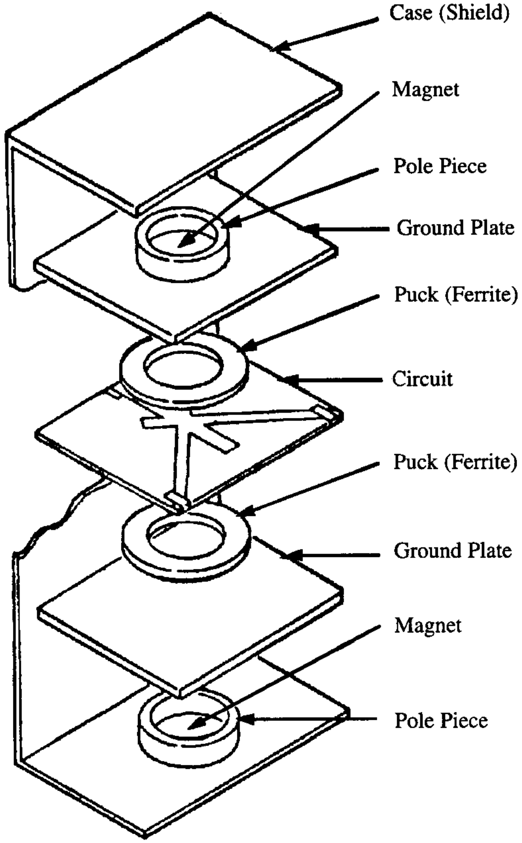
μ and X become ∞ at gyromagnetic resonance *(w=w_o)*

as a rf signal applied with the same polarization $\rightarrow$ precession builds up $\rightarrow$ transfer energy to entire iron atom $\rightarrow$ rf energy is dissipated as heat $\rightarrow$ signal attenuates

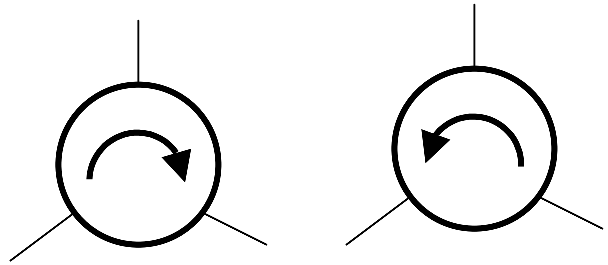
as a rf signal traveling in the opposite direction ($\perp$ polarization) does not cause precession to occur $\rightarrow$ signal passes through

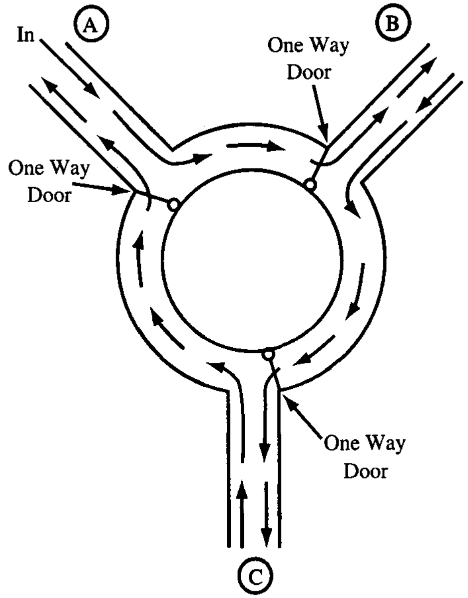
5.6 Circulators

1. Structure/symbol



Internal Structure

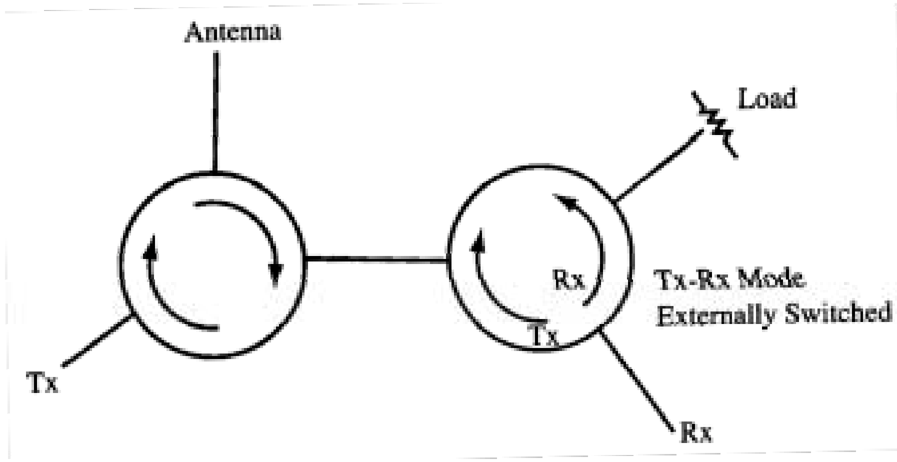




Signal Flow

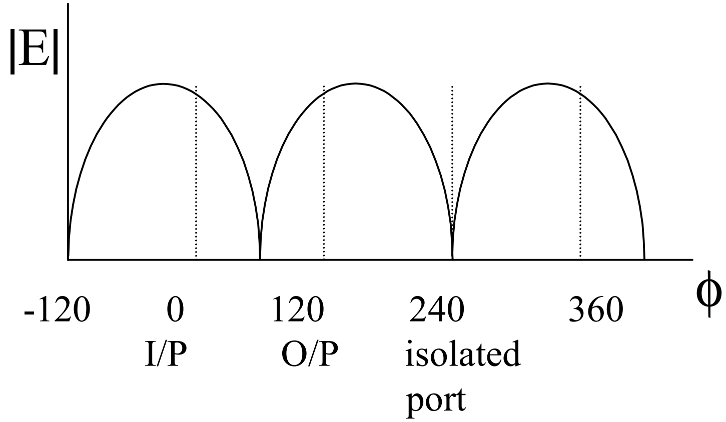
2. Application: separate transmit signal and return signal

Ferrite switch uses less power, has less IL, more reliable and work at higher power than diode switch (phase array application).



