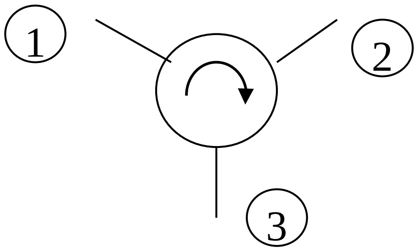
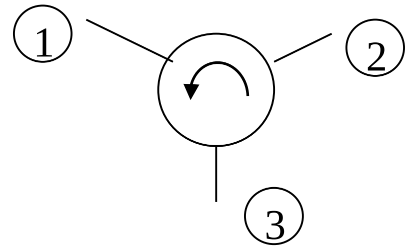
Chapter 9 Theory and Design of Ferrimagnetic Components

9.6 Ferrite circulator



$$\begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$



$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

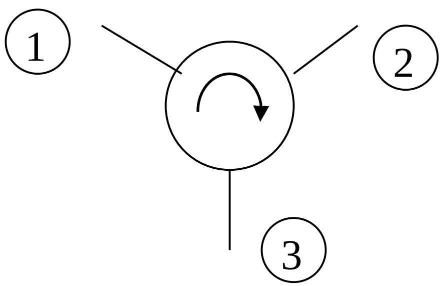
<u>Discussion</u>

1. Circular structure (p.487, Fig.9.22) includes stripline, ferrite disk and bias magnet.
2. A lossless, small mismatched Γ circulator

$$\begin{bmatrix} \Gamma & \Gamma & 1-\Gamma^2 \\ 1-\Gamma^2 & \Gamma & \Gamma \\ \Gamma & 1-\Gamma^2 & \Gamma \end{bmatrix}$$

3. Terminate one port of circulator $\rightarrow$ isolator

(derivation of 2 for a lossless, small mismatched Γ circulator)



$$\begin{bmatrix} \Gamma & \beta & \alpha \\ \alpha & \Gamma & \beta \\ \beta & \alpha & \Gamma \end{bmatrix} \xrightarrow{\text{lossless}} \begin{matrix} |\Gamma|^2 + |\alpha|^2 + |\beta|^2 = 1 \\ \Gamma\beta^* + \alpha\Gamma^* + \beta\alpha^* = 0 \end{matrix}$$

$$\xrightarrow{|\Gamma|<<1,|\alpha|\approx 1,|\beta|<<1} \alpha\Gamma^* + \beta\alpha^* \approx 0 \rightarrow |\Gamma| \approx |\beta|$$

$$\rightarrow 2|\Gamma|^2 + |\alpha|^2 = 1 \rightarrow |\alpha| \approx 1 - |\Gamma|^2$$

$$\Rightarrow \begin{bmatrix} \Gamma & \Gamma & 1-\Gamma^2 \\ 1-\Gamma^2 & \Gamma & \Gamma \\ \Gamma & 1-\Gamma^2 & \Gamma \end{bmatrix}$$

$$\text{isolation:} |S_{23}| \approx |S_{12}| \approx |S_{31}| \approx |\Gamma|$$

Chapter 10 Noise and Nonlinear Distortion

10.1/2 Noise in microwave circuits/Noise figure

noise power, equivalent noise temperature, noise figure of various networks

10.3/4 Nonlinear distortion/Dynamic range

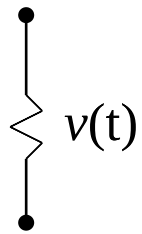
gain compression, third-order intermodulation distortion, 3^{rd}-order intercept point, linear and spurious free dynamic range

10.1/10.2 Noise in microwave circuits/Noise figure

• noise power, equivalent noise temperature, noise figure

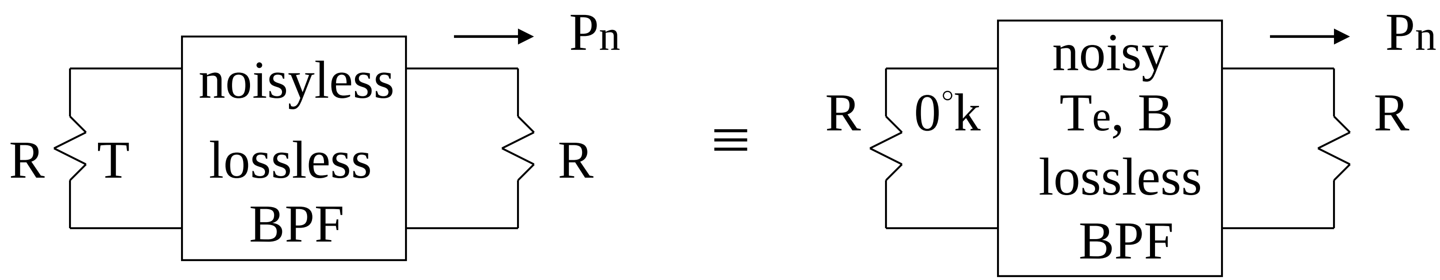
noisy
resistor

R, T°k



rms voltage $v_n = \sqrt{4kTBR}$

at microwave frequencies:white noise source



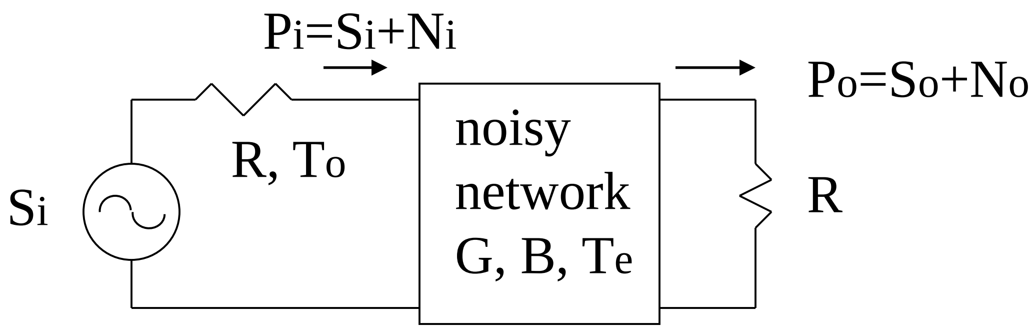
maximum power delivered from the noisy resistor

$$P_n = (\frac{v_n}{2R})^2 R = \frac{4kTBR}{4R^2} R = kTB$$

equivalent noise temperature Te ≡ Pn/kB

excess noise ratio

$$ENR(dB) \equiv 10\log\frac{P_n - P_o}{P_o} = 10\log\frac{T_e - T_o}{T_o}, \quad T_o = 290^o K$$

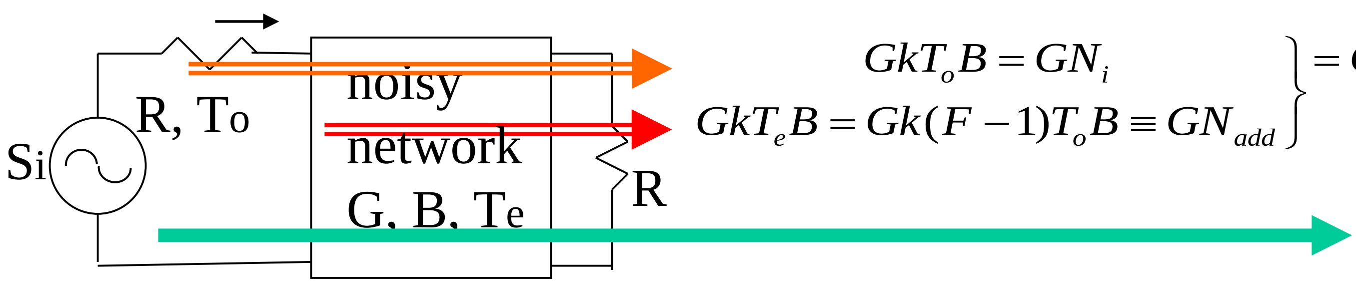


$$S_o = GS_i, N_i = kT_oB, N_o = Gk(T_o + T_e)B$$

$$\text{noise figure } F \equiv \frac{S_i/N_i}{S_o/N_o} = \frac{S_i}{S_o}\frac{N_o}{N_i} = \frac{1}{G}\frac{Gk(T_o+T_e)B}{kT_oB} = 1 + \frac{T_e}{T_o} > 1$$

$$T_e = (F-1)T_o$$

$$N_i = kT_oB$$

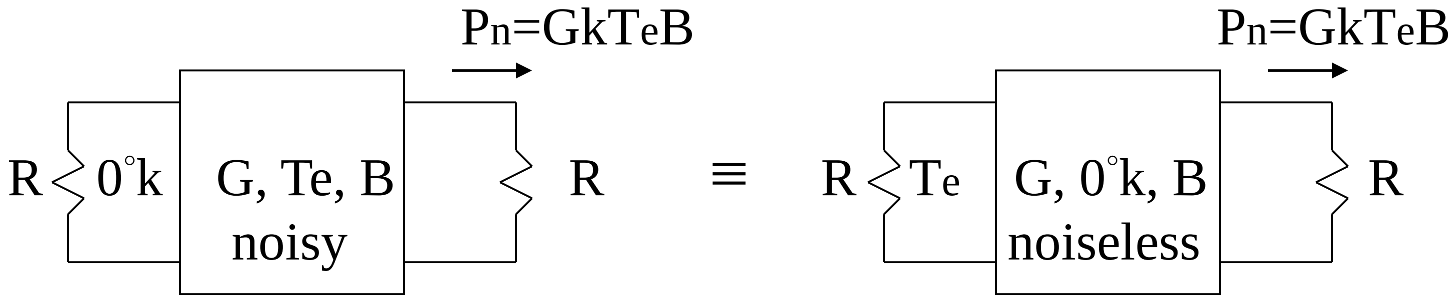


$$\left.\begin{aligned} GkT_oB &= GN_i \\ GkT_eB = Gk(F-1)T_oB &\equiv GN_{add} \end{aligned}\right\} \begin{aligned} &= Gk(T_o+T_e)B \\ &= GkT_oBF \end{aligned} = N_o$$

