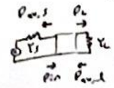
Matthew Tran
EE 142
MT1

- Eqs.
  - $P[dBm] = 10 \cdot \log\left(\frac{P[mW]}{1mW}\right)$
    - $20\log_{10}$ for voltage b/c $P \propto V^2$
  - $P = \frac{V^2}{2Z_0} = \frac{V_{rms}^2}{Z_0}$
    - amplitude of peak

$V = L\frac{dI}{dt}$ $Z_L = j\omega L$ $Y_L = \frac{1}{j\omega L}$
$I = C\frac{dV}{dt}$ $Z_C = \frac{1}{j\omega C}$ $Y_C = j\omega C$
impedance ↔ admittance duals
$V = IR = IZ$, $I = VY$
series/parallel - add, parallel - $\frac{Y_1 Y_2}{Y_1+Y_2}$ eqn



- T-line time domain
  - distributed LC
    $L' = L/\ell$, $C' = C/\ell$ (Z', Y' for lossy)
  - Telegrapher's Equations
    - $\frac{\partial i}{\partial z} = C'\frac{\partial v}{\partial t}$ → $\frac{\partial^2 v}{\partial z^2} = L'C'\frac{\partial^2 v}{\partial t^2}$
    - $\frac{\partial v}{\partial z} = L'\frac{\partial i}{\partial t}$ → $\frac{\partial^2 i}{\partial z^2} = L'C'\frac{\partial^2 i}{\partial t^2}$
  - solution wave eqn $\frac{\partial^2 f}{\partial z^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$
    w/ $v = \frac{1}{\sqrt{L'C'}}$, $\lambda f = v$
  $Z_0 = \sqrt{\frac{L'}{C'}} = \sqrt{\frac{Z'}{Y'}}$ $\gamma = \sqrt{Z'Y'}$
  - $\frac{\partial i}{\partial z} = Z'i(z)$ → $\frac{\partial^2 v}{\partial z^2} = Z'Y'v(z) = \gamma^2 v(z)$
  - $\frac{\partial v}{\partial z} = Y'v(z)$ → $\frac{\partial^2 i}{\partial z^2} = Z'Y'i(z) = \gamma^2 i(z)$
  - wave V^+, $I^+ = \frac{V^+}{Z_0}$, $P^+ = \frac{V^{+2}}{Z_0}$ (steady state)
    V^-, $I^- = -\frac{V^-}{Z_0}$, $E_{tot}(\ell/v) = P^+ t_d = \ell L' \frac{V_0^2}{(Z_0 \ldots)^2}$
  - termination $\ell = vt$
    $V_L(t) = V^+(\ell,t) + V^-(\ell,t)$ ← add
    $I_L(t) = \frac{1}{Z_0}(V^+(\ell,t) - V^-(\ell,t)) = V_L(t)/R_L$
    $\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{z_L - 1}{z_L + 1}$, $z_L = \frac{Z_L}{Z_0}$, $= \frac{V^-}{V^+}$
    $\Gamma_i = -\Gamma_v$
    $z_L = \frac{1+\Gamma_L}{1-\Gamma_L}$
    $\Gamma_s = \frac{Z_s - Z_0}{Z_s + Z_0}$ ← reflection at source too
    $x = \Gamma_L\Gamma_s$
    $V_{ss} = V_1^+ + V_1^- + \ldots = V_1^+(1 + x + x^2 + \ldots + \Gamma_L(1 + x + x^2 + \ldots))$
    $= V_1^+(1+\Gamma_L)(1 + x + x^2 + \ldots)$
  - cascade
    - continuous current, conservation (basically like load at end)
    $\tau = 1 + \Gamma = \frac{2Z_2}{Z_1 + Z_2}$ transmission coefficient
    $P_{in} = \frac{|V_1^+|^2}{2Z_0}$ $P_{ref} = |\Gamma|^2 P_{in}$ $P_{trans} = |\tau|^2 \frac{|V_1^+|^2}{2Z_1}$
    $P_{in} = P_{ref} + P_{trans}$
  - junction
    - same, cont. voltage, cont. current, treat as new

- T-line frequency domain
  - $\gamma = \alpha + j\beta = \sqrt{Z'Y'} = \sqrt{(R' + j\omega L')(G' + j\omega C')}$ lossless $\gamma = j\omega\sqrt{L'C'}$
  - $v(z) = V^+e^{-\gamma z} + V^-e^{\gamma z}$
  - $i(z) = I^+e^{-\gamma z} + I^-e^{\gamma z}$
    V^+/Z_0, $-V^-/Z_0$
    $\beta = \frac{2\pi}{\lambda}$ ($\ell = \lambda$ is 2π shift) $\theta = \beta\ell$
  - $v_p = \frac{\omega}{\beta}$ $\omega = 2\pi f$, $\beta = \frac{2\pi}{\lambda}$ → $v_p = \lambda f$!
  - termination
    - same $\rho_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{z_L - 1}{z_L + 1}$, $z_L = \frac{1+\rho_L}{1-\rho_L}$, $\rho_i = -\rho_v$
      $v(z) = V^+(e^{-\gamma z} + \rho_L e^{\gamma z})$
      $i(z) = \frac{V^+}{Z_0}(e^{-\gamma z} - \rho_L e^{\gamma z})$
    - $V^+ + V^-$ → standing and traveling waves!
      $P_{av} = \frac{1}{2}\Re(v(z)i^*(z)) = \frac{|V^+|^2}{2Z_0}(1 - |\rho_L|^2)$ ← indep. of z for P_{av}
  - VSWR (Voltage Standing Wave Ratio)
    $|v(z)| = |V^+| \cdot |1 + \rho_L e^{2j\beta z}|$ $\rho_L = |\rho_L|e^{j\theta}$
    $= |V^+| \cdot |1 + |\rho_L|e^{j(\theta - 2\beta\ell)}|$ ← $z = -\ell$
    $z_L > 1$, max at load; $z_L < 1$, min at load
    $V_{max} = |V^+| \cdot (1 + |\rho_L|)$ ← $2\beta\ell = \theta + 2\pi k$
    $V_{min} = |V^+|(1 - |\rho_L|)$ ← $2\beta\ell = \theta + \pi k$, $k \neq 0$
    $VSWR = \frac{V_{max}}{V_{min}} = \frac{1+|\rho_L|}{1-|\rho_L|}$ ← θ is dist to first min/max
    $\Delta z = \frac{\pi}{2\beta} = \frac{\lambda}{4}$ $\theta - 2\beta\ell_{min} = \pi$ ← true?
    if Z_L real, $\theta = 0$
  - input impedance (lossless)
    $\rho(z = -\ell) = \rho_L e^{-2j\beta\ell}$
    $Z_{in}(z = -\ell) = Z_0\frac{1 + \rho_L e^{-2j\beta\ell}}{1 - \rho_L e^{-2j\beta\ell}} = Z_0\frac{Z_L + jZ_0\tan(\beta\ell)}{Z_0 + jZ_L\tan(\beta\ell)}$
    - shorted: $Z_{in}(-\ell) = jZ_0\tan(\beta\ell)$ $\beta\ell \to \pi/2$ ← $\lambda/4$ resonant parallel LC!
      $\beta\ell \to 0$!
    - open: $Z_{in}(-\ell) = -jZ_0\cot(\beta\ell)$ $\lambda/4 \to 0$! resonant series LC!
      $\lambda/2 \to \infty$
  - $\lambda/2$: $Z_{in} = Z_L$ $\lambda/4$: $Z_{in} = \frac{Z_0^2}{Z_L}$ ← transformer!
  - input impedance (lossy)
    $Z_{in}(-\ell) = Z_0\frac{Z_L + Z_0\tanh(\gamma\ell)}{Z_0 + Z_L\tanh(\gamma\ell)}$ $\tanh(x) = \frac{e^{2x}-1}{e^{2x}+1}$
    $Q = \frac{\beta}{2\alpha}$
  - dispersion - freq dependent
    $\alpha \approx -\frac{R}{Z_0}$, should set $\frac{R}{L} = \frac{G}{C}$ ← all freqs equal
    $P_L = \frac{1}{2}|V^+|^2\Re(Y_0)(1 - |\rho_L|^2)$
    $P_{in} = \frac{|V^+|^2}{2|Z_0|^2}e^{-2\alpha z}\Re(Z_0)$
    $P_{dc} = \frac{|V^+|^2}{2Z_0}\left((e^{2\alpha\ell} - 1) + |\rho|^2(1 - e^{-2\alpha\ell})\right)$ ← total

- Resonance
  - series RLC
    $\omega = \sqrt{\frac{1}{LC}}$
    $Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 RC} = \frac{Z_0}{R}$ $v_L = jQv_s$ wow!
    $\frac{\Delta\omega}{\omega_0} = \frac{1}{Q}$ $\omega_0 = \sqrt{\omega^+\omega^-}$
  - parallel RLC
    - dual admittance in Y
    $Q = \frac{\omega_0 C}{G} = \frac{R}{\omega_0 L} = \frac{R}{Z_0}$ $i_0 = -jQi_s$
    $\frac{d\angle Y(\omega)}{d\omega}\Big|_{\omega_0} = \frac{2Q}{\omega_0}$ $= 2Q\frac{\delta\omega}{\omega_0}$
  - short T-line
    $\lambda/4$ - infinite impedance
    $\lambda/2$ - 0 impedance
    } not if lossy
    $\gamma\delta\ell \ll 1$
    $Z_{in} = Z_0\gamma\delta\ell = Z'\delta\ell = R + j\omega L$
  - open T-line
    $\lambda/4$ - 0 impedance
    $\lambda/2$ - ∞ impedance
  - Q-factor
    $Q = \omega_0\frac{\text{energy stored}}{\text{energy lost/cycle}} = 2\pi\frac{\text{energy stored/cycle}}{\text{energy lost/cycle}}$
    - consider $\delta\omega$ from ω_0 → input impedance
    - ~~Equivalent~~ series/parallel RLC form?
    - find R_{eq}, L_{eq}, C_{eq}
      $Q = \frac{1}{\omega_0 RC} = \frac{\omega_0 L}{R}$ if RLC
    series $Z(\delta\omega) = R\left(1 + j2Q\frac{\delta\omega}{\omega_0}\right)$
    $= R + j2\delta\omega L$
    parallel $Y(\delta\omega) = G\left(1 + j2Q\frac{\delta\omega}{\omega_0}\right)$ $Q = \frac{\omega_0 C}{G}$
    $= G + j2\delta\omega C$
    $\lambda/2$, $\lambda/4$ $Q = \frac{\beta}{2\alpha}$
  - filters
    bandpass, band reject
  - ladder filter, order = # comp

- Two-Ports
  good for
  Z $\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix}\begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$ series-series (add)
  Y $\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix}\begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$ parallel-parallel (add)
  H $\begin{pmatrix} v_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}\begin{pmatrix} i_1 \\ v_2 \end{pmatrix}$ series-parallel (add)
  G $\begin{pmatrix} i_1 \\ v_2 \end{pmatrix} = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix}\begin{pmatrix} v_1 \\ i_2 \end{pmatrix}$ parallel-series (add)
  S $\begin{pmatrix} v_1^- \\ v_2^- \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix}\begin{pmatrix} v_1^+ \\ v_2^+ \end{pmatrix}$ out / in
  ABCD $\begin{pmatrix} v_1 \\ i_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} v_2 \\ -i_2 \end{pmatrix}$ cascade (mult)
  - feedback
    - choose two-port to easily sep into amplifier + feedback
    unilateral, ideal
    - w/ Y param unilateral if $y_{12} = 0$
      $A_v = \frac{v_2}{v_1} = \frac{-y_{21}}{y_{22} + Y_L}$
      $Y_{in} = Y_{11} - \frac{Y_{12}Y_{21}}{Y_{22} + Y_L} = \frac{i_1}{v_1}$
      $Y_{out} = Y_{22} - \frac{Y_{12}Y_{21}}{Y_{11} + Y_s} = \frac{i_2}{v_2}$
    ☆ closed loop gain $\frac{A}{1 + Af}$
      $A_{vo} = \frac{-Y_s Y_{21}}{(Y_s + Y_{11})(Y_L + Y_{22})}$ "open loop" gain ($Y_{12} = 0$) $f = \frac{Y_{12}}{Y_s}$
      $Y_{in} = (Y_s + Y_{11})(1 + T)$
      $A_v' = \frac{A_{vo}}{1 + T}$ "closed loop" gain
      $T = A_{vo}f$ ← loop gain
  - stability
    def: non-zero I/V for passive termination
    $\begin{pmatrix} Y_{11} + Y_s & Y_{12} \\ Y_{21} & Y_{22} + Y_L \end{pmatrix}\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = 0$ → negative Y_{in}, Y_{out}
    ↳ $1 + T = 0$?
    $T = -1$
    conditions of stability: $\Re(Y_{11}) > 0$, $\Re(Y_{22}) > 0$, $k > 1$
    $k = \frac{2\Re(Y_{11})\Re(Y_{22}) - \Re(Y_{12}Y_{21})}{|Y_{12}Y_{21}|}$ ← stability factor
    $k > 1$ - unconditional stability ← for all source/load
    $k < 1$ - conditionally stable

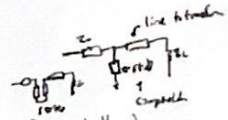
- Two-Ports (cont.)
  - power gain $G_p = \frac{P_L}{P_{in}}$
    - dep on Y, Y_L; not Y_s
    - $P_L = P_{in}G_p = (1 - |\rho|^2)P_{avs}G_p$
  - available power gain $G_A = \frac{P_{av,L}}{P_{av,s}}$
    - dep on Y, Y_s; not Y_L
  - transducer gain $G_T = \frac{P_L}{P_{av,s}}$
    - dep on Y, Y_s, Y_L
    - efficiency of source conjugate match
  as Y (all come from actually)
    $Y_{eq} = Y_{22} - \frac{Y_{21}Y_{12}}{Y_{11} + Y_s}$
    $G_A = \left|\frac{Y_{21}}{Y_{11} + Y_s}\right|^2\frac{\Re(Y_s)}{\Re(Y_{eq})}$
    $G_T = \frac{4\Re(Y_L)\Re(Y_s)|Y_{21}|^2}{|(Y_s + Y_{11})(Y_L + Y_{22}) - Y_{12}Y_{21}|^2}$
  - which power gain? all same!
    $G_{A,max} = G_{p,max} = G_{T,max}$
    ↳ bi-conjugate match to achieve
    $Y_{in} = Y_s^*$, $Y_{out} = Y_L^*$
    - lots of algebra
    $G_{p,max} = \frac{Y_{21}}{Y_{12}}\frac{1}{K + \sqrt{K^2 - 1}}$ $Y_{11} = g_{11} + jb_{11}$
    $K = \frac{2g_{11}g_{22} - P}{L} > 1$ $Y_{22} = g_{22} + jb_{22}$
  - stability (cont.)
    - iff admittance either port has $-Y$ for passive termination of other port
    - Linvill stability factor - C, $K = 1/C$
      $K > 1$ - max stable gain
      $K < 1$ - max gain $= \infty$
    max gain → $G_{max} = \frac{Y_{21}}{Y_{12}}\left(K - \sqrt{K^2 - 1}\right)$
    at $K = 1$, $G_{MSG} = \frac{Y_{21}}{Y_{12}}$
    max stable gain
  - maximum unilateral gain
    $Y_{12} = 0$ → $G_{T,max} = \frac{|Y_{21}|^2}{4g_{11}g_{22}}$
    bi-conjugate match!

- Matching Networks
  - series parallel conversion
    R_s, $X_s j$ → R_p, jX_p
    $Q = \frac{X_s}{R_s} = \frac{R_p}{X_p}$
    $R_s = \frac{R_p}{1 + Q^2}$ $X_s = \frac{X_p}{1 + 1/Q^2}$
  - convert Z_s → Z_L
  - L-match
    $R_s > R_L$ ↓ $R_s < R_L$ ↑
  - series-parallel trans, fixes Q
  - process
    1. $m = \frac{R_{hi}}{R_{lo}}$
    2. $Q = \sqrt{m - 1}$ b/c $1 + Q^2$ factor change
    3. $R_s > R_L$ $X_s = Q \cdot R_L$ } match Q
       $R_s < R_L$ $X_p = \frac{R_L}{Q}$ } fixed
    4. $R_s > R_L$ $X_p = -X_s(1 + Q^{-2})$
       $R_s < R_L$ $X_s = -\frac{X_p}{1 + Q^{-2}}$
  - L-match insertion loss IL
    $IL = \frac{P_L}{P_{in}} = \frac{1}{1 + \frac{R_{s,x}}{R_L}} = \frac{1}{1 + Q/Q_C}$ component Q
    ↓IL → ↓Q
  - Pi-match
    $R_s > R_i < R_L$ → 2 L-matches
    - intermediate R_i $Q_1 = \sqrt{\frac{R_s}{R_i} - 1}$ } $R_s > R_L$
    $Q_2 = \sqrt{\frac{R_L}{R_i} - 1}$
    $B = \frac{\omega_0}{Q}$ $Q = \frac{Q_1 + Q_2}{2}$
  - T-match $R_s < R_i > R_L$ doesn't
    $Q = \frac{1}{2}\left(\sqrt{\frac{R_i}{R_L} - 1} + \sqrt{\frac{R_i}{R_s} - 1}\right)$
  - $R_{i,opt} = \sqrt{R_L R_s}$ $Q_{opt} = \sqrt{Q} = m^{1/4}$
  - Multi-section L
    - optimal low Q
    $IL \approx \frac{1}{1 + N\frac{Q}{Q_u}} = \frac{1}{1 + \frac{N}{Q_u}\sqrt{\left(\frac{R_{hi}}{R_{lo}}\right)^{1/N} - 1}}$
    ↳ $\frac{1}{(1 + Q/Q_u)^N}$

- Matching Networks (cont.)
  - T-line w/ lumped elements
    X_s ← cancel the reactive part
    Z_L w/ ℓ
    ↳ set Z_{in} match Z_L
  - T-line w/ T-line stubs
    each of $\ell < \lambda/4$, short → inductor
    open → capacitor
    - short easier
    line to transform, compensate, series
  - Smith Chart both T-line
    - plot normalized impedance (rotate by π if using admittance)
    - add T-line to move to intersect w/ $r = 1.0$ (real match)
    - add stub to compensate reactive part
    key: switch to Admittance/Smith as needed if short/series
  - Smith Chart lumped
    - plot normalized
    - get shunt or series first (one next to component)
      (change imaginary part)
    - back to impedance (or admittance) for 2nd shunt/series
      (should be on $r = 1.0$ to match)
      (easy w/ all value to move to $x = 0$)

- Smith Chart
  - map normalized impedance/admittance to graph
    - real → circles, imag → above below
  - SWR circle (about origin)
    ? radius based from (clockwise)
    - max at $\theta = 0$, min at $\theta = \pi$
    $|\rho_L|$, θ is angle (real value)
  - impedance, admittance; convert by π rotation on SWR
    ind $+j$, cap $-j$; cap $-j$, ind $+j$
    - combine → need both!
  - lumped component
    impedance series - constant r, ↑L ↓C
    admittance shunt - constant g, ↑C ↓L
  - Q ↑Q if more outside
    - multisection = diff path stay in low Q

- Noise
  - mean 0, rms $V_{n,rms} = \sqrt{\overline{v_n^2}}$
  - $SNR = \frac{S}{N}$ $SNR(dB) = 10\log_{10}\frac{P_{sig}}{P_{noise}}$
  - SFDR - like SNR but for spurs
  - types
    - thermal - Johnson-Nyquist, thermal agitation of charge carriers $\overline{v_n^2} = 4kTBR$ ← $B = \Delta f$
    - shot shot noise - $\overline{i_d^2} = 2qI_{dc}B$ ↳ BJT
    - FET channel noise, flicker noise V_f
      $\overline{i_{dn}^2} = 4kT\gamma g_m B + K\frac{I_D}{C_{ox}L^2}\cdot\frac{\Delta f}{f}$
    $\overline{v_n^2} = 4kTR_{rad}B$ body, antenna, radiation resistance
    L, C no noise
  - Noise Figure
    $F = \frac{SNR_i}{SNR_o}$ $NF = 10\cdot\log_{10}(F)$ dB
    (define input noise $= 4kTBR$ ← equiv. for all noise to input
    $F = 1 + \frac{N_{amp,i}}{N_s} \geq 1$
  - cascade
    $F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \ldots$
    F_1 matters most!!
  - MDS (Min Detectable Signal)
    (SNR_o requirement ← 10^3 for dBm, else dBW
    $P_{in,MDS} = SNR_o + NF + 10\cdot\log(kT) + 10\cdot\log(B)$
    -174 dBm at 290K
  - Two-port model
    - decompose into noiseless two-port + noise sources
  - Dist
    $v = \frac{c}{\sqrt{\epsilon_r}} = \frac{1}{\sqrt{\epsilon\mu}} = \sqrt{\frac{1}{L'C'}}$
    shorted $\lambda/2$ series RLC, $\lambda/4$ parallel RLC short, open
    - find resonator = LC network
      Smith chart to find first resonance
    $\theta = 2\beta\ell$
    S^2 → power
    power NF F_1, G_1 increase of cascade



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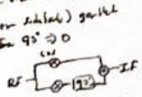
EE 142
Final

