#21

4/17/03

BROADBAND AMP DESIGN

FREQ VARIATIONS DUE TO

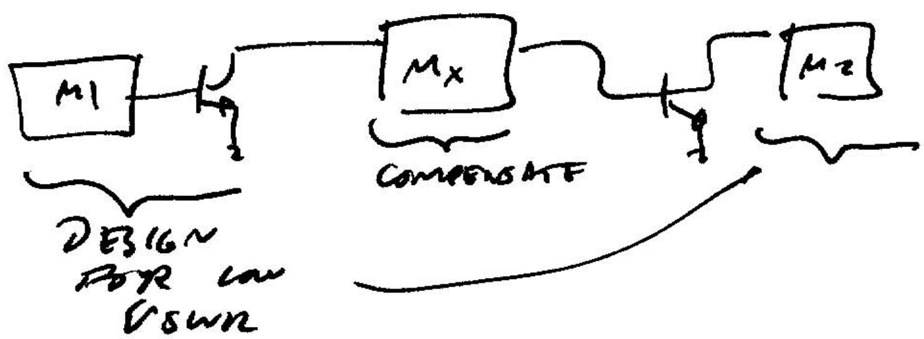
(1) $|S_{21}|$ AS A FUNCT OF FREQ
$|S_{12}|$ AS A FUNCT OF FREQ

S_{21} ↓ 6dB/OCTAVE
S_{12} ↑ 6dB/OCTAVE

(2) S_{11} & S_{22} FREQ DEPENDENT

SOLUTION

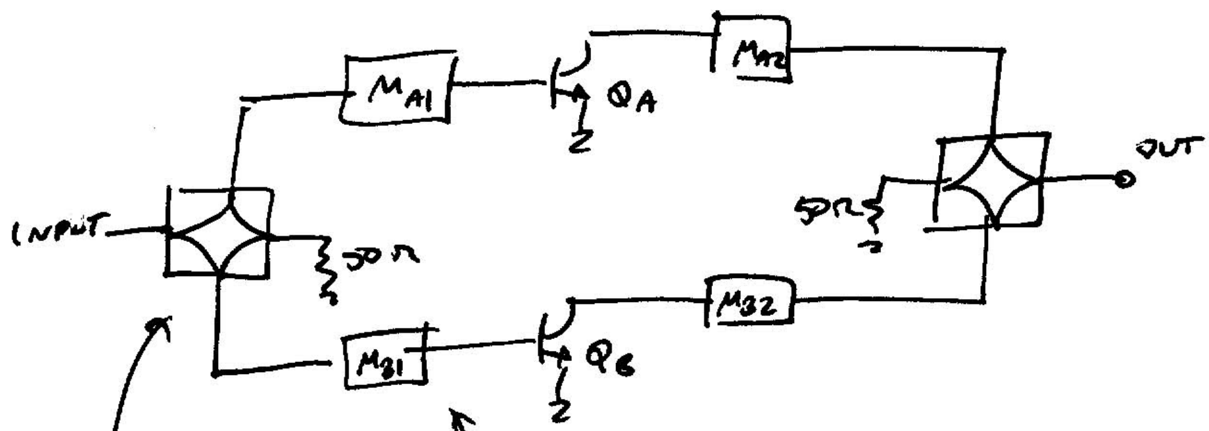
(1) COMPENSATION : MAKE M_1 & M_2 MATCHING NETWORKS THAT COMPENSATE FOR VARIATIONS IN S_{21}



→ NETWORK SYNTHESIS
→ INSERTION LOSS TECHNIQUE "ACTIVE FILTER"

(2) BALANCED AMPLIFIERS
(3) FEEDBACK
(4) DISTRIBUTED AMPS

BALANCED AMPS (MIDTERM)



MATCH FOR OPTIMAL NOISE!