3. Operating principle

ferrite is an anisotropic magnetic material→[u] →CW wave and CCW wave interferes inside ferrite →cancelled at the isolated port

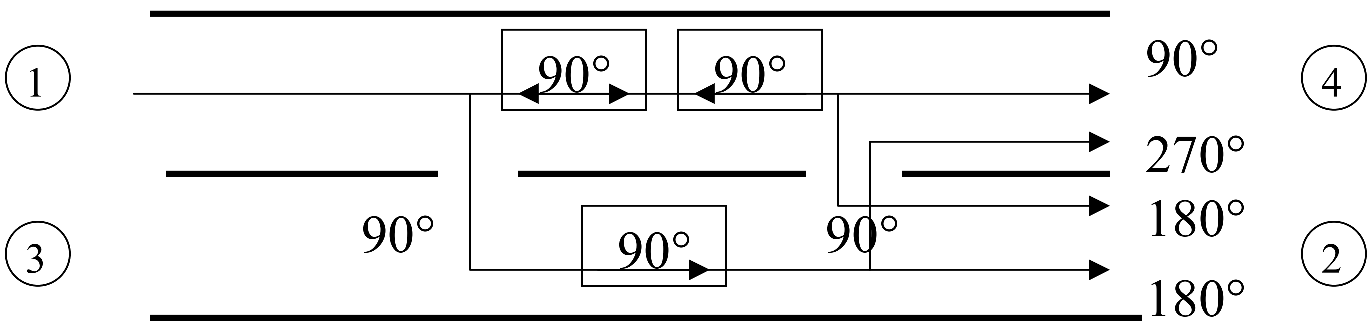


4. A 4-port circulator using 3dB directional coupler (ref. Collin Sec.6.10)

nonreciprocal 90° phase shifter: using ferrite with $(\beta^R - \beta^L)l = 90^0$

β^R : propagation constant for forward pagation

β^L : propagation constant for reverse pagation



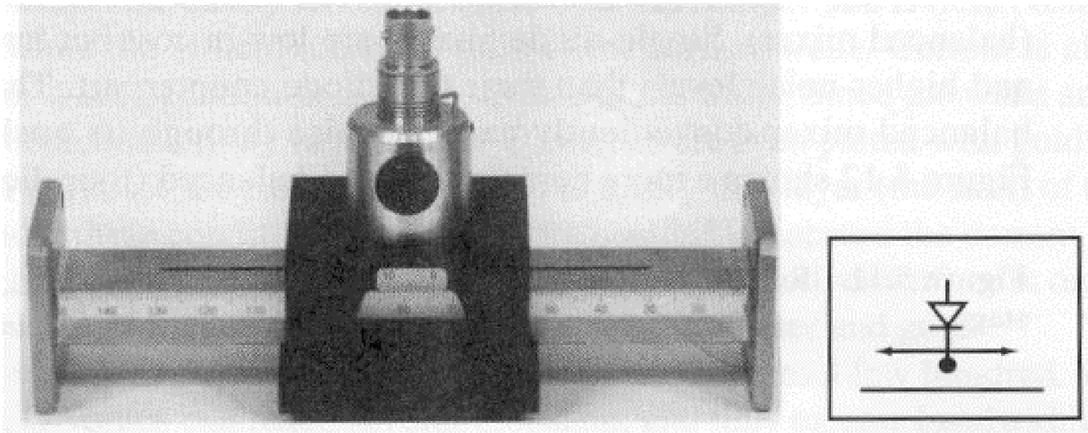
1→2 not →4

2→3 not →1

3→4 not →2

5.7 Slotted line

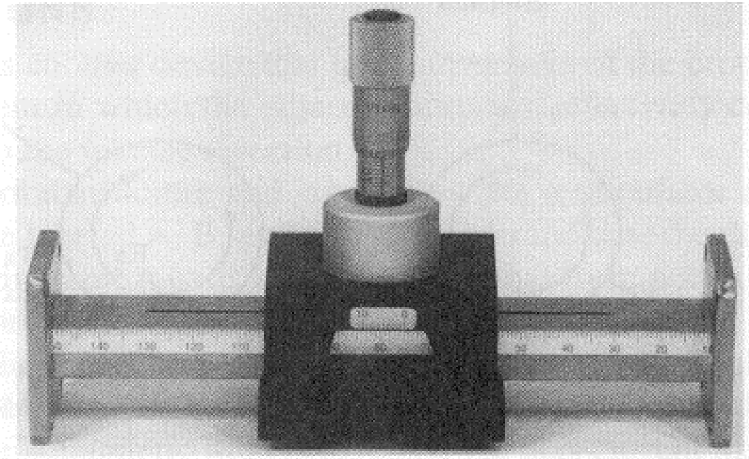
1. Configuration/symbol

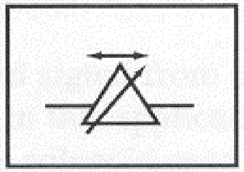


2. Application: measure VSWR, λ_g, Z_{in} using shifted-minima technique
3. Operating principle: detect $|E|$ of TE_{10} mode through a E-probe and a crystal detector to give a DC output

5.8 Slide-screw tuner (stub-tuner)

1. Configuration/symbol

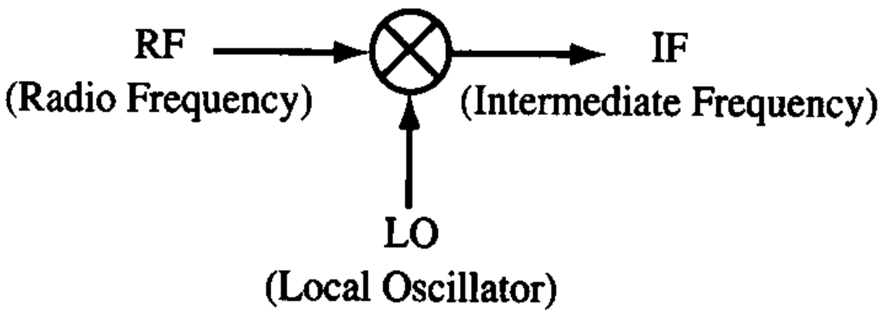


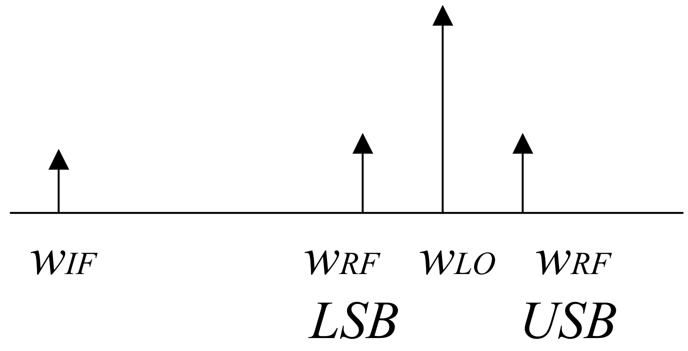


2. Application: impedance match
3. Operating principle: shunt C as probe penetration depth<λ/4$\rightarrow$ locate slide-screw tuner at a distance from load to have an inductive impedance

5.9 Mixers

1. Application: frequency up/down conversion (hytrodyne)





2. Advantages

hytrodyne receiver:

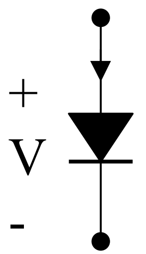
(1) lower noise amplification at IF than RF

(2) change LO frequency to receive a wideband RF than using a high-gain wideband RF amplifier

hytrodyne transmitter:

use same LO for transmitter and receiver

3. Operating principle



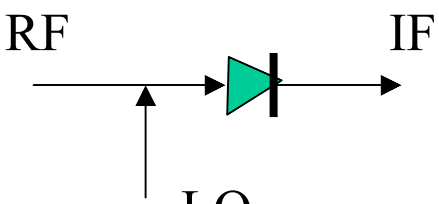
$$I(V)=I_s(e^{\alpha V}-1)$$

$$I(V)=I(V_o)+v\left.\frac{dI}{dV}\right|_{V_o}+\frac{1}{2}v^2\left.\frac{d^2I}{dV^2}\right|_{V_o}+\ldots$$

$$=I_o+vG_d+\frac{1}{2}v^2G'_d+\ldots$$

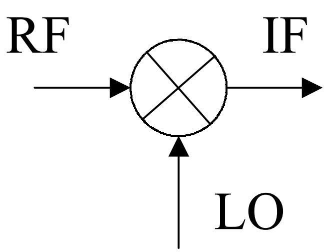
$$=I_o+i_R+i_C+\ldots$$

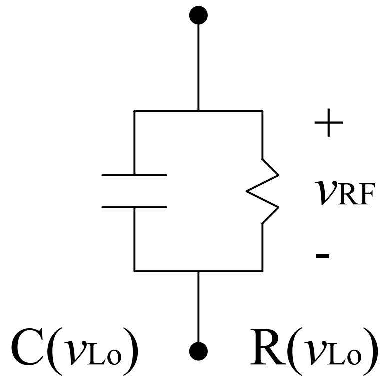
$$i_C=\frac{dQ}{dt}=\frac{dCv}{dt}=v\frac{dC(v_{LO})}{dt}+\ldots\propto v^2+\ldots$$



down converter

$$i(t)=\frac{v^2}{2}G'_d$$





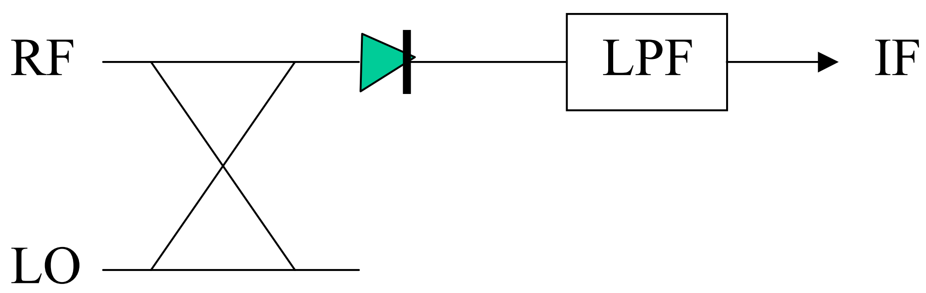
linear time-varying components

4. Mixer characteristics

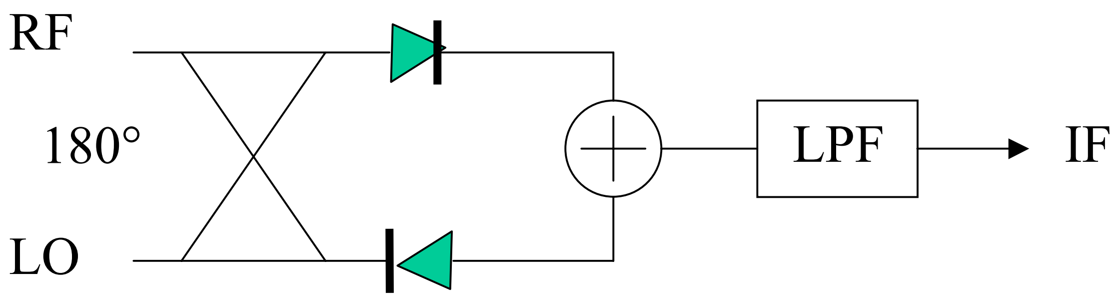
Conversion loss $L_c(dB) = 10\log\dfrac{\text{available RF input power}}{\text{IF output power}}$

LO/RF isolation

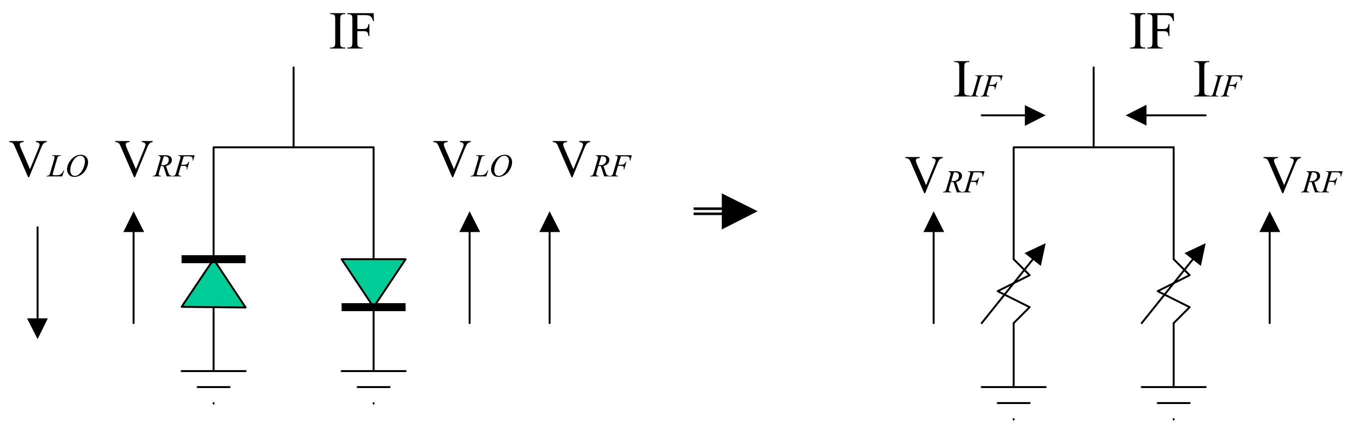
5. Single-ended diode mixer: high conversion loss, no isolation between LO and RF ports



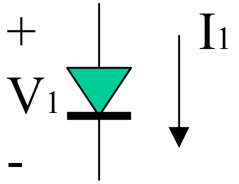
6. Single-balanced diode mixer: good LO/RF isolation



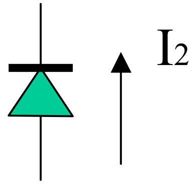
phasor representation



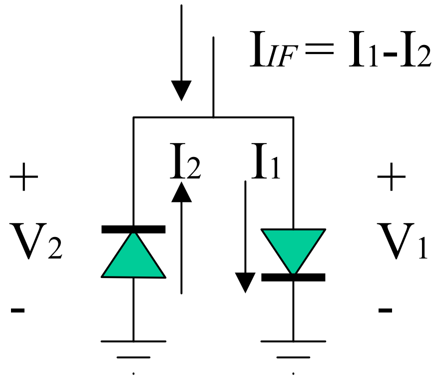
LO even-harmonic suppression



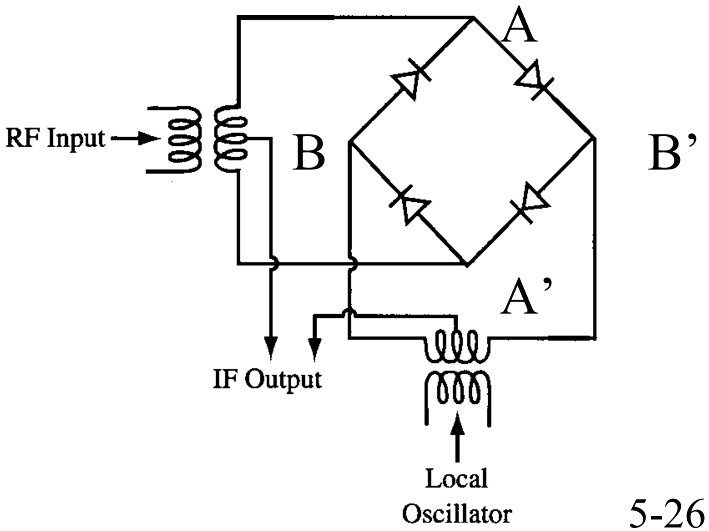
$$I_1 = aV_1 + bV_1^2 + cV_1^3 + dV_1^4$$



$$I_2 = -aV_2 + bV_2^2 - cV_2^3 + dV_2^4$$



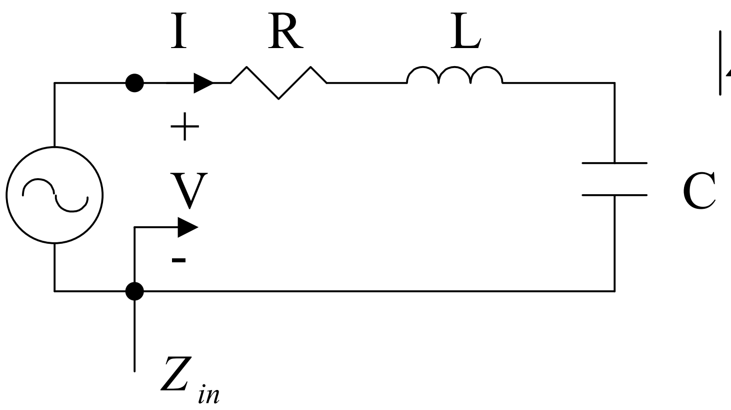
7. Double-balanced mixer: good RF/LO isolation, LO and RF even-harmonics suppressed

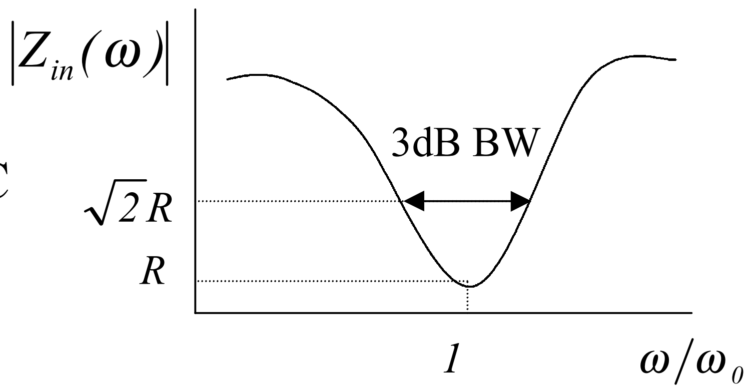


RF: BB' GND
LO: AA' GND

5.10 Cavity resonator

1. Series RLC resonator





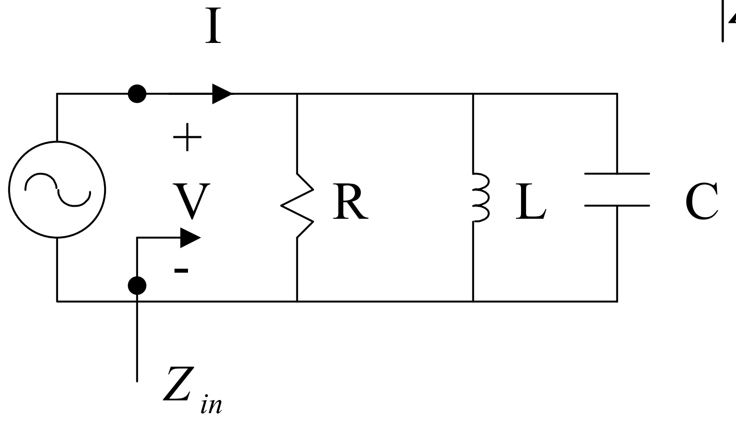
$$Z_{in}(\omega) \equiv \frac{V}{I} = R + j\omega L + \frac{1}{j\omega C} = R + j\omega L\,\frac{\omega^2 - \omega_o^2}{\omega^2}$$