- LNA
  - noisy 2p → noiseless 2p
    - open, short input → $\overline{v_n^2}$, $\overline{i_n^2}$
  - R_s source impedance
    - low – $\overline{v_n^2}$ important (BJT)
    - high – $\overline{i_n^2}$ important (MOS)
      - optimal R_s exists!
        (but have to compromise gain)
  - noise sensitivity parameter $F = F_{min} + R_n R_s |G_s - G_{s}|^2$
  - plot noise and gain circles
  - source/emitter degeneration
- Distortion
  - nonlinear gain! (ex. saturation)
  - power series exp. $S_0 = a_1 S_i + a_2 S_i^2 + \dots$
  - Harmonic Distortion
    - 1 freq $S_i = S_1 \cos \omega_1 t$
    - 2nd order ⇒ $\frac{1}{2} a_2 S_1^2$ DC, 2nd harmonic
    - 3rd order ⇒ gain compression/expansion
    - $HD2 = \frac{1}{2}\frac{a_2}{a_1} S_1 \leftarrow 1\,dB/dB$
    - $HD3 = \frac{1}{4}\frac{a_3}{a_1} S_1^2 \leftarrow 2\,dB/dB$
    - $THD = \sqrt{HD_2^2 + HD_3^2 + \dots}$
  - Intermodulation Distortion
    - 2 tone $S_i = S_1 \cos \omega_1 t + S_2 \cos \omega_2 t$
      $IM2 = \frac{a_2}{a_1} S_i \leftarrow @ \begin{matrix} \omega_1 - \omega_2 \\ \omega_1 + \omega_2 \end{matrix} = 2HD2$
      $IM3 = \frac{3}{4}\frac{a_3}{a_1} S_i^2 \leftarrow @ \begin{matrix} 2\omega_1 - \omega_2 \\ 2\omega_2 - \omega_1 \end{matrix} = 3HD3$ in band?
    - higher order are also spaced by $\omega_1 - \omega_2$
      $j\omega_1 \pm k\omega_2$, $j + k = n^{th}$ order
  - Gain Compression
    - 1 dB pt., $a_3/a_1 < 0 \Rightarrow S_1 = \sqrt{\frac{4}{3}\left|\frac{a_1}{a_3}\right|}\sqrt{0.11} = IIP3 - 9.6\,dB$ ($\leftarrow -9.6\,dB$)
  - IP2 (IIP2, OIP2) where IM2 = 0 dB (1 dB/dB slope)
  - IP3 (IIP3, OIP3) where IM3 = 0 dB (2 dB/dB slope)
    $IIP2 = \frac{a_1}{a_2}$, $IIP3 = \sqrt{\frac{4}{3}\left|\frac{a_1}{a_3}\right|}$
  - jammer → lower apparent gain
  - Cascade
    $\frac{1}{V_{IIP2}} = \frac{1}{V_{IIP2A}} + \frac{a_1}{V_{IIP2B}} \leftarrow$ input after IIP2
    $\frac{1}{V_{IIP3}^2} = \frac{1}{V_{IIP3A}^2} + \frac{a_1^2}{V_{IIP3B}^2} \leftarrow$ squared instead
  - Feedback
    $b_1 = \frac{a_1}{1 + a_1 f} = \frac{a_1}{1+T}$, $b_2 = \frac{a_2}{(1+T)^3}$ $b_3 = \frac{a_3(1+T) - 2a_2^2 f}{(1+T)^5}$
    - HD null – HD3 = 0
- Mixers
  - multiplication in time → in frequency
    $\cos\theta = \frac{1}{2}(e^{j\theta} + e^{-j\theta})$ $\sin\theta = \frac{1}{2j}(e^{j\theta} - e^{-j\theta})$
  - image rejection $Q = \frac{\omega_0}{BW}$
    - dual IF stages before (but 2nd image!) (2 oscillators!)
  - direct conversion (zero IF) issues
    - even-order distortion is big issue
    - flicker noise at low F
    - LO leakage = DC offset (L $\cos^2(\omega_1 t)$ = DC + 2nd-order) ← self-mixing
    - complex and (uneven subbands) gain
    - random phase offset 90° ⇒ 0
  - I/Q Hartley mixer
    image reject!

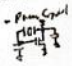


$IRR(dB) = 10 \cdot \log \frac{1}{4}\left(\left(\frac{\Delta A}{A}\right)^2 + \delta\phi^2\right)$
  - RC filter (HPF/LPF) → 90° offset
  - I/Q used in modulation/demodulation
    - delay → makes I/Q modulation
  - Practical mixers
    - periodic $h(t+T) = h(t)$ $T \to LO$
    - noise folding from other frequencies
      - any IF will fold, need BPF
      - SSB, F = 2; DSB, F = 1
    - diff switching pair – between 2 diff pairs
    - MOS "ring mixer"
    - both a tank or active power?

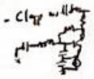
- Oscillators
  - power, freq, stability, phase noise, tuning range
    timing jitter
  - LC tank + feedback
    - "negative" resistance or $|T| > 1$ oscillation
    - complex pole LHP, RHP from noise
    - move to $AL = 1$ ω_0
  - tank/saturation also limit amplitude
  - squegging – periodic oscillation in bias
  - Colpitts oscillator – never squegs

  - relaxation oscillator
  - ring oscillator
  - MOS
  - Pierce oscillator

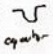
  - Pierce Crystal



  - Clapp oscillator



- VCO
  - $TR = 2\frac{f_{max} - f_{min}}{f_{max} + f_{min}}$
  - PLL – VCO, freq divider, phase detector, loop filter
  - Varactor (variable cap)
    - PIN, reverse biased PN junction
    - MOS cap



    - switched capacitor
- Extra
  - Dixon
    - inductor depends to resonate in the capacitor $\omega_T L_s = R_s$
  - Hartley
    - loop gain $g_m R$, startup gain > 1
    - parallel → resistance, series → resistance
      ← negative for startup