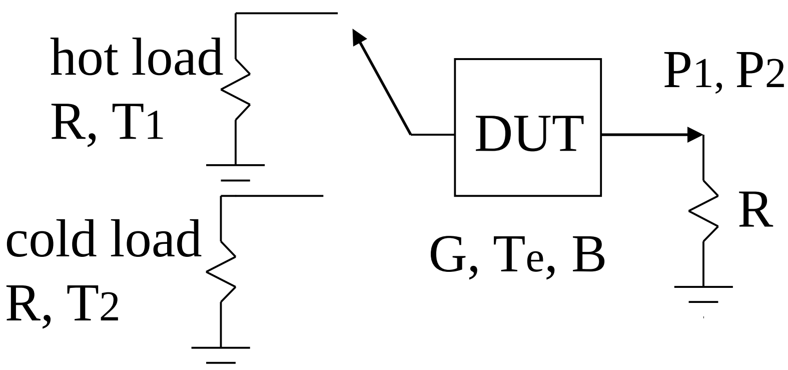
$$GS_i = S_o$$

Discussion

1. noisy amplifier with T_e



2. Y-factor (noise figure, noise temperature) measurement method

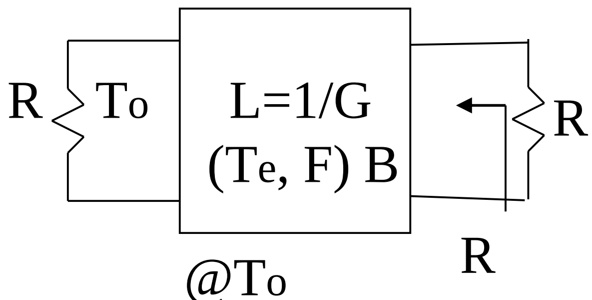


$$Y \equiv \frac{P_1}{P_2} = \frac{Gk(T_1 + T_e)B}{Gk(T_2 + T_e)B} = \frac{T_1 + T_e}{T_2 + T_e}$$

$$\rightarrow T_e = \frac{T_1 - YT_2}{Y - 1}, \quad F = 1 + \frac{T_e}{T_o}$$

3. Ex10.1 X-band amplifier, G=20dB, B=1GHz, gives Y-factor measured results as T_1=290°k, P_1= -62dBm, T_2=77°k, P_2= - 64.7dBm.
   $Y = P_1 - P_2$ = 2.7dB = 1.86 $\rightarrow$ T_e =170°k $\rightarrow$ F =1.585=2dB
   if T_s = 450°k $\rightarrow$ $P_n = k(T_s+T_e)BG$= -60.7dBm

4. F of a passive lossy matched 2-port circuit



$$\begin{pmatrix} N_o = kT_oB = \frac{1}{L}kT_oB + \frac{1}{L}kT_eB \\ \rightarrow T_e = (L-1)T_o, F = L \end{pmatrix}$$

$@T_o$ $\because$ thermal equilibrium $N_o = N_i = kT_oB, S_o = \dfrac{S_i}{L}$

$$F = \frac{S_i/N_i}{S_o/N_o} = \frac{S_i}{S_o}\frac{N_o}{N_i} = L(=1+\frac{T_e}{T_o})$$

$$\rightarrow T_e = (L-1)T_o = \frac{1-G}{G}T_o, N_{add} = kT_eB = (L-1)kBT_o$$

$$\Rightarrow @T,\ T_e = (L-1)T,\ F = 1+\frac{(L-1)T}{T_o}$$

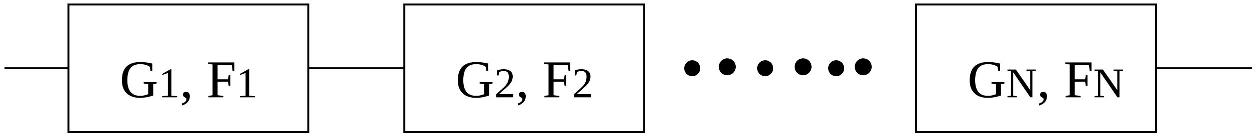
5. Ex. 10.3 a matched lossy Wilkinson power divider (IL=L$_w$) with port 3 connected to a matched load, find its F

$$[S] = \frac{-j}{\sqrt{2L_w}}\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}, L = \frac{1}{|S_{21}|^2} = 2L_w$$

$$T_e = (L-1)T = (2L_w-1)T\ , F = 1+\frac{T_e}{T_o} = 1+(2L_w-1)\frac{T}{T_o}$$

if $L_w = 1$ (lossless), $T = T_o \rightarrow F = 2 = 3dB$

6. F of a cascaded circuit



$$F = \frac{S_i / N_i}{S_o / N_o} = \frac{S_i}{S_o}\frac{N_o}{N_i}$$

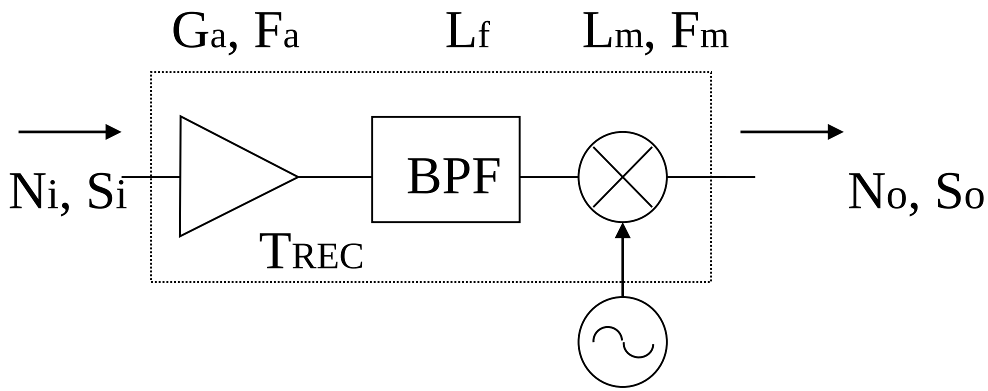
$$= \frac{1}{\prod_{i=1}^{N} G_i} \frac{kT_oB\prod_{i=1}^{N}G_i + k(F_1-1)T_oB\prod_{i=1}^{N}G_i + k(F_2-1)T_oB\prod_{i=2}^{N}G_i + \ldots + k(F_N-1)T_oBG_N}{kT_oB}$$

$$= 1 + (F_1 - 1) + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1G_2} + \ldots + \frac{F_N-1}{G_1 \ldots G_{N-1}}$$

$$= F_1 + \frac{F_2-1}{G_1} + \frac{F_3-1}{G_1G_2} + \ldots + \frac{F_N-1}{G_1 \ldots G_{N-1}}$$

$$T = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1G_2} + \ldots + \frac{T_{eN}}{G_1 \ldots G_{N-1}}$$

7. noise analysis of a microwave receiver



i/p noise ower from antenna $T_A \rightarrow N_i = kT_A B$

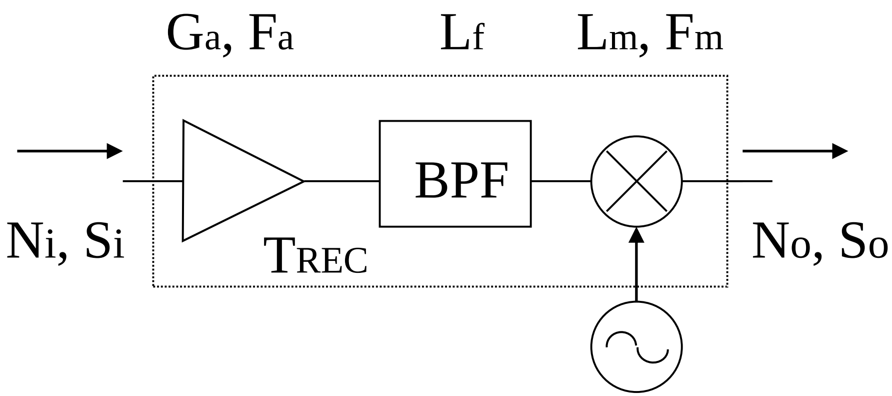
receiver noise $F_{REC} = F_a + \frac{F_f - 1}{G_a} + \frac{F_m - 1}{G_a G_f} \rightarrow T_{REC} = (F_{REC} - 1)T$

o/p signal power $S_o = S_i \frac{G_a G_m}{L_f} = S_i G_{REC}$

o/p noise power $N_o = (N_i + kBT_{REC})G_{REC} = kB(T_A + T_{REC})G_{REC}$

o/p $\frac{S_o}{N_o} = \frac{S_i}{kB(T_A + T_{REC})}$

8. Ex.10.2



$$T_A = 150^o k$$
$$G_a = 10dB = 10, F_a = 2dB = 1.58$$
$$L_f = 1dB = 1.26, G_f = 0.79$$
$$G_m = -3dB = 0.5, F_m = 4dB = 2.51$$
$$B_{IF} = 10MHz, T_o = 290^o k$$

i/p noise power $N_i = kT_A B = 1.38 \times 10^{-23} \times 150 \times 10^7 = 2.07 \times 10^{-14} W = -106.8dBm$

receiver noise figure $F_{REC} = F_a + \dfrac{F_f - 1}{G_a} + \dfrac{F_m - 1}{G_a G_f} = 1.8 = 2.5dB$

receiver noise temperature $T_{REC} = (F_{REC} - 1)T_o = 232^o k$

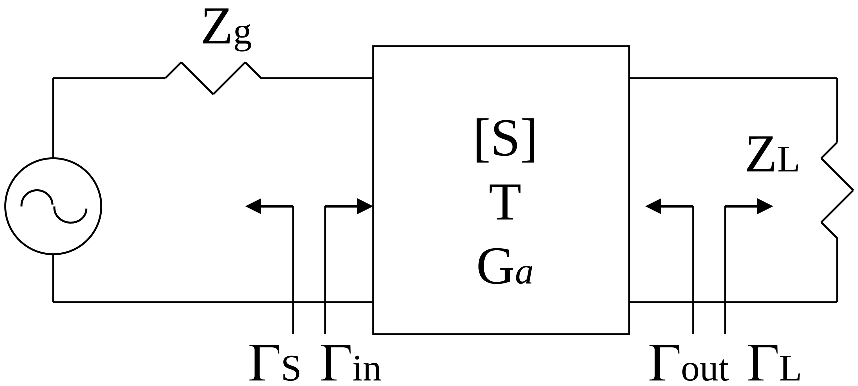
receiver gain $G_{REC} = \dfrac{G_a G_m}{L_f} = 3.95 = 6dB$

o/p noise power $N_o = kB(T_A + T_{REC})G_{REC}$

$$= 1.38 \times 10^{-23} \times 10^7 \times 382 \times 3.95 = 2.08 \times 10^{-13} W = -96.8dBm$$

if $SNR_o = 20dB \xrightarrow{-96.8dBm} S_o = -76.8dBm \xrightarrow{-6dB} S_i = -82.8dBm \rightarrow SNR_i \geq 24dB$

9. F of a passive lossy mismatched ($\Gamma_S \neq 0, \Gamma_{out} \neq 0$) 2-port circuit



$$G_a = \frac{|S_{21}|^2 (1 - |\Gamma_S|^2)}{|1 - S_{11}\Gamma_S|^2 (1 - |\Gamma_{out}|^2)} \quad ..(12.12)$$

$$= |S_{21}|^2, \text{for } \Gamma_S = \Gamma_{out} = 0$$

i/p noise power $N_i = kTB$

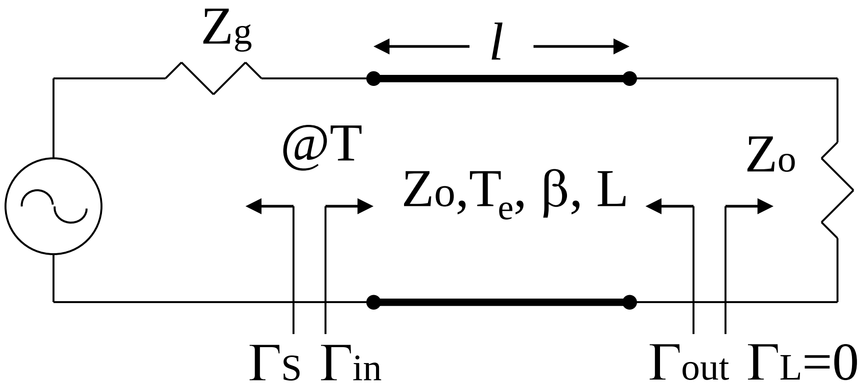
available power gain $G_a \equiv \dfrac{P_{avn}}{P_{avs}} = \dfrac{P_L|_{\Gamma_L = \Gamma_{out}^*}}{P_{in}|_{\Gamma_{in} = \Gamma_S^*}} \equiv \dfrac{1}{L_a} < 1$

available o/p noise power $N_o = G_a(N_i + N_{added}) = G_a k(T + T_e)B$

$= kTB$(thermal equilibrium)

$$\rightarrow T_e = \frac{1 - G_a}{G_a} T = (L_a - 1)T, F = 1 + \frac{T_e}{T_o} = 1 + \frac{1 - G_a}{G_a}\frac{T}{T_o} = 1 + \frac{(L_a - 1)T}{T_o}$$

10. F of a mismatched ($\Gamma_S \neq 0$) lossy line



$$[S] = \begin{bmatrix} 0 & \frac{1}{\sqrt{L}} e^{-j\beta l} \\ \frac{1}{\sqrt{L}} e^{-j\beta l} & 0 \end{bmatrix}$$

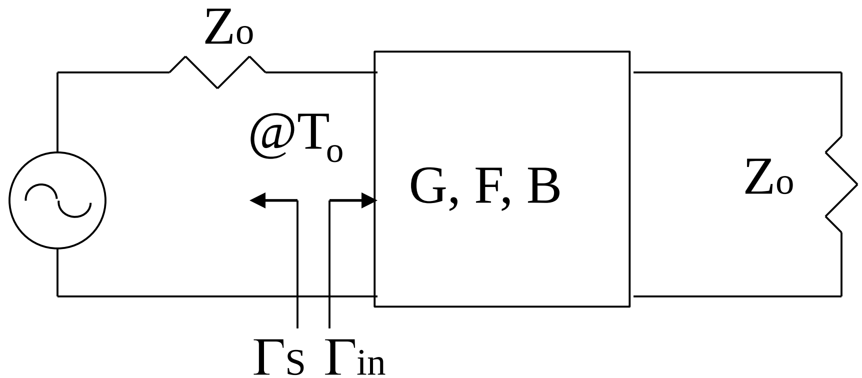
$$\Gamma_S = \frac{Z_g - Z_o}{Z_g + Z_o}$$

$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} = \frac{\Gamma_S}{L} e^{-j2\beta l}$$

$$G_a = \frac{|S_{21}|^2 (1 - |\Gamma_S|^2)}{|1 - S_{11}\Gamma_S|^2 (1 - |\Gamma_{out}|^2)} = \frac{\frac{1}{L}(1 - |\Gamma_S|^2)}{1 - \frac{|\Gamma_S|^2}{L^2}} = \frac{L(1 - |\Gamma_S|^2)}{L^2 - |\Gamma_S|^2} \equiv \frac{1}{L_a}$$

$$\rightarrow T_e = (L_a - 1)T = \frac{(L-1)(L + |\Gamma_S|^2)}{L(1 - |\Gamma_S|^2)} T > (L-1)T\Big|_{\Gamma_S = 0}, F = 1 + \frac{(L_a - 1)T}{T_o}$$

11. F of a mismatched ($\Gamma_{in} \neq 0$) amplifier



$$N_i = kT_o B$$

$$N_o = kT_o GB(1-|\Gamma_{in}|^2) + kT_o (F-1)GB = kT_o GB(F-|\Gamma_{in}|^2)$$

$$S_o = G(1-|\Gamma_{in}|^2)S_i$$

$$\rightarrow F_m = \frac{S_i / N_i}{S_o / N_o} = \frac{S_i N_o}{S_o N_i} = \frac{S_i}{G(1-|\Gamma_{in}|^2)S_i} \frac{kT_o GB(F-|\Gamma_{in}|^2)}{kT_o B} = \frac{F-|\Gamma_{in}|^2}{1-|\Gamma_{in}|^2}$$

$$= 1 + \frac{F-1}{1-|\Gamma_{in}|^2}, |\Gamma_{in}| = 0, F_m = F$$

10.3/4 Nonlinear distortion/Dynamic range

• gain compression

$$v_o = a_o + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots$$

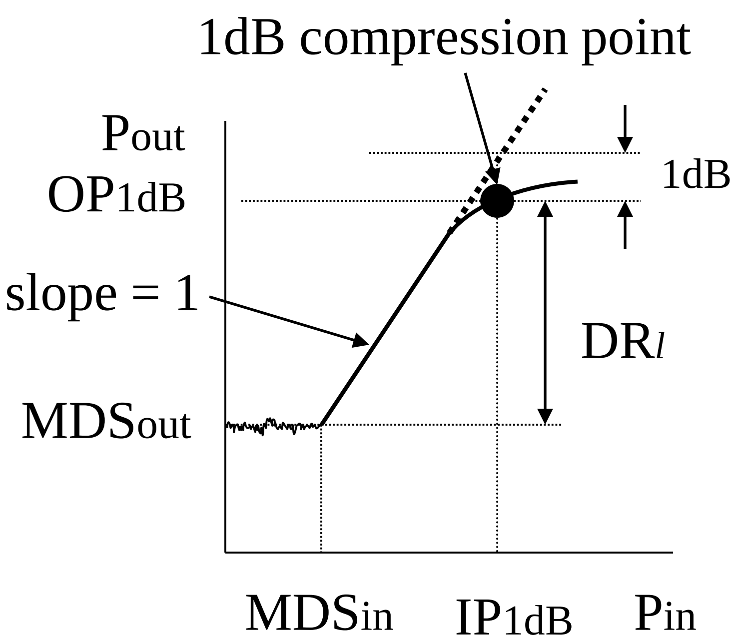
$OP_{1dB} = IP_{1dB} + G - 1dB$

linear dynamic range of an amplifier with gain G

MDS_{in} (dBm) = kTB+F (+3dB)

MDS_{out} (dBm) = kTB+F+G (+3dB)

DR_l (dB) = OP_{1dB} - MDS_{out}



"dB-plot"

- intermodulation distortion

$$v_o = a_o + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots$$

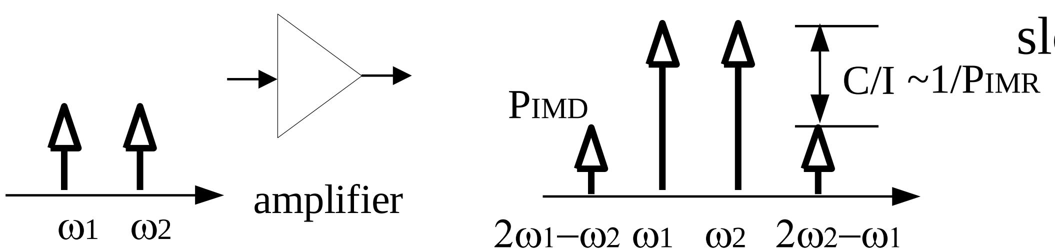
$v_i^2 : w_1, w_2 \rightarrow 2w_1, 2w_2, w_1 - w_2, w_1 + w_2$ 2nd-order products

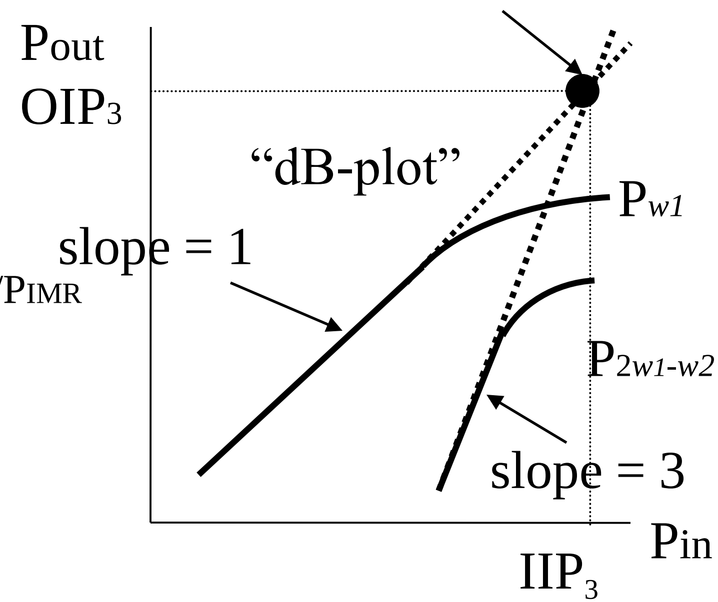
$v_i^3 : w_1, w_2 \rightarrow 3w_1, 3w_2, 2w_1 - w_2, 2w_1 + w_2, 2w_2 - w_1, 2w_2 + w_1$ 3rd- order products

$2w_1 - w_2, 2w_2 - w_1$: 3rd- order intermodulation distortion (IMD3)

3rd-order intercept point (IP3)

$OIP_3(dB) = G + IIP_3$





Discussion

1. device nonlinearity effect

If $v_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3$

single tone input $v_i = A\cos w_1 t \quad \Rightarrow v_o\big|_{w_1} = (a_1 A + \frac{3}{4} a_3 A^3)\cos w_1 t$

$\rightarrow$ voltage gain@w_1 $\quad G_v = a_1 + \frac{3}{4} a_3 A^2$

two tone input $v_i = A(\cos w_1 t + \cos w_2 t)$

$$\Rightarrow v_o\big|_{2w_1 - w_2} = \frac{3}{4} a_3 A^3 \cos(2w_1 - w_2)t$$

at third-order intercept point $a_1 A = \frac{3}{4} a_3 A^3 \rightarrow A^2 = \frac{4}{3}\frac{a_1}{a_3}$

$$\rightarrow OIP_3 = \frac{1}{2}\frac{(a_1 A)^2}{R} = \frac{2}{3}\frac{a_1^3}{a_3 R}, P_{2w_1 - w_2}(\equiv P_{IMD}) = \frac{1}{2}\frac{(\frac{3}{4}a_3 A^3)^2}{R} = \frac{9}{32}\frac{a_3^2 A^6}{R}$$

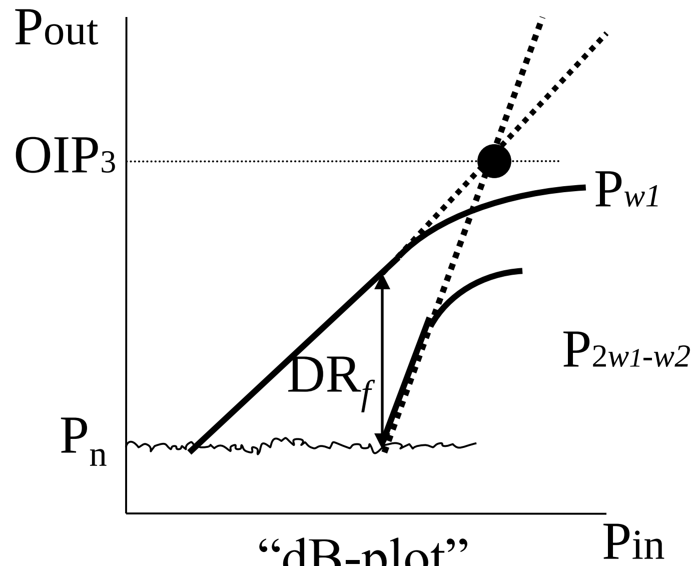
$$\frac{P_{w_1}^3}{OIP_3^2} = \frac{[\frac{1}{2}\frac{(a_1 A)^2}{R}]^3}{[\frac{2}{3}\frac{a_1^3}{k_3 R}]^2} = \frac{9}{32}\frac{a_3^2 A^6}{R} = P_{2w_1 - w_2} \Rightarrow 3P_{w_1} - 2OIP_3 = P_{2w_1 - w_2}(dBm)$$

2. spurious-free dynamic range

$$DR_f \equiv \left.\frac{P_{w_1}}{P_{2w_1-w_2}}\right|_{P_{2w_1-w_2}=P_n}$$

$$= \left.\frac{P_{2w_1-w_2}^{\frac{1}{3}} OIP_3^{\frac{2}{3}}}{P_{2w_1-w_2}}\right|_{P_{2w_1-w_2}=P_n} = \left(\frac{OIP_3}{P_n}\right)^{\frac{2}{3}}$$

$$DR_f(dB) = \frac{2}{3}(OIP_3 - P_n)$$



"dB-plot"

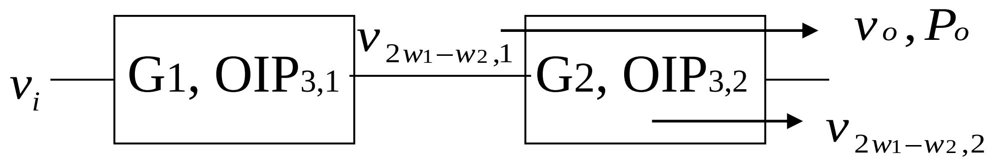
3. Ex. 10.5 A receiver with F=7dB, OP_{1dB}=25dBm, G=40dB, OIP_3=35dBm, B=100MHz, i/p antenna noise temperature T_A=150°k, desired SNR_o=10dB, find DR_l and DR_f

o/p noise power $P_n = GkB[T_A + (F-1)T_o] = 10^4 \times 1.38 \times 10^{-23} \times 10^8 \times [150 + (5-1) \times 290] = -47.4dBm$

$DR_l = OP_{1dB} - P_n = 25 - (-47.4) = 72.4dB$

$DR_f = \frac{2}{3}(OIP_3 - P_n) = 55dB, or\ \frac{2}{3}(OIP_3 - P_n) - SNR_o = 45dB$

4. Cascaded two-port circuits



$$P_o = P_i G_1 G_2 = P_{o,1} G_2 (@ \text{ fundamental frequency } w_o)$$

$$\frac{P_o^3}{OIP_3^2} = P_{2w_1-w_2} \rightarrow v_{2w_1-w_2} = \sqrt{P_{2w_1-w_2} Z_o} = \frac{\sqrt{P_o^3 Z_o}}{OIP_3}$$

worst case, two intermods $@2w_1 - w_2$ add in phase $\rightarrow$

$$v_{2w_1-w_2} = v_{2w_1-w_2,1}\sqrt{G_2} + v_{2w_1-w_2,2} = \frac{\sqrt{G_2 P_{o,1}^3 Z_o}}{OIP_{3,1}} + \frac{\sqrt{P_o^3 Z_o}}{OIP_{3,2}} = \frac{\sqrt{G_2 (P_o^3 / G_2^3) Z_o}}{OIP_{3,1}} + \frac{\sqrt{P_o^3 Z_o}}{OIP_{3,2}}$$

$$= \left(\frac{1}{G_2 OIP_{3,1}} + \frac{1}{OIP_{3,2}}\right)\sqrt{P_o^3 Z_o}$$

$$P_{2w_1-w_2} = \frac{v_{2w_1-w_2}^2}{Z_o} = \left(\frac{1}{G_2 OIP_{3,1}} + \frac{1}{OIP_{3,2}}\right)^2 P_o^3 = \frac{P_o^3}{OIP_3^2}$$

$$\Rightarrow \frac{1}{OIP_3} = \frac{1}{G_2 OIP_{3,1}} + \frac{1}{OIP_{3,2}}$$

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5. Ex. 10.4 An LNA with G_1=20dB and $OIP_{3,1}$=22dBm, a mixer with G_2=-6dB and $IIP_{3,2}$=13dBm, find the cascaded P_{IP3}

$$G_1 = 100, G_2 = 0.25, OIP_{3,1} = 22dBm = 158mW, OIP_{3,2} = 13-6 = 7dBm = 5mW$$

$$\frac{1}{OIP_3} = \frac{1}{G_2 OIP_{3,1}} + \frac{1}{OIP_{3,2}} = \frac{1}{0.25\times 158} + \frac{1}{5} \rightarrow OIP_3 = 4.4mW = 6.4dBm$$

(case 2, interchange LNA and mixer, prob.10.15)

$$G_1 = 0.25, OIP_{3,1} = 13-6 = 7dBm = 5mW$$

$$G_2 = 100, OIP_{3,2} = 22dBm = 158mW$$

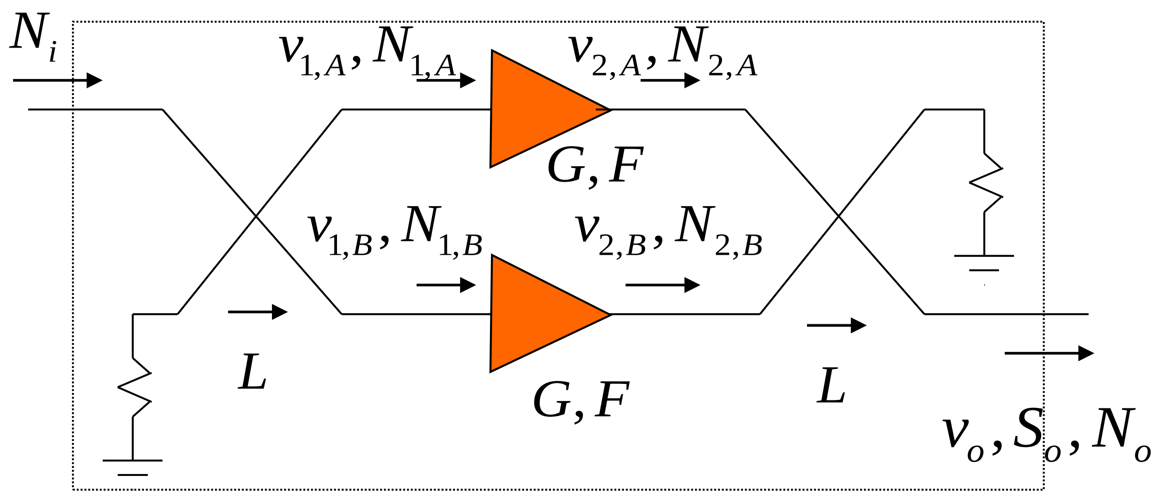
$$\frac{1}{OIP_3} = \frac{1}{G_2 OIP_{3,1}} + \frac{1}{OIP_{3,2}} = \frac{1}{100\times 5} + \frac{1}{158} \rightarrow OIP_3 = 120mW = 20.8dBm$$

6. OIP_3 of a cascaded circuit

$$\frac{1}{OIP_3} = \frac{1}{G_n \ldots G_2 OIP_{3,1}} + \frac{1}{G_n \ldots G_3 OIP_{3,2}} + \ldots. + \frac{1}{OIP_{3,n}}$$

Solved problems: Prob. 10.11 F of a balanced amplifier

$$\frac{1}{\sqrt{2L}}\begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$

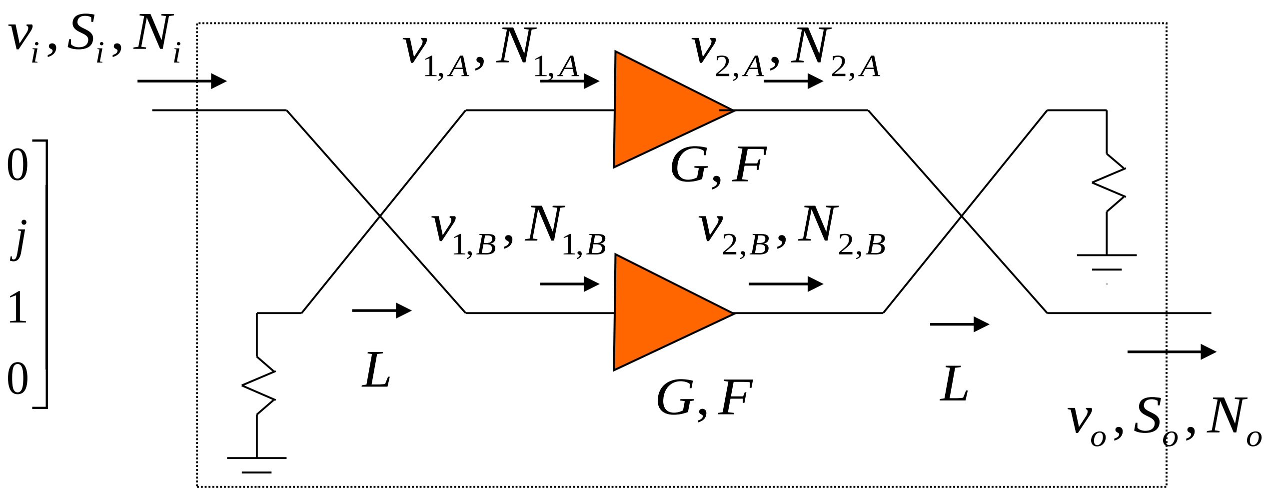


$$S_i = \frac{1}{2}v_i^2, v_{1,A} = v_i\sqrt{\frac{1}{2L}}, v_{1,B} = jv_i\sqrt{\frac{1}{2L}} \rightarrow v_{2,A} = v_i\sqrt{\frac{G}{2L}}, v_{2,B} = jv_i\sqrt{\frac{G}{2L}}$$

$$v_o = j\sqrt{\frac{1}{2L}}v_{2,A} + \sqrt{\frac{1}{2L}}v_{2,B} = \frac{jv_i\sqrt{G}}{2L} + \frac{jv_i\sqrt{G}}{2L} = \frac{jv_i\sqrt{G}}{L}$$

$$S_o = \frac{1}{2}v_o^2 = \frac{1}{2}v_i^2\frac{G}{L^2} = \frac{G}{L^2}S_i$$

$$\frac{1}{\sqrt{2L}}\begin{bmatrix} 0 & 1 & j & 0 \\ 1 & 0 & 0 & j \\ j & 0 & 0 & 1 \\ 0 & j & 1 & 0 \end{bmatrix}$$



$\because$ thermal equilibrium @T_o $\rightarrow N_{1,A} = N_{1,B} = kT_oB$

$$N_{2,A} = N_{2,B} = kT_oBG + kT_o(F-1)BG = kT_oBGF$$

$$N_o = \frac{1}{2L}N_{2,A} + \frac{1}{2L}N_{2,B} + \frac{1}{L}kT_eB = \frac{1}{L}kT_oBGF + (1-\frac{1}{L})kT_oB = kT_oB(\frac{GF}{L} + 1 - \frac{1}{L}) = kT_oB\frac{GF+L-1}{L}$$

$\because$ coupler $F = L, T_e = (F-1)T_o = (L-1)T_o \rightarrow \frac{1}{L}N_{add} = \frac{1}{L}kT_eB = \frac{1}{L}(L-1)kT_oB = (1-\frac{1}{L})kT_oB$

$$F_{BA} = \frac{S_i/N_i}{S_o/N_o} = \frac{S_iN_o}{S_oN_i} = \frac{L^2}{G}\frac{GF+L-1}{L} = LF + \frac{L}{G}(L-1) \rightarrow F_{BA} = F, \text{for } L=1$$

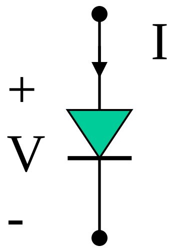
ADS examples: Ch10_prj

Chapter 11 Active RF and Microwave Devices

11.1 Diodes and diode circuits
Schottky diode, PIN diode, varactor diode
11.2/3 Bipolar junction transistors/Field effect transistors
BJT, MESFET
11.4 Microwave integrated circuits
HMIC, MMIC
11.5 Microwave tubes

11.1 Diodes and diode circuits

- Diode



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

DC I-V characteristics

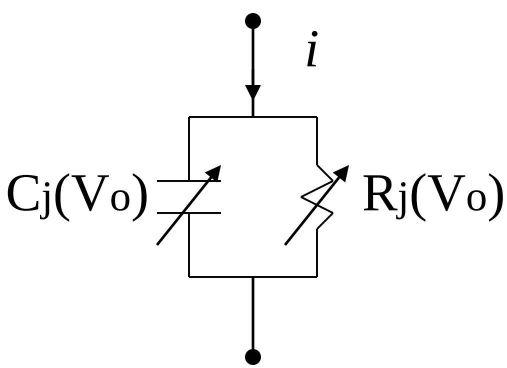
small signal approximation $\quad V = V_o + v$

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

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

$$= I_o + i$$

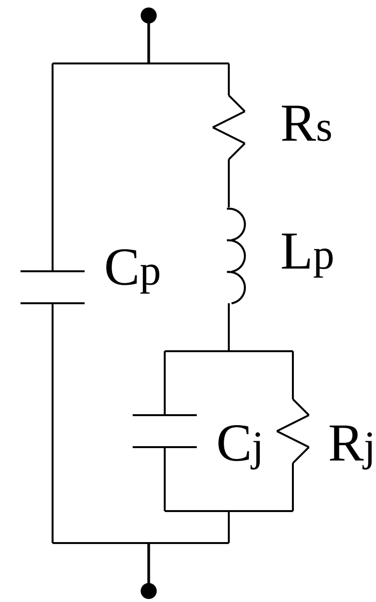
$$G'_d = \alpha G_d$$



AC model

Rj: junction resistance = 1/G*d*

Cj: junction capacitance



applications: detector, mixer,...

Discussion

1. square-law detector

$$v(t) = V_o + v_o \cos w_o t$$

$$i(t) = I_o + v_o G_d \cos w_o t + \frac{v_o^2}{2} G'_d \cos^2 w_o t$$

$$= I_o + \frac{v_o^2}{4} G'_d + v_o G_d \cos w_o t + \frac{v_o^2}{4} G'_d \cos 2 w_o t$$

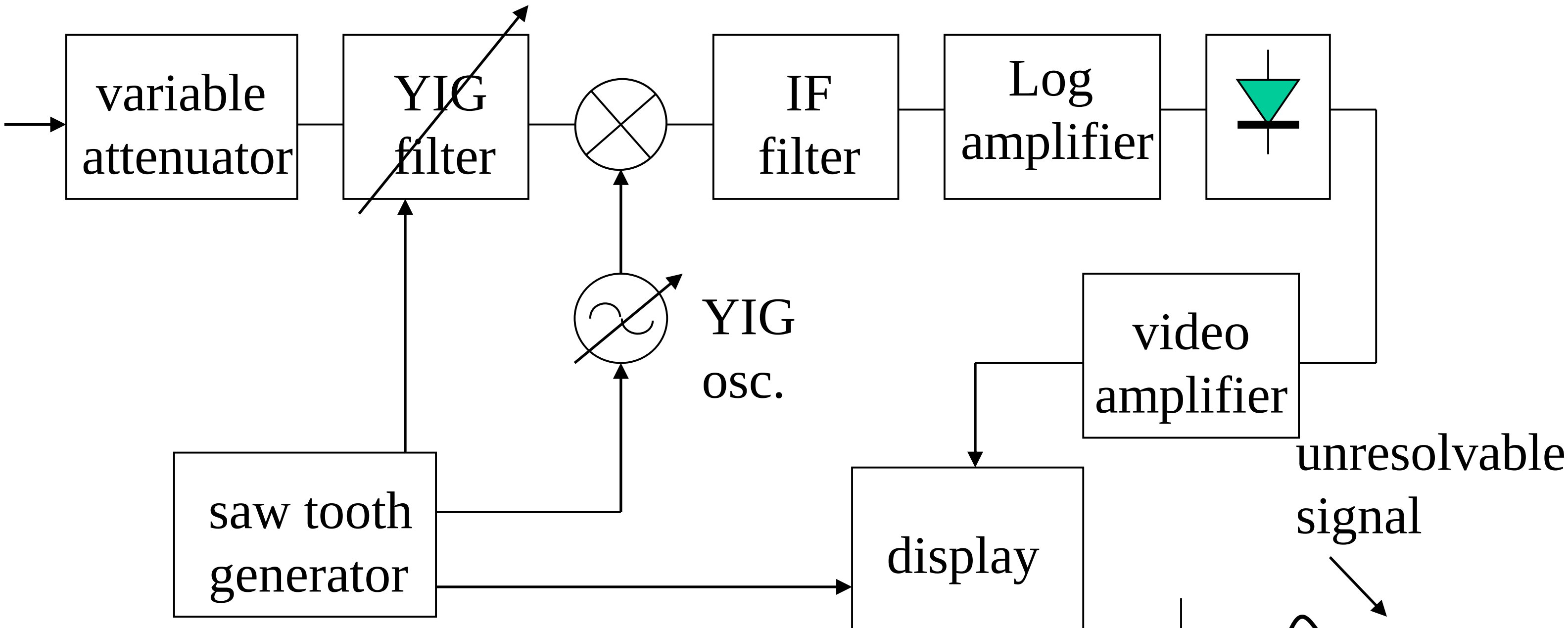
current sensitivity $\beta_i \equiv \frac{\triangle I_{dc}}{P_{in}} = \frac{\frac{v_o^2}{4} G'_d}{\frac{v_o^2}{2} G_d} = \frac{G'_d}{2G_d}$, voltage sensitivity $\beta_v = \beta_i R_j$

AM demodulation

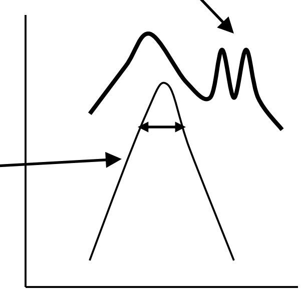
$$v(t) = v_o [1 + m(t) \cos w_m t] \cos w_o t$$

$$i(t) = v G_d + \frac{v^2}{2} G'_d = v G_d + \frac{v_o^2}{4} G'_d [\underbrace{2m(t) \cos w_m t}_{\propto P_{in}} + \ldots]$$

2. spectrum analyzer



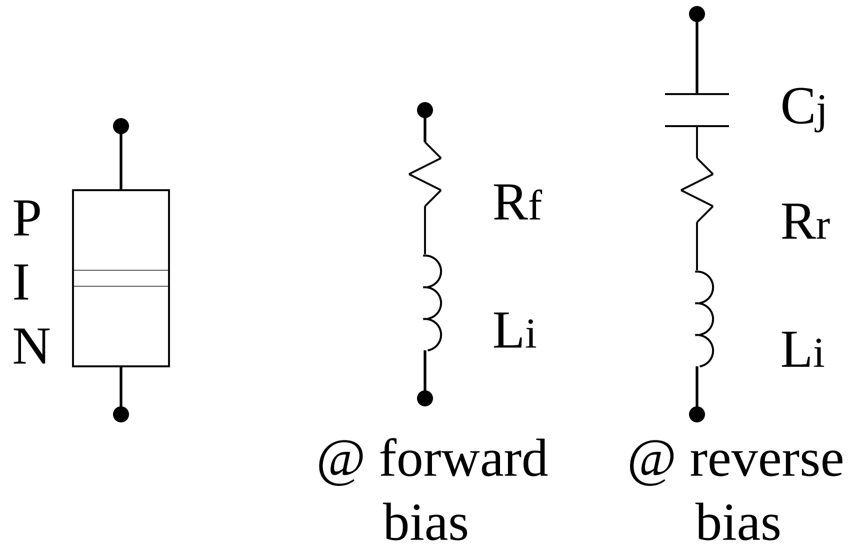
unresolvable signal



IF filter bandwidth ⇒ spectrum resolution
(resolution bandwidth)

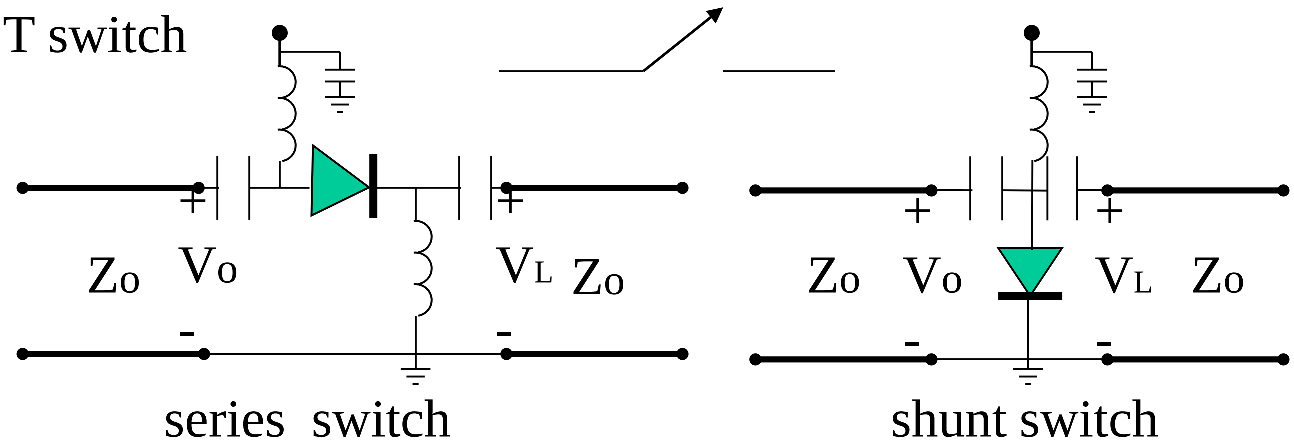
swept frequency range

3. PIN diode



applications: microwave switch, pulse modulator, control elements for phase shifter and attenuator,...

4. SPST switch

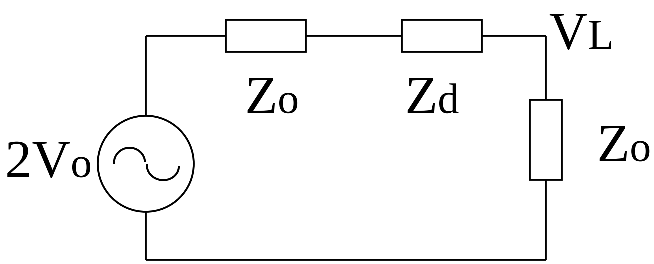


$$IL \equiv -20\log\left|\frac{V_L}{V_o}\right|$$

$$IL = -20\log\left|\frac{2Z_o}{2Z_o + Z_d}\right| \qquad IL = -20\log\left|\frac{2Z_d}{2Z_d + Z_o}\right|$$

$$Z_d = \begin{cases} R_f + jwL_i & \text{forward bias} \\ R_r + jwL_i + \dfrac{1}{jwC_j} & \text{reverse bias} \end{cases}$$

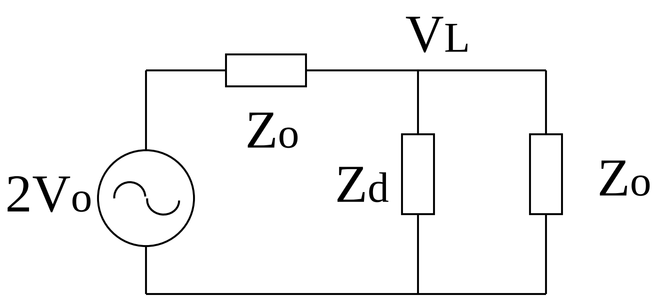
(*derivation*)



series switch

$$V_L = 2V_o \frac{Z_o}{2Z_o + Z_d} = V_o \frac{2Z_o}{2Z_o + Z_d}$$

$$IL \equiv -20\log\left|\frac{V_L}{V_o}\right| = -20\log\left|\frac{2Z_o}{2Z_o + Z_d}\right|$$



shunt switch

$$V_L = 2V_o \frac{Z_o // Z_d}{Z_o + Z_o // Z_d} = V_o \frac{\frac{Z_o Z_d}{Z_o + Z_d}}{Z_o + \frac{Z_o Z_d}{Z_o + Z_d}}$$

$$= V_o \frac{2Z_d}{2Z_d + Z_o}$$

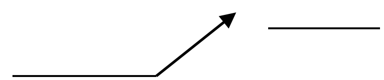
$$IL \equiv -20\log\left|\frac{V_L}{V_o}\right| = -20\log\left|\frac{2Z_d}{2Z_d + Z_o}\right|$$

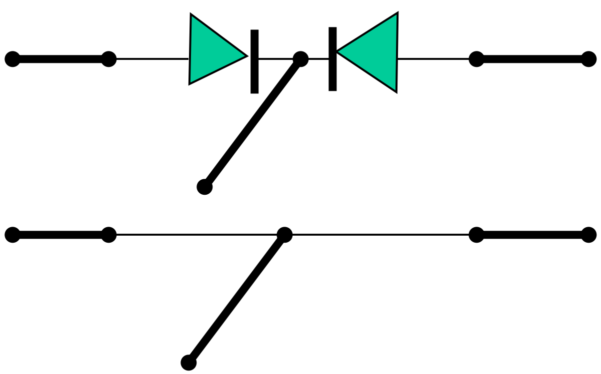
5. Ex.11.1 C_j=0.5pF, L_i=0.5nH, R_r=2Ω, R_f=1.5Ω, f=1.8GHz, Z_o=50Ω

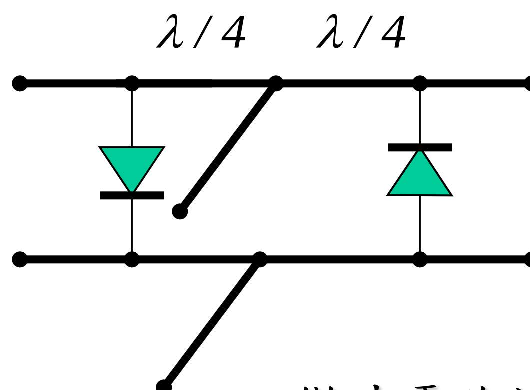
$$Z_d = \begin{cases} 1.5+j5.6\Omega & \text{forward bias} \\ 2.0 - j171.2\Omega & \text{reverse bias} \end{cases}$$

$$\text{series switch } IL = \begin{cases} 0.14dB & \text{ON} \\ 6dB & \text{OFF} \end{cases} \quad \text{shunt switch } IL = \begin{cases} 0.11dB & \text{ON} \\ 13.3dB & \text{OFF} \end{cases}$$

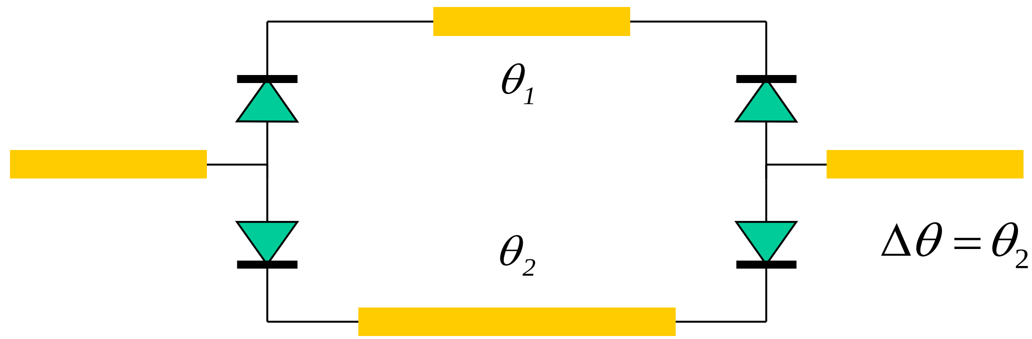
6. SP2T switch







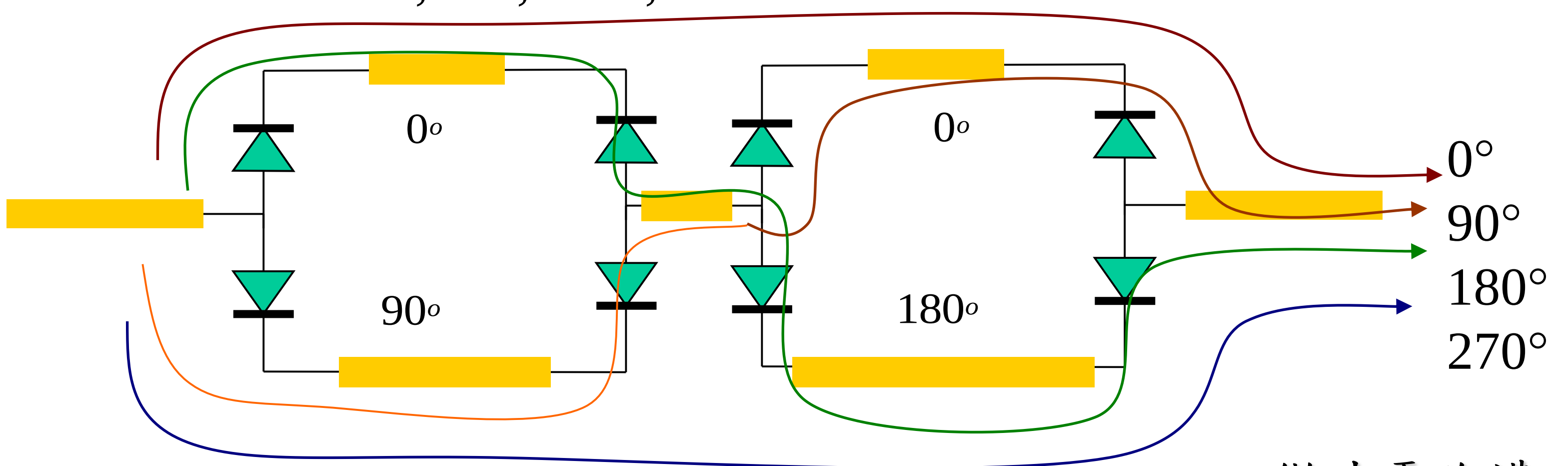
7. switched-line phase shifter



$$\Delta\theta = \theta_2 - \theta_1 = \beta(l_2 - l_1)$$

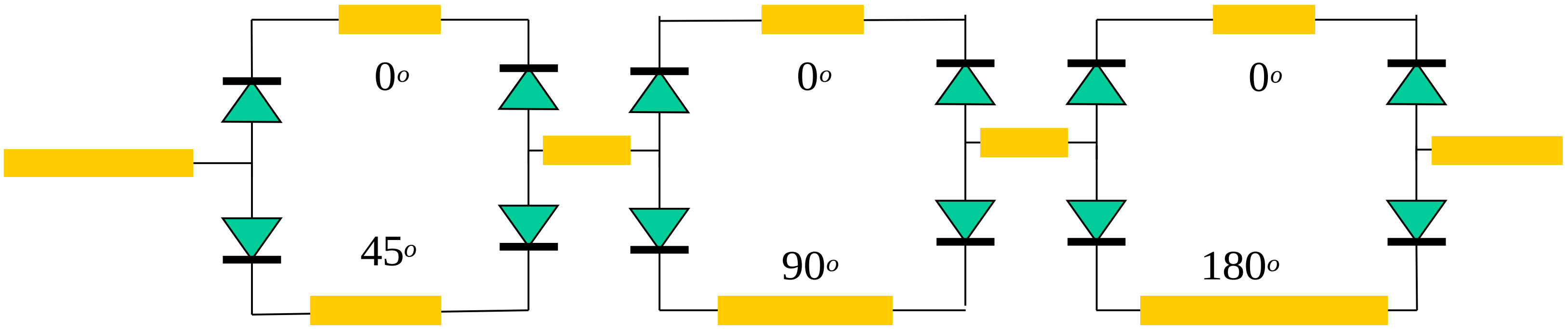
8. 2 bit phase shifter 90°, 180°

$2^2 = 4 \rightarrow 0°, 90°, 180°, 270°$



3 bit phase shifter 45°, 90°, 180°

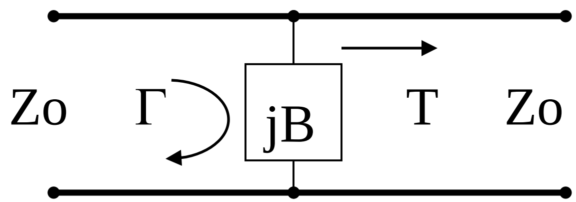
$2^3=8 \rightarrow$ 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°



4 bit phase shifter 22.5°, 45°, 90°, 180°

$2^4=16 \rightarrow$ 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°,180°, 202.5°, 225°, 247.5°, 270°, 292.5°, 315°, 337.5°

9. load-line phase shifter



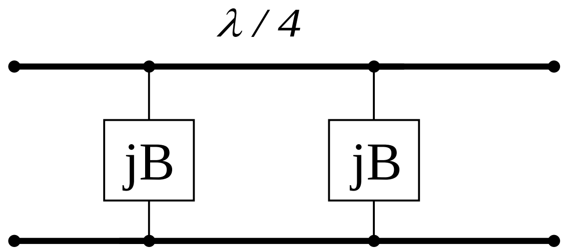
$$\Gamma = \frac{-jb}{2+jb}, T = 1+\Gamma = \frac{2}{2+jb}$$

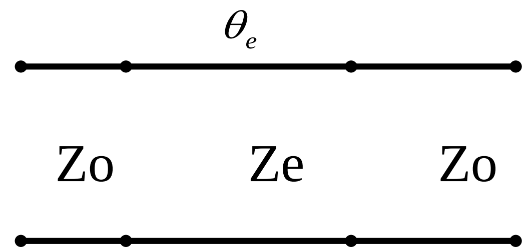
$$b = BZ_o, \angle T = -\tan^{-1}\frac{b}{2}$$

(*derivation*)

$$Z_L = Z_o // \frac{1}{jB} = \frac{1}{\frac{1}{Z_o}+jB} = \frac{Z_o}{1+jBZ_o}, \frac{Z_L}{Z_o} = \frac{1}{1+jb}, b = BZ_o$$

$$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o} = \frac{Z_L / Z_o - 1}{Z_L / Z_o + 1} = \frac{\frac{1}{1+jb}-1}{\frac{1}{1+jb}+1} = \frac{-jb}{2+jb}$$



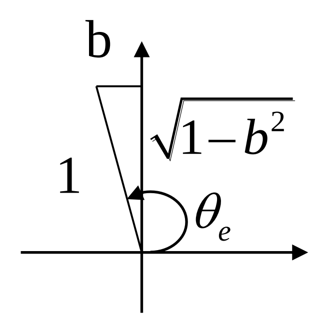


$$(\text{left})\ \begin{bmatrix} 1 & 0 \\ jB & 0 \end{bmatrix}\begin{bmatrix} 0 & jZ_o \\ \dfrac{j}{Z_o} & 0 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ jB & 0 \end{bmatrix}=\begin{bmatrix} -BZ_o & jZ_o \\ j(\dfrac{1}{Z_o}-B^2Z_o) & -BZ_o \end{bmatrix}$$

$$(\text{right})\begin{bmatrix} \cos\theta_e & jZ_e\sin\theta_e \\ \dfrac{j\sin\theta_e}{Z_e} & \cos\theta_e \end{bmatrix}$$

$$\cos\theta_e = -BZ_o \equiv -b \qquad \theta_e \approx \frac{\pi}{2}+b$$

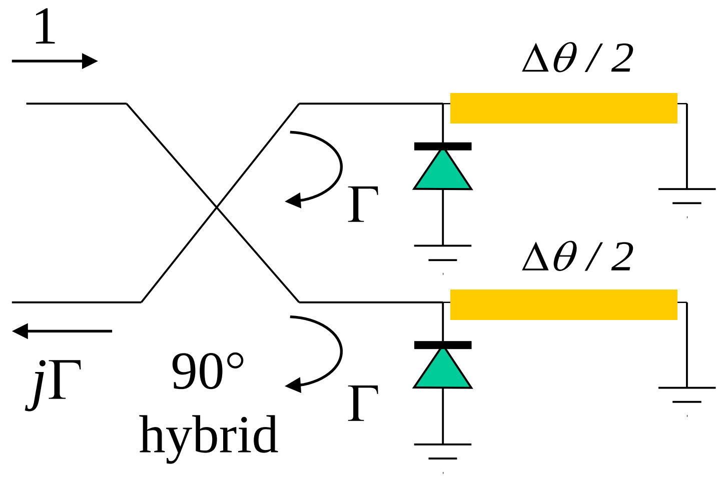
$$\Rightarrow Z_e = \frac{Z_o}{\sin\theta_e} = \frac{Z_o}{\sqrt{1-b^2}} \xrightarrow[\text{small } b]{} Z_e \approx Z_o(1+\frac{b}{2})$$



10. reflection-type phase shifter

diode ON, $\Gamma = e^{j\theta}$

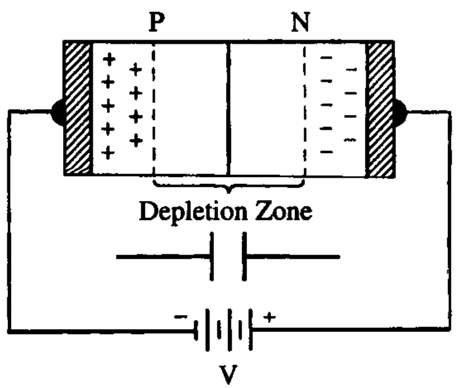
diode OFF, $\Gamma = e^{j(\theta+\Delta\theta)}$

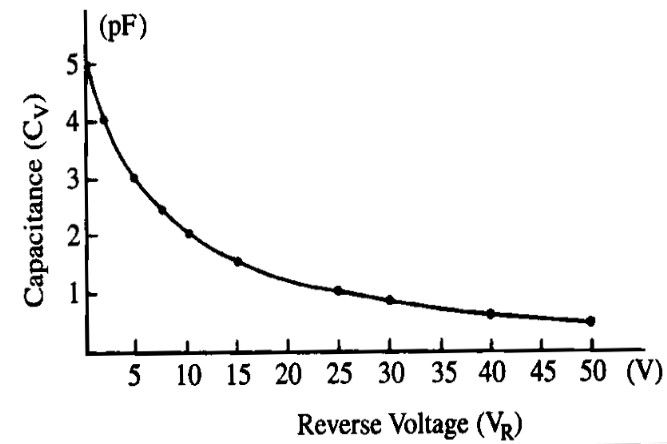


$$\frac{1}{\sqrt{2}}\begin{bmatrix}0 & 1 & j & 0\\ 1 & 0 & 0 & j\\ j & 0 & 0 & 1\\ 0 & j & 1 & 0\end{bmatrix}\begin{bmatrix}1\\0\\0\\0\end{bmatrix}=\begin{bmatrix}0\\ \frac{1}{\sqrt{2}}\\ \frac{j}{\sqrt{2}}\\ 0\end{bmatrix}, \frac{1}{\sqrt{2}}\begin{bmatrix}0 & 1 & j & 0\\ 1 & 0 & 0 & j\\ j & 0 & 0 & 1\\ 0 & j & 1 & 0\end{bmatrix}\begin{bmatrix}0\\ \frac{\Gamma}{\sqrt{2}}\\ \frac{j\Gamma}{\sqrt{2}}\\ 0\end{bmatrix}=\begin{bmatrix}0\\0\\0\\j\Gamma\end{bmatrix}$$