USE BROADBAND COUPLER

$$|S_{11}| = \frac{1}{2}\left|S_{11A} - S_{11B}\right| \simeq 0$$

$$|S_{21}| = \frac{1}{2}\left|S_{21A} + S_{21B}\right| \simeq S_{21A}$$

$$|S_{12}| = \frac{1}{2}\left|S_{12A} + S_{21B}\right|$$

USE MATCHED AMPS

$$|S_{22}| = \frac{1}{2}\left|S_{22A} - S_{22B}\right| \simeq 0$$

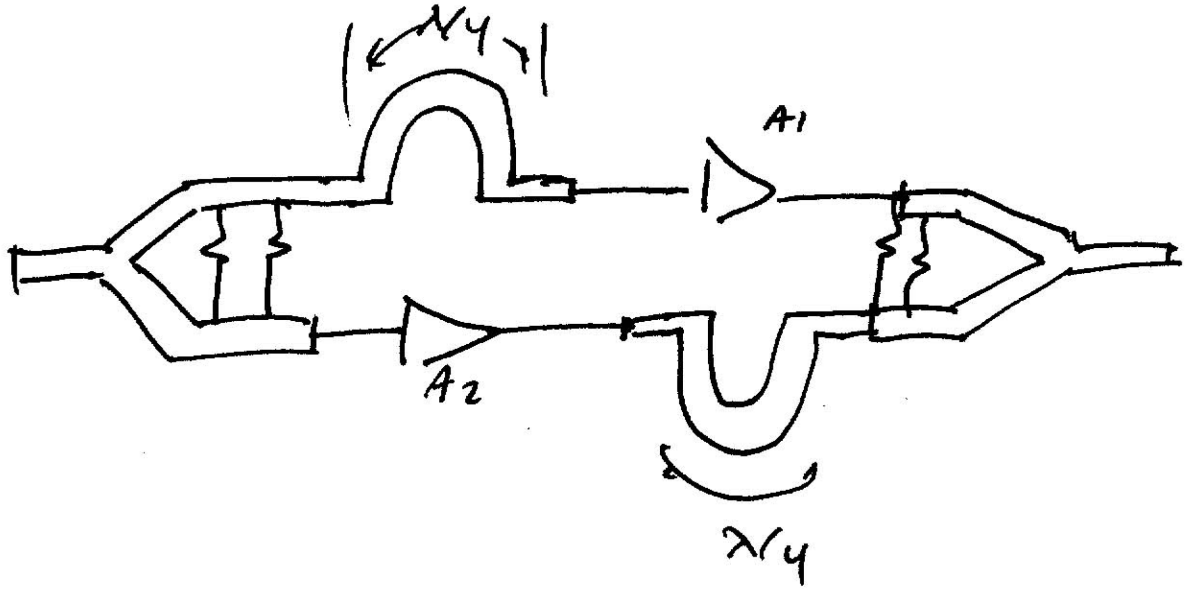
$$NF = \frac{1}{2}\left|N_{FA} + N_{FB}\right|$$

ADVANTAGES:

- GOOD STABILITY
- O/P POWER TWICE
- IF ONE AMP FAILS, UNIT STILL OPERATES
- EACH INDIVIDUAL AMP DESIGNED FOR FLAT-GAIN, NOISE FIGURE ... AND I/P & O/P MATCH PROVIDED BY COUPLER

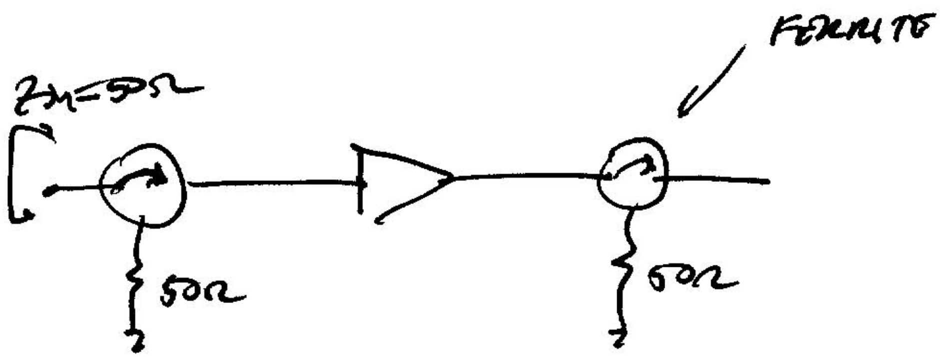
→ HIGHER COST / HIGHER POWER / LARGER AREA

3-dB WILKINSON POWER DIVIDER



POWER SPLIT IN PHASE & λ/4 LINE PROVIDES 90° SHIFT

"ISOLATOR" ANOTHER CHOICE

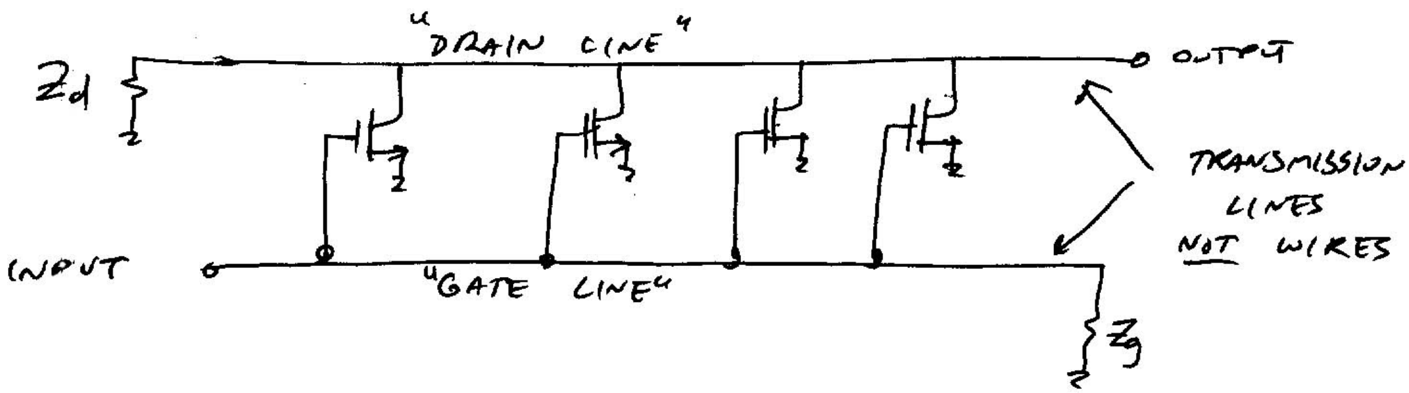


OFTEN USED TO ISOLATE THE PA FROM CHANGING LOAD ENVIRONMENT

DISTRIBUTED AMPLIFIERS

→ ALSO CALLED A TRAVELING WAