Final Term Syllabus

RF AND MICROWAVE ENGINEERING LECTURE NO.4

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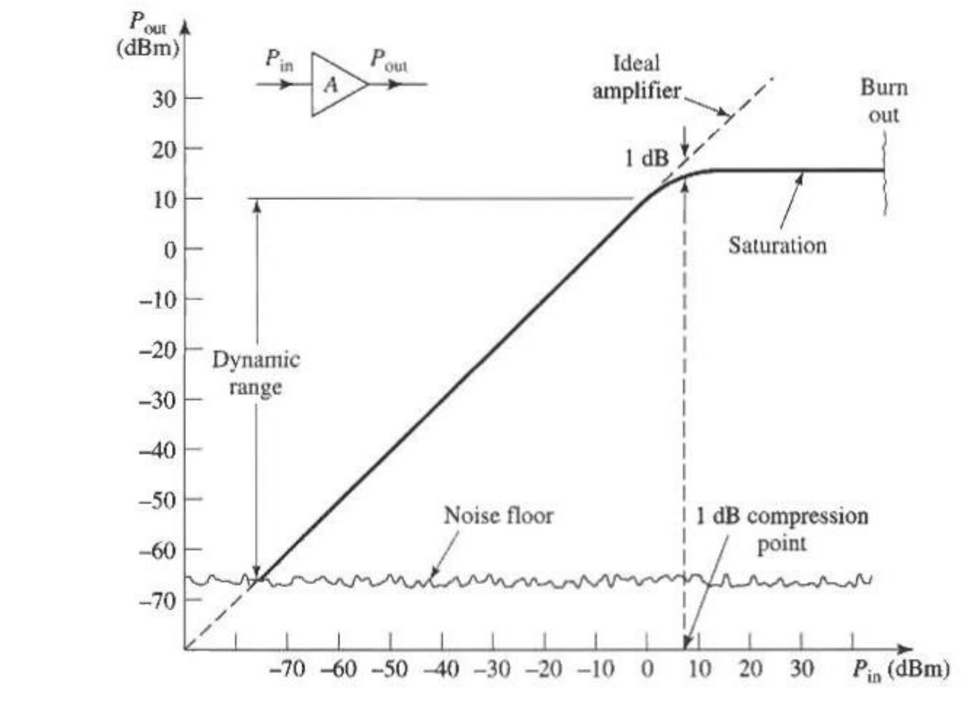
- **Noise In Microwave Circuits**
- **Detectors and Mixers**

Noise

- A result of random processes such as the flow of charges/holes in device, propagation through the ionosphere or other ionized gas, thermal vibrations
- Linear components: the output is directly proportional to the input
- Deterministic components: the output is predictable from the input



Noise floor: At very low input power levels, the output will be dominated by the noise of the amplifier. This level is often called the noise floor of the component or system

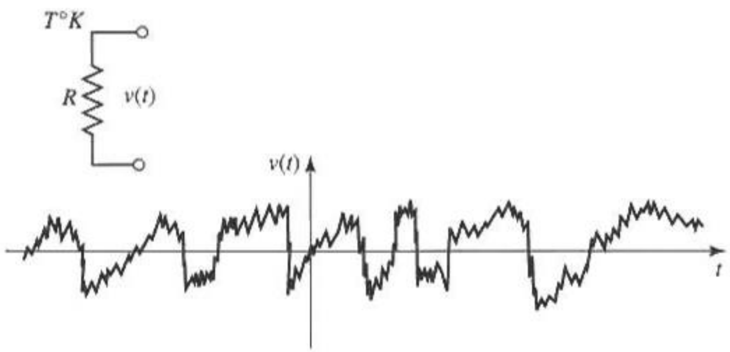
1 dB compression point: the input power for which the output is 1 dB below that of the ideal amplifier

Thermal noise is the most basic type of noise, being caused by thermal vibration of bound charges. Also known as Johnson or Nyquist noise.

Shot noise is due to random fluctuations of charge carriers in an electron tube or solid-state device. **Flicker noise** occurs in solid-state components and vacuum tubes. Flicker noise power varies inversely with frequency, and so is often called 1/f-noise.