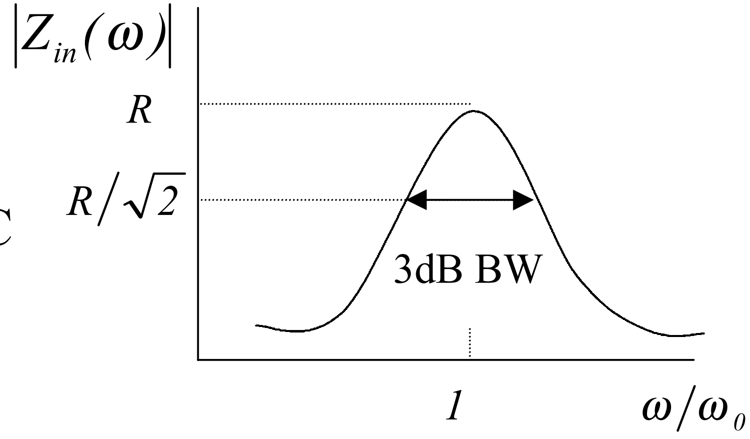
$$\equiv \frac{2P_{in}}{|I|^2} = \frac{P_{loss} + 2j\omega(W_m - W_e)}{|I|^2/2}, \quad \omega_o = \frac{1}{\sqrt{LC}}$$

$$P_{loss} = \frac{1}{2}|I|^2 R, \quad W_m = \frac{1}{4}|I|^2 L, \quad W_e = \frac{1}{4}|V_c|^2 C = \frac{1}{4}|I|^2\frac{1}{\omega^2 C}$$

At resonance, $W_m = W_e$, $P_{in} = P_{loss}$

2. Parallel RLC resonator





$$Z_{in}(\omega) = \left(\frac{1}{R} + \frac{1}{j\omega L} + j\omega C\right)^{-1} = \left[\frac{1}{R} + \frac{1}{j\omega L}\left(1 - \frac{\omega^2}{\omega_o^2}\right)\right]^{-1}, \quad \omega_o = \frac{1}{\sqrt{LC}}$$

$$\equiv \frac{2P_{in}}{|I|^2} = \frac{P_{loss} + 2j\omega(W_m - W_e)}{|I|^2/2}$$

$$P_{loss} = \frac{1}{2}|I|^2 R, \quad W_m = \frac{1}{4}|I_L|^2 L = \frac{1}{4}|V|^2 \frac{1}{\omega^2 L}, \quad W_e = \frac{1}{4}|V|^2 C$$

3. Quality factor

$$Q \equiv \omega \frac{\textit{average energy stored}}{\textit{energy loss}/\sec\textit{ond}} = \omega \frac{W_m + W_e}{P_{loss}}$$

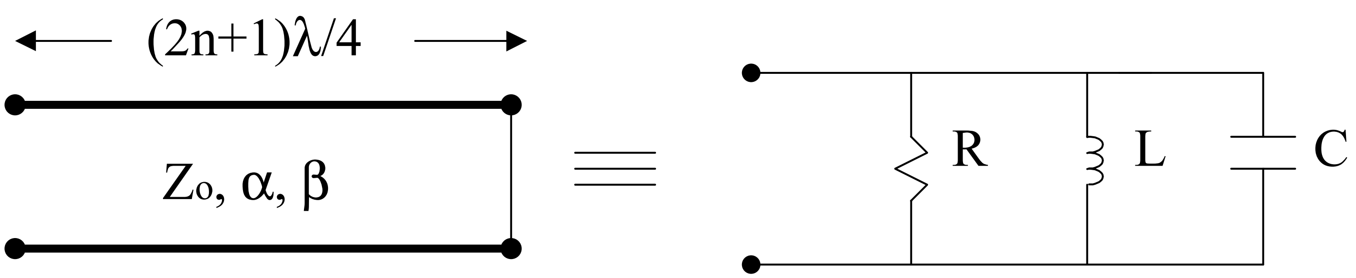
series RLC resonator $\quad Q = \dfrac{\omega_o L}{R} = \dfrac{1}{\omega_o RC}, \quad R\downarrow \;\Rightarrow\; Q\uparrow$

parallel RLC resonator $\quad Q = \dfrac{R}{\omega_o L} = \omega_o RC, \quad R\uparrow \Rightarrow Q\uparrow$

4. Half-power fractional bandwidth

$$BW \equiv \frac{2\Delta\omega}{\omega_o} \;\rightarrow\; R = X \;\rightarrow\; Q = \frac{1}{BW} = \frac{\omega_o}{2\Delta\omega}$$

5. Transmission line resonator



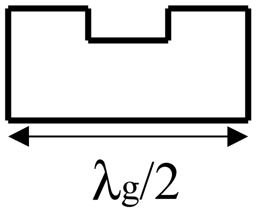
6. Rectangular cavity

$$f_{mnl} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{c}\right)^2}$$

cylindrical cavity

$$f_{mnl} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{B_{m,n}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2}$$

reentrant cavity: cavity with irregular shape to insure the oscillation frequency is not harmonically related.