11. varactor diode

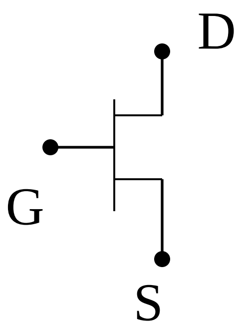
applications: VCO, frequency multiplier

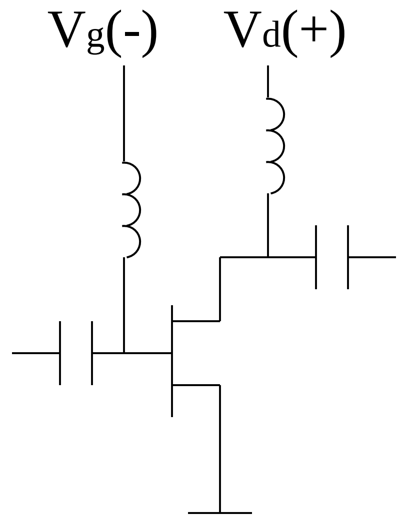


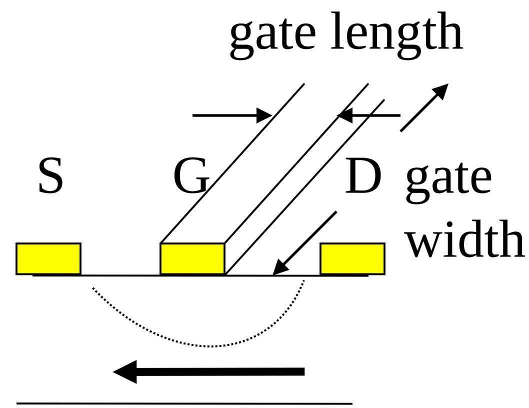


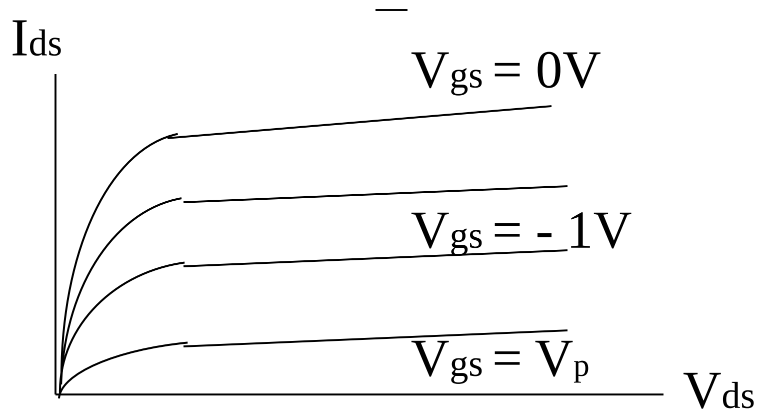
10.2/3 Bipolar junction transistors/Field effect transistors

- microwave FET (depletion type)

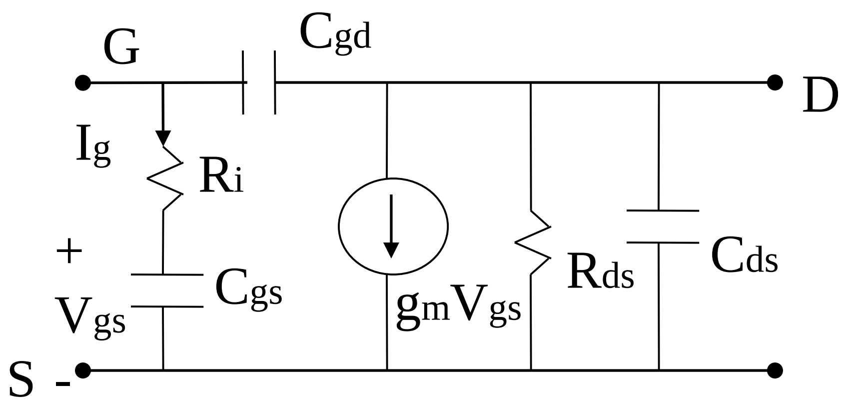


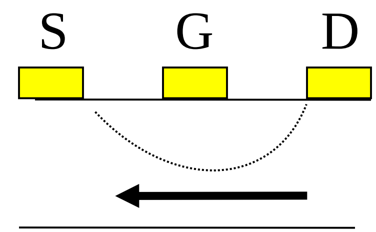






small-signal equivalent circuit





gate length $\downarrow \Rightarrow$ f $\uparrow$

gate width $\uparrow \Rightarrow$ power $\uparrow$

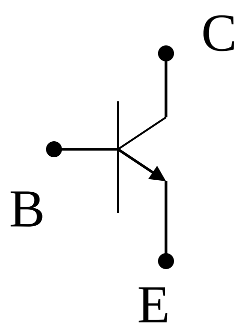
short circuit current gain

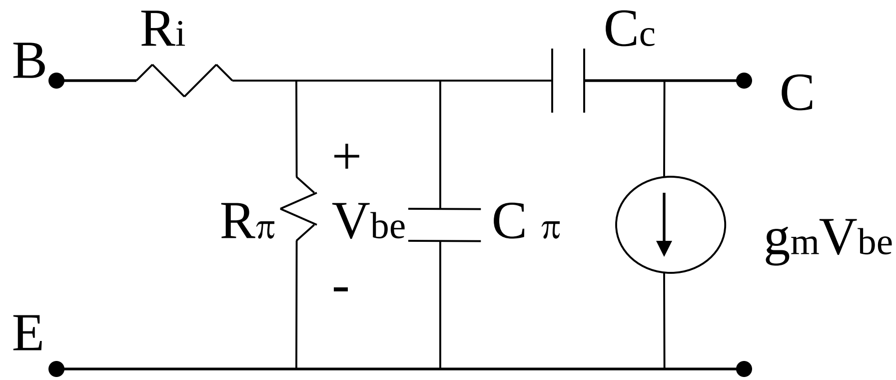
$$G_i^{SC} = \left|\frac{I_d}{I_g}\right| = \left|\frac{g_m V_{gs}}{I_g}\right| = \frac{g_m}{wC_{gs}}$$

$$G_i^{SC} = 1 @ f_T \quad \rightarrow \quad \text{cut off frequency} \quad f_T = \frac{g_m}{2\pi C_{gs}}$$

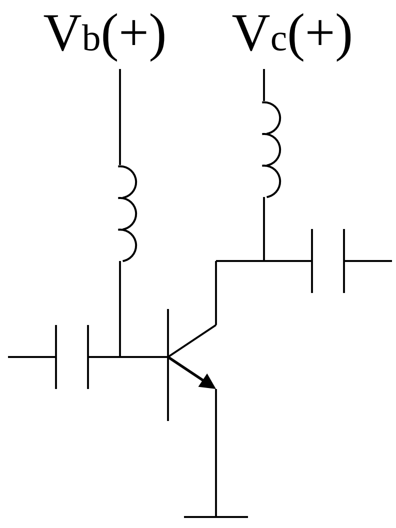
$S(f,$ bias, $T, P_{in},$ device geometry, device fabrication,...)

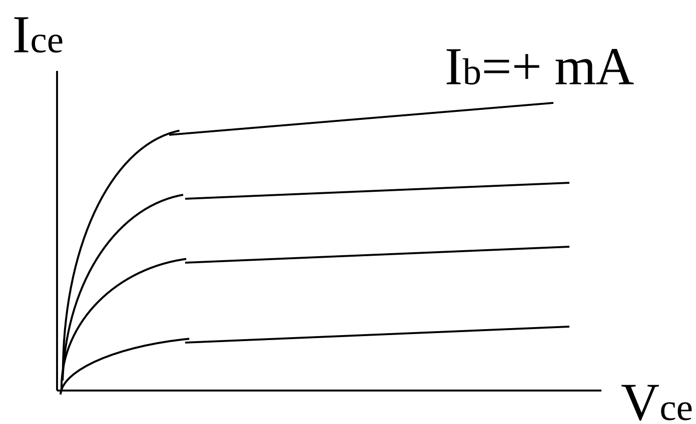
• microwave BJT





$$f_T = \frac{g_m}{2\pi C_\pi}$$





- comparison of microwave transistors

Property	D-mode FET/HEMT	III-V HBT	Si BJT	SiGe HBT	MOSFET
Cost	moderate and decreasing	high and decreasing	low and mature	moderate and decreasing	low to moderate
Single polarity supply	no	yes	yes	yes	yes
Integration capability	excellent (MMIC)	excellent	OK at low	OK at low	OK at low
Parasitic loss	very good	very good	modest	modest	modest
Turn-on voltage control	modest	very good	excellent	excellent	good
PAE	excellent	very good	poor	moderate	very good

10.5 Microwave integrated circuits

Discussion

1. HMIC (Fig. 11.25)
   MMIC (Figs. 11.26 and 11.27)
2.

Feature	MMIC	HMIC
substrate	semi-insulator	insulator
interconnections	deposited	wire-bonded / deposited
distributed elements	microstrip, CPW	microstrip, CPW
lumped elements	deposited	discrete/deposited
solid state device	deposited	discrete
controlled parasitics	Yes	No
labor intensive	No	Yes
reparability	No	Yes
equipment costs	high	low

Feature	MMIC	HMIC
mass production	Yes	No
debugging	difficult	easy
integrated with digital and electrooptic ICs	possible	impossible
cost	low	high
size and weight	small	large
design flexibility	very good	good
circuit tweaking	impractical	practical
broadband performance	relatively good	limited
reproducibility	excellent	good
reliability	excellent	good

11.5 Microwave tubes

Discussion

1. Solid-state sources operate at lower power and lower frequency, while microwave tubes operate at higher power and higher frequency (p.553, Fig.11.28).
2. Solid-state sources use diode circuitss (Gunn diode, IMPATT diode) or transistor circuits (GaAs MESFET, DRO, YIG oscillator) with power combining circuits for higher output power (p.539).
3. Microwave tubes

   power-frequency for oscillator tubes (p.555, Fig. 11.29)

   power-frequency for amplifier tubes (p.556, Fig. 11.30)