Plasma noise is caused by random motion of charges in an ionized gas

Noise Power and Equivalent Noise Temperature

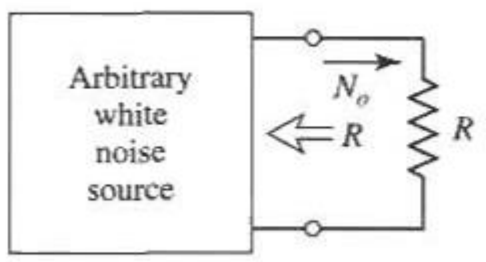


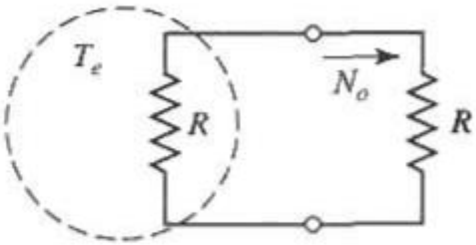
$$V_n = \sqrt{\frac{4hfBR}{e^{hf/kT}-1}}$$

$$hf \ll kT$$

$$V_n = \sqrt{4kTBR}$$

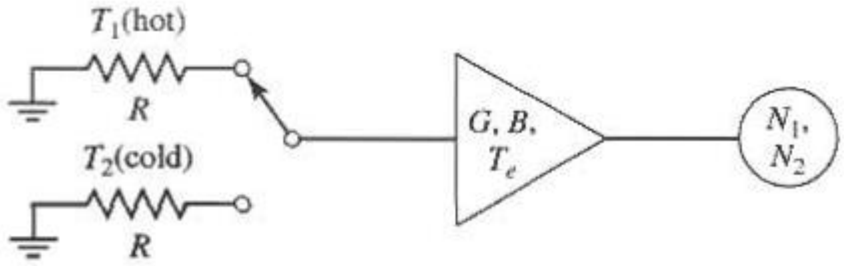
$$P_n = \left(\frac{V_n}{2R}\right)^2 R = \frac{V_n^2}{4R} = kTB$$





$$T_e = \frac{N_o}{kB}$$

equivalent noise temperature



$$N_1 = GkT_1B + GkT_eB$$

$$N_2 = GkT_2B + GkT_eB$$

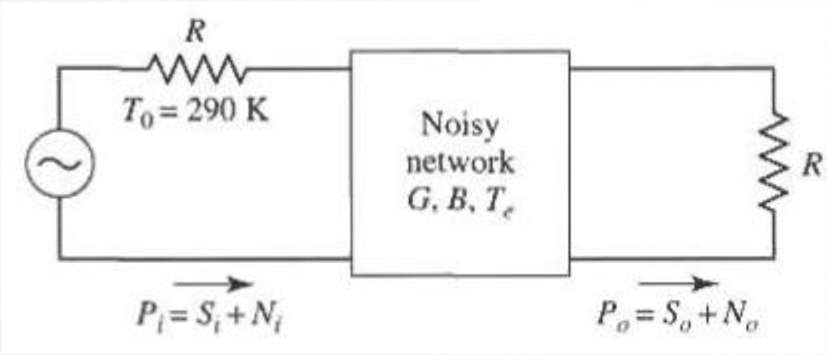
$$Y = \frac{N_1}{N_2} = \frac{T_1 + T_e}{T_2 + T_e} > 1$$

$$T_e = \frac{T_1 - YT_2}{Y - 1}$$

Noise Figure

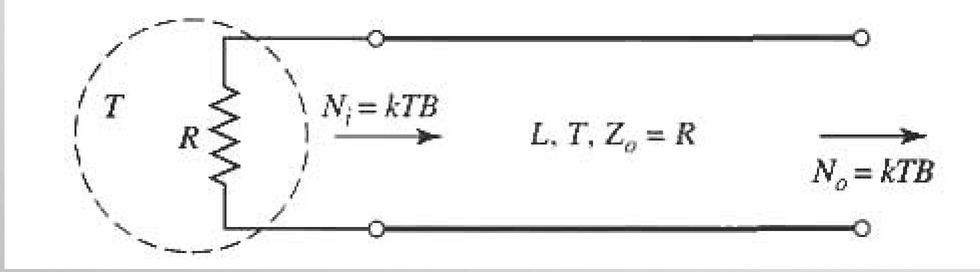
A measure of the degradation in the signal-to-noise ratio between the input and output of the component.