7. In general

$$Q \propto w \frac{volume}{surface\ area}$$

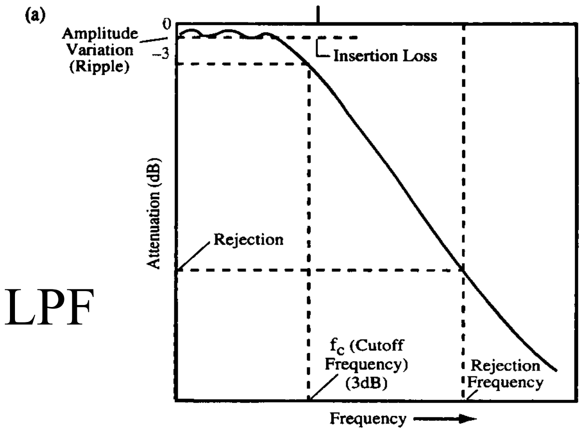
$Q_{sherical} > Q_{cylindrical} > Q_{rectangular} > Q_{coaxial} > Q_{microstrip}$

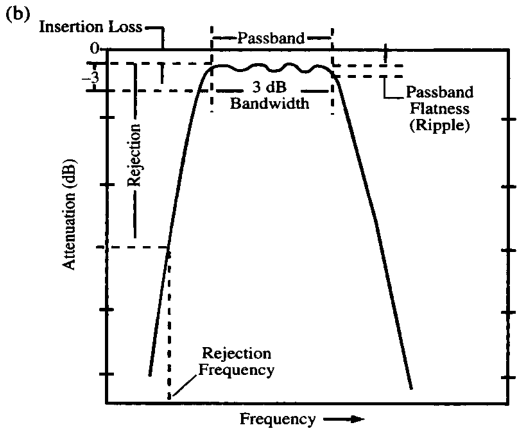
8. Application: oscillator, filter, mixing chamber, matching circuit, wave meter