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



$$F = \frac{S_i}{kT_0B}\frac{kGB(T_0+T_e)}{GS_i} = 1 + \frac{T_e}{T_0} \geq 1$$

$$T_e = (F-1)T_0$$



$$N_o = kTB = GkTB + GN_{\text{added}}$$

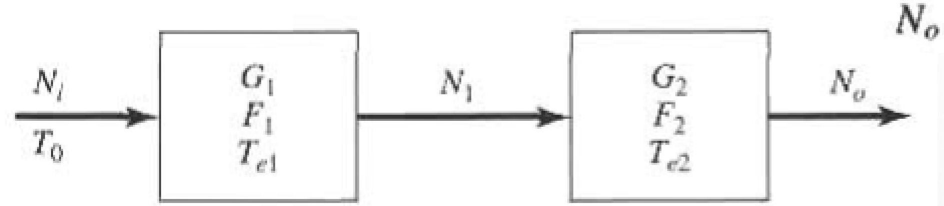
$$N_{\text{added}} = \frac{1-G}{G}kTB = (L-1)kTB$$

$$T_e = \frac{1-G}{G}T = (L-1)T$$

$$F = 1 + (L-1)\frac{T}{T_0}$$

Noise Figure of a Cascaded System

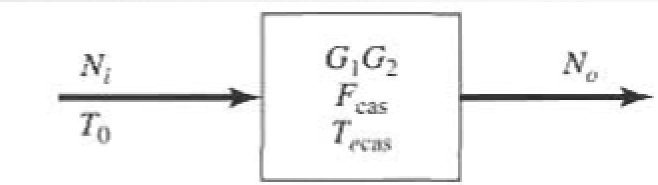
$$N_1 = G_1 k T_0 B + G_1 k T_{e1} B$$



$$N_o = G_2 N_1 + G_2 k T_{e2} B$$

$$= G_1 G_2 k B \left(T_0 + T_{e1} + \frac{1}{G_1} T_{e2} \right)$$

$$N_o = G_1 G_2 k B (T_{\text{cas}} + T_0)$$



$$T_{\text{cas}} = T_{e1} + \frac{1}{G_1} T_{e2}$$

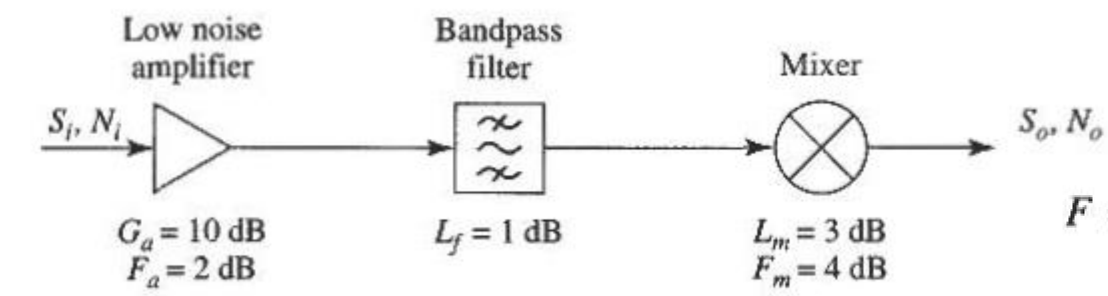
$$F_{\text{cas}} = F_1 + \frac{1}{G_1}(F_2 - 1)$$

$$T_{\text{cas}} = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots$$

$$F_{\text{cas}} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

T-Junction Power Divider

The block diagram of a wireless receiver front-end is shown below. Compute the overall noise figure of this subsystem. If the input noise power from a feeding antenna is $N_i = kT_AB$, where T_A =150 K, find the output noise power in dBm. If we require a minimum signal-to-noise of 20 dB at the output of the receiver, what is the minimum signal voltage that can be applied at the receiver input? Assume the system is at temperature T_0, with a characteristic impedance of 50 Ω, and an IF bandwidth of 10 MHz.



$G_a = 10 \text{ dB} = 10$ $\quad G_f = -1.0 \text{ dB} = 0.79$

$G_m = -3.0 \text{ dB} =$ $\quad F_a = 2 \text{ dB} = 1.58$

$F_f = 1 \text{ dB} = 1.26$ $\quad F_m = 4 \text{ dB} = 2.51$

$$F = F_a + \frac{F_f - 1}{G_a} + \frac{F_m - 1}{G_aG_f}$$

$$= 1.58 + \frac{(1.26 - 1)}{10} + \frac{(2.51 - 1)}{(10)(0.79)}$$

$$= 1.80 = 2.55 \text{ dB}$$

$$T_e = (F - 1)T_0$$

$$= (1.80 - 1)(290) = 232 \text{ K.}$$

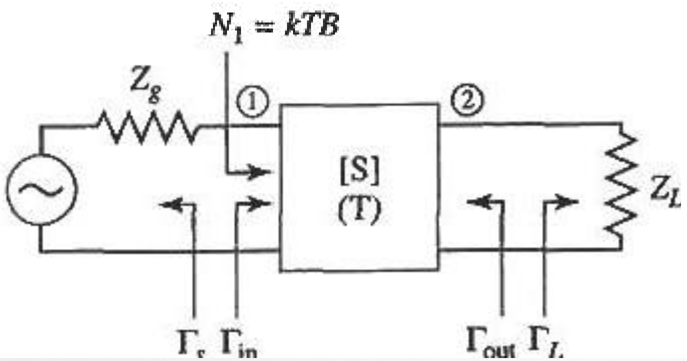
$$N_o = k(T_A + T_e)BG$$

$$= 2.08 \times 10^{-13} \text{ W} = -96.8 \text{ dBm}$$

$$S_i = \frac{S_o}{G} = \frac{S_o}{N_o}\frac{N_o}{G} = 100\frac{2.08 \times 10^{-13}}{3.95} = 5.27 \times 10^{-12} \text{ W} = -82.8 \text{ dBm.}$$

$$V_i = \sqrt{Z_oS_i} = \sqrt{(50)(5.27 \times 10^{-12})} = 1.62 \times 10^{-5} \text{ V} = 16.2\ \mu\text{V (rms).}$$

Noise Figure of a Passive Two-Port Network



$$N_2 = G_{21} kTB + G_{21} N_{added}$$

$$G_{21} = \frac{\text{power available from network}}{\text{power available from source}} = \frac{|S_{21}|^2(1-|\Gamma_S|^2)}{|1-S_{11}\Gamma_S|^2(1-|\Gamma_{out}|^2)}$$

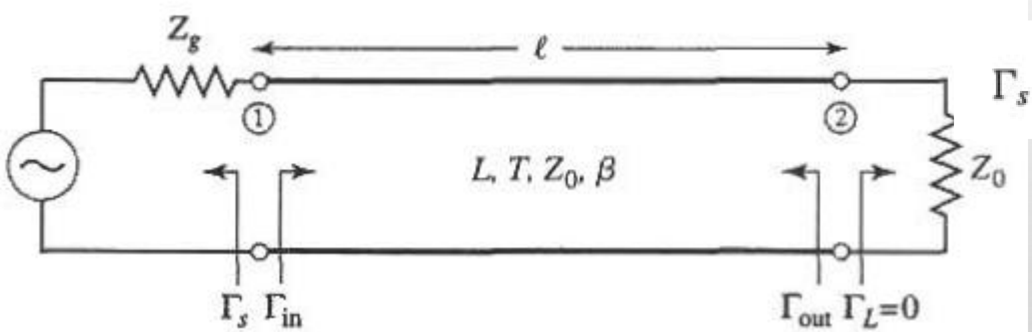
$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}$$

$$N_{added} = \frac{1-G_{21}}{G_{21}} kTB$$

$$T_e = \frac{N_{added}}{kB} = \frac{1-G_{21}}{G_{21}} T$$

$$F = 1 + \frac{T_e}{T_0} = 1 + \frac{1-G_{21}}{G_{21}} \frac{T}{T_0}$$

Noise Figure of a Mismatched Lossy Line



$$\Gamma_s = \frac{Z_g - Z_0}{Z_g + Z_0} \neq 0$$

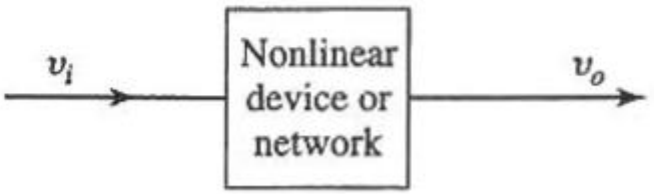
$$[S] = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \frac{e^{-j\beta\ell}}{\sqrt{L}}$$

$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_s}{1-S_{11}\Gamma_s} = \frac{\Gamma_s}{L} e^{-2j\beta\ell}.$$

$$G_{21} = \frac{\frac{1}{L}(1-|\Gamma_s|^2)}{1-|\Gamma_{out}|^2} = \frac{L(1-|\Gamma_s|^2)}{L^2-|\Gamma_s|^2}$$

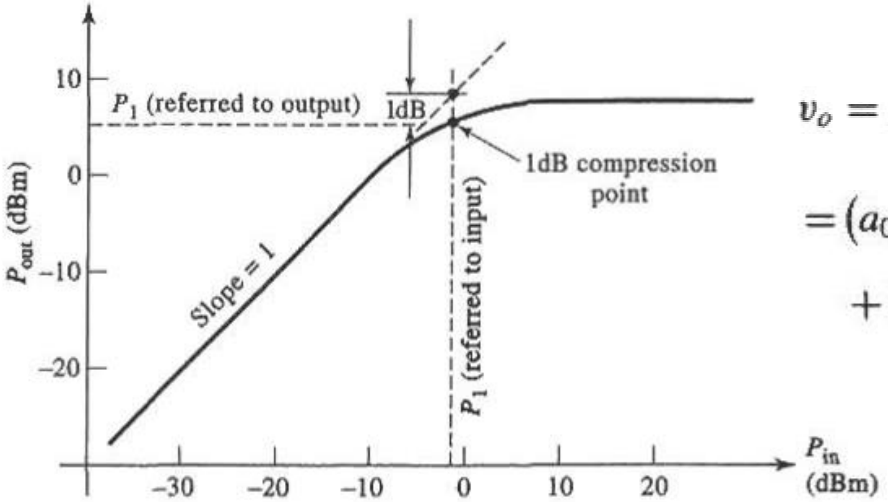
$$T_e = \frac{1-G_{21}}{G_{21}} T = \frac{(L-1)(L+|\Gamma_s|^2)}{L(1-|\Gamma_s|^2)} T$$

NonLinear Distortion



$$v_o = a_0 + a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \cdots$$

$$a_0 = v_o(0) \qquad a_1 = \left.\frac{dv_o}{dv_i}\right|_{v_i=0} \qquad a_2 = \left.\frac{d^2 v_o}{dv_i^2}\right|_{v_i=0}$$



$$v_i = V_0 \cos \omega_0 t$$

$$v_o = a_0 + a_1 V_0 \cos \omega_0 t + a_2 V_0^2 \cos^2 \omega_0 t + a_3 V_0^3 \cos^3 \omega_0 t + \cdots$$

$$= \left(a_0 + \tfrac{1}{2} a_2 V_0^2\right) + \left(a_1 V_0 + \tfrac{3}{4} a_3 V_0^3\right) \cos \omega_0 t + \tfrac{1}{2} a_2 V_0^2 \cos 2\omega_0 t + \tfrac{1}{4} a_3 V_0^3 \cos 3\omega_0 t + \cdots .$$

$$G_v = \frac{v_o^{(\omega_0)}}{v_i^{(\omega_0)}} = \frac{a_1 V_0 + \frac{3}{4} a_3 V_0^3}{V_0} = a_1 + \tfrac{3}{4} a_3 V_0^2$$

gain compression, or saturation

Intermodulation Distortion

two-tone input voltage

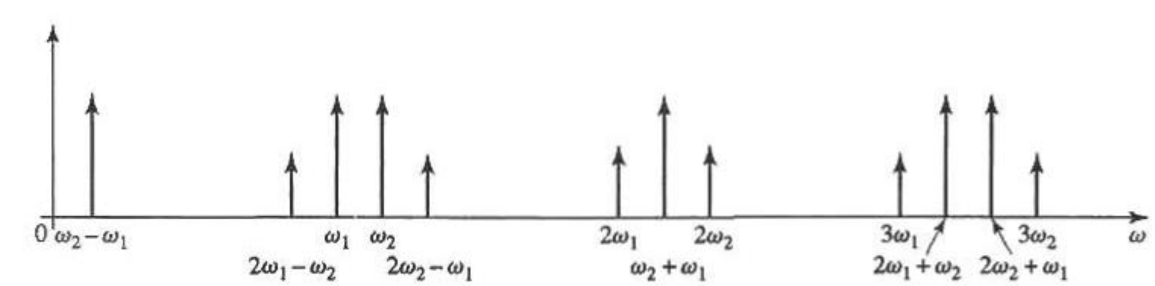
$$v_i = V_0(\cos\omega_1 t + \cos\omega_2 t)$$

$$v_o = a_0 + a_1 V_0(\cos\omega_1 t + \cos\omega_2 t) + a_2 V_0^2(\cos\omega_1 t + \cos\omega_2 t)^2 + a_3 V_0^3(\cos\omega_1 t + \cos\omega_2 t)^3 + \cdots$$

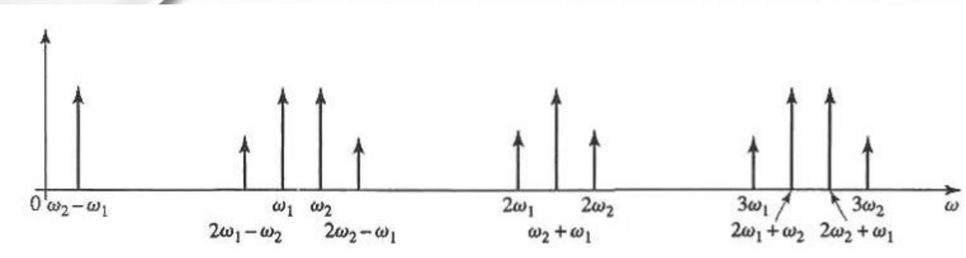
$$= a_0 + a_1 V_0\cos\omega_1 t + a_1 V_0 \cos\omega_2 t + \tfrac{1}{2}a_2 V_0^2(1+\cos 2\omega_1 t) + \tfrac{1}{2}a_2 V_0^2(1+\cos 2\omega_2 t)$$
$$+ a_2 V_0^2\cos(\omega_1-\omega_2)t + a_2 V_0^2\cos(\omega_1+\omega_2)t +$$
$$+ a_3 V_0^3\left(\tfrac{3}{4}\cos\omega_1 t + \tfrac{1}{4}\cos 3\omega_1 t\right) + a_3 V_0^3\left(\tfrac{3}{4}\cos\omega_2 t + \tfrac{1}{4}\cos 3\omega_2 t\right) +$$
$$+ a_3 V_0^3\left[\tfrac{3}{2}\cos\omega_2 t + \tfrac{3}{4}\cos(2\omega_1-\omega_2)t + \tfrac{3}{4}\cos(2\omega_1+\omega_2)t\right] +$$
$$+ a_3 V_0^3\left[\tfrac{3}{2}\cos\omega_1 t + \tfrac{3}{4}\cos(2\omega_2-\omega_1)t + \tfrac{3}{4}\cos(2\omega_2+\omega_1)t\right] + \cdots$$