5.11 Filters

1. Filter characteristics

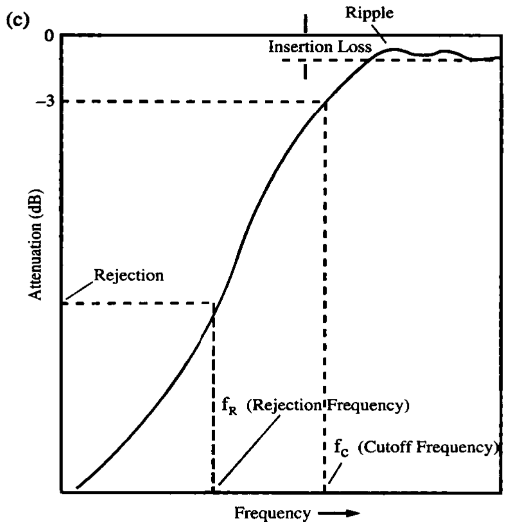
LPF





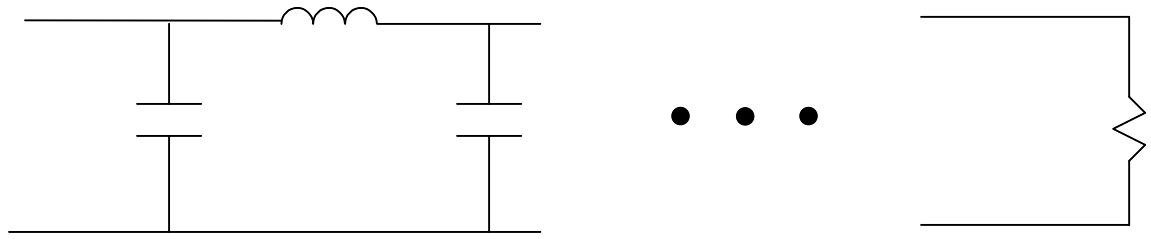
BPF

HPF

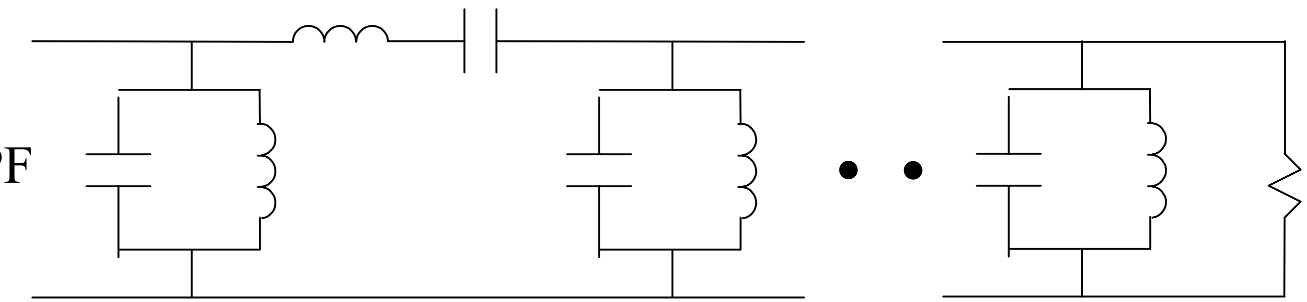


2. Filter equivalent circuits

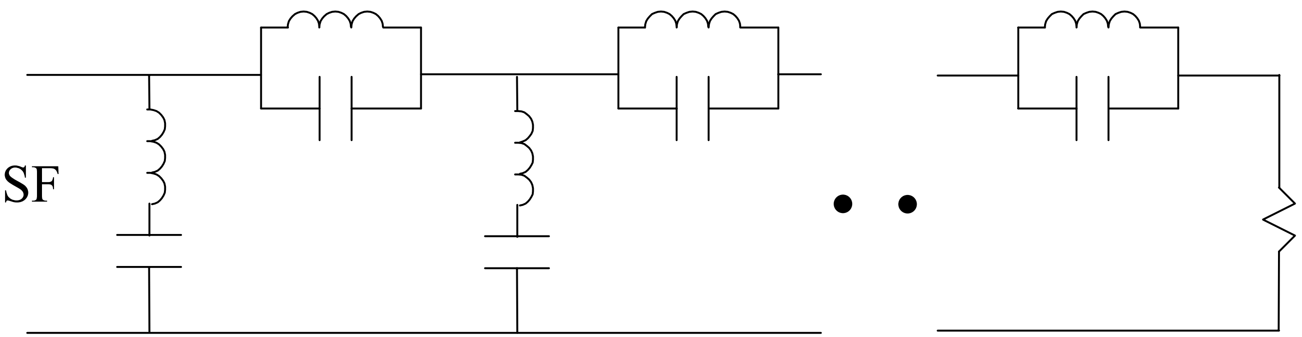
LPF



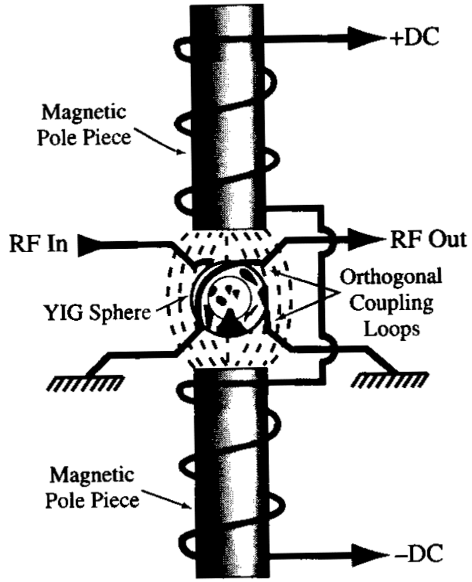
BPF



BSF

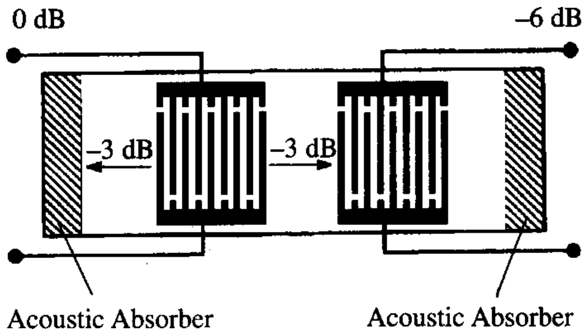


3. YIG (yttrium iron garnet) filter

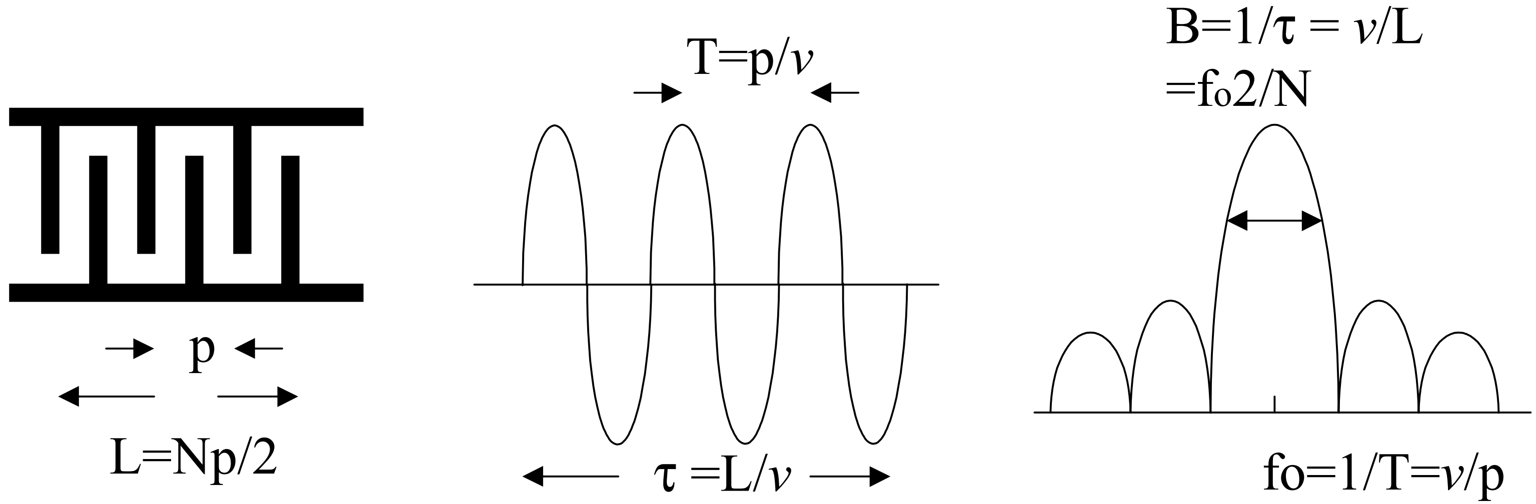


Operating principle:
DC I →change bias H →change resonant f
→ select rf i/p signal frequency →tunable over a wide frequency range about a few GHz
→wide band BPF with Q≈1000
Application:
tunable BPF, oscillator for instrument

4. SAW (surface acoustic wave) filter

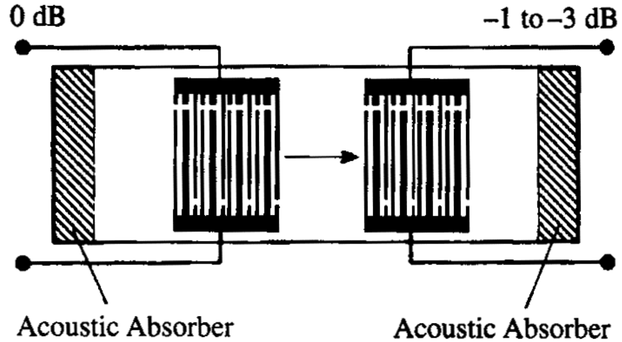


Operating principle:
rf i/p signal frequency →i/p transducer (piezoelectric substrate material, lithium niobate $LiNbO_3$, quartz,...)
→ surface acoustic wave→o/p transducer



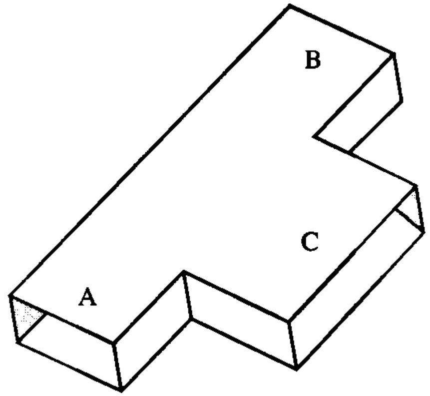
Characteristics: frequency range 30-2000MHz, steep skirt within the passband, IL>15dB(typ.), can be improved using SPUDT (single-phase unidirectional transducer) structure

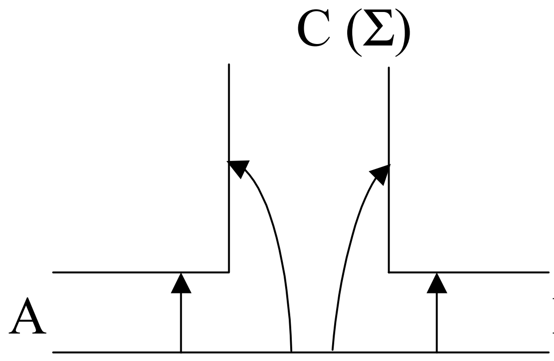
Application: resonator, IF BPF



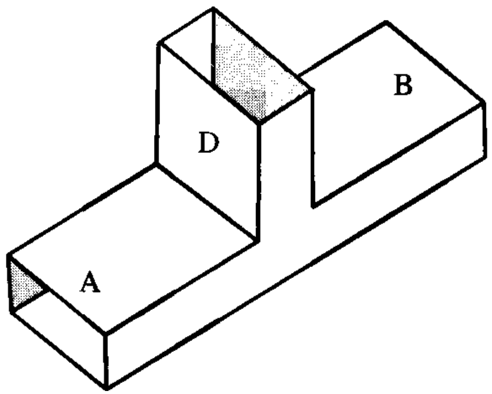
5.12 T-sections

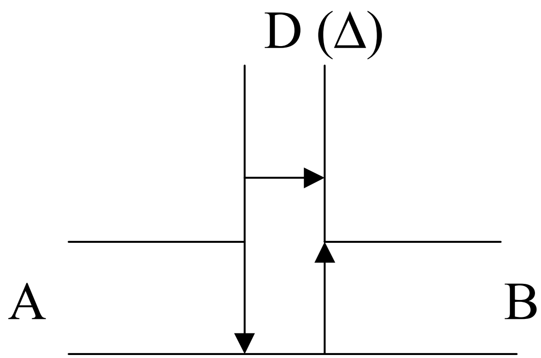
1. H-plane T (shunt T)



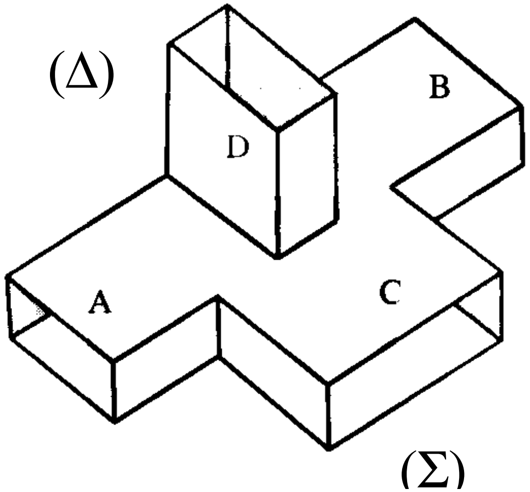


2. E-plane T (series T)

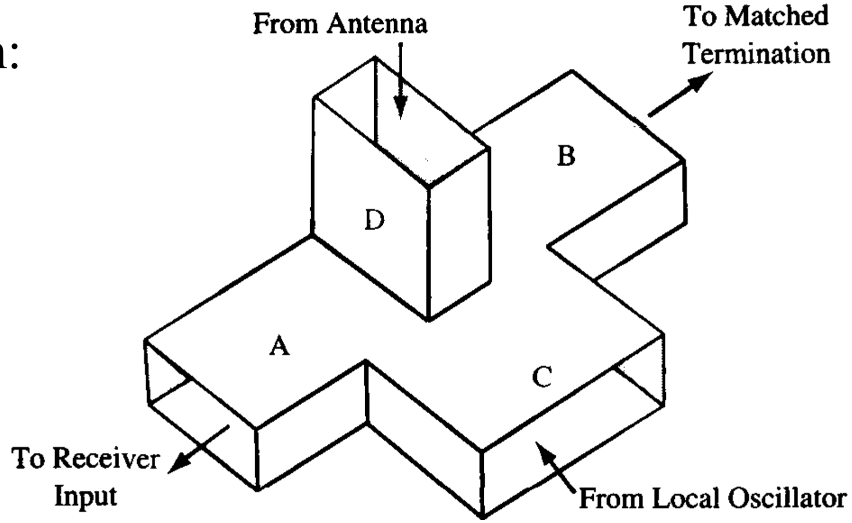




3. Magic T (hybrid T): ports C and D are isolated ports

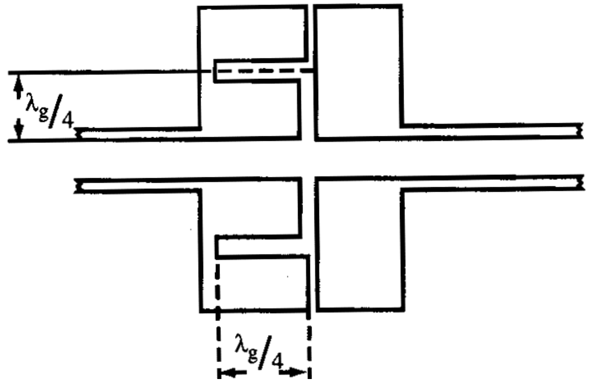


Application:



5.13 Flanges/joints

Types: plane flange has smooth surface
choke flange gives electric short at the joint surface



	IEC		MIL or JAN		Great Britain		EIA	
Frequency Band (GHz)	Plain	Choke	Plain	Choke	Plain	Choke	Plain	Choke
2.60–3.95	PDR 32	CAR 32	UG 53/U	UG 54/U	083-0010	083-0009	CPR 284	—
3.95–5.85	PDR 48	CAR 48	UG 149/U	UG 148/U	083-0041	—	CMR 187	—
5.85–8.20	PDR 70	CAR 70	UG 344/U	UG 343/U	083-0038	083-0037	CMR 137	—
8.20–12.40	PDR 100	CBR 100	UG 39/U	UG 40/U	083-0004	083-0003	CMR 90	—
12.40–18.00	PBR 140	—	UG 419/U	UG 420/U	083-0030	083-0029	—	WR-62
18.00–26.50	PBR 220	CBR 220	UG 595/U	UG 596/U	011-9666	011-9667	—	WR-42
26.50–40.00	PBR 320	CBR 320	UG 599/U	UG 600/U	083-0018	083-0019	—	WR-28
40.00–60.00	PBR 500	—	—	—	083-0026	083-0027	—	WR-19
50.00–75.00	PBR 620	—	UG 385/U	UG 386/U	083-1612	083-1613	—	WR-15

PDR is rectangular pressurized; PBR is square pressurized; CAR is choke circular. CBR is choke square.

<u>Homework #5</u> (due 2 weeks)
Chap.5: problems 1-7