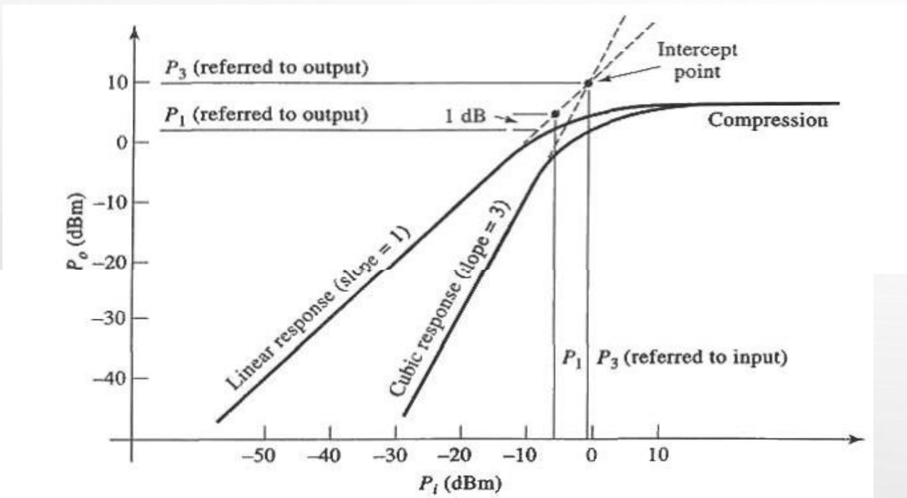
$m\omega_1 + n\omega_2$

$2\omega_1$	(second harmonic of ω_1)	$m = 2$	$n = 0$	order $= 2$
$2\omega_2$	(second harmonic of ω_2)	$m = 0$	$n = 2$	order $= 2$
$\omega_1 - \omega_2$	(difference frequency)	$m = 1$	$n = -1$	order $= 2$
$\omega_1 + \omega_2$	(sum frequency)	$m = 1$	$n = 1$	order $= 2$

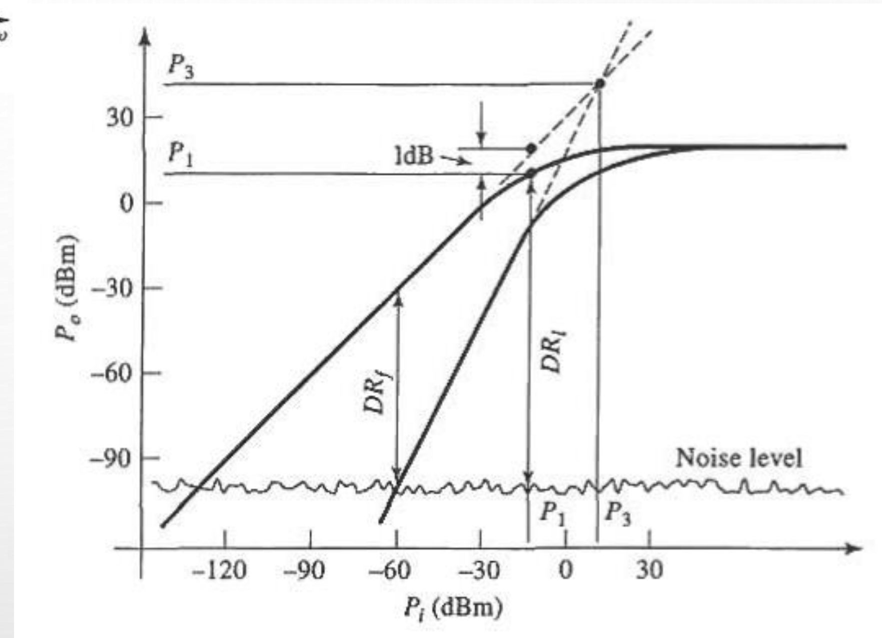


Third-Order Intercept Point





Dynamic range



linear dynamic range: power range that is limited at the low end by noise and at the high end by the compression point

spurious-free dynamic range:noise at the low end and the maximum power level for which intermodulation distortion becomes unacceptable

DETECTORS AND MIXERS

Detectors and mixers use a nonlinear device to achieve frequency conversion of an input signal. Microwave diodes are most commonly used as the nonlinear element, but transistors can also be used. Figure 10.10 illustrates he three basic frequency conversion functions of rectification, detection, and mixing. We will first discuss the nonlinear voltage-current characteristics of a diode. and then use a small-signal analysis to describe the operation of various circuits that perform these functions.

Diode Rectifiers and Detectors

A diode is basically a nonlinear resistor, with a DC V-1 characteristic that can be expressed as :

$$I(V) = I_s(e^{\alpha V} - 1), \qquad 10.24$$

where α = q/nkT, and q is the charge of an electron, k is Boltzmann's constant, T is temperature, n is the ideaty factor, and I_s, is the saturation current .

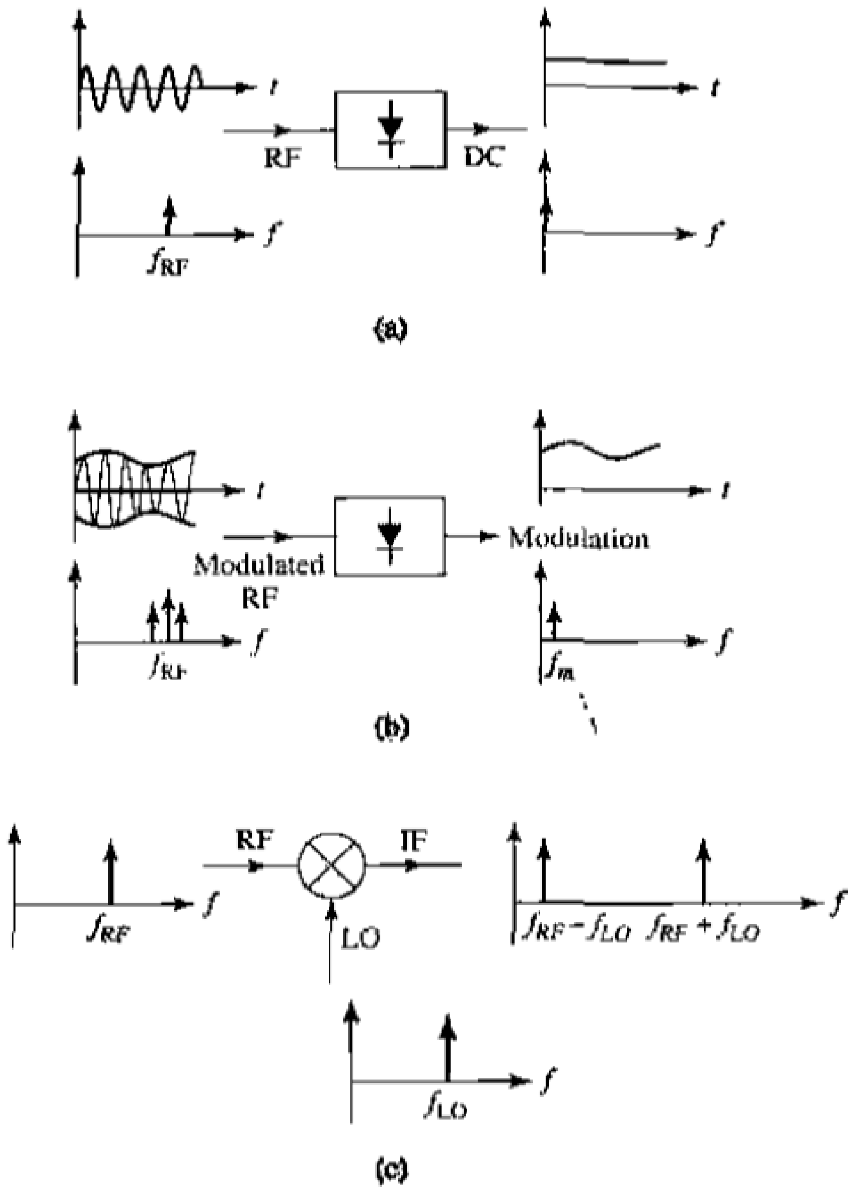


FIGURE 10.10 Basic operations of rectification, detection, and mixing. (a) Diode rectifier. (b) Diode detector. (c) Mixer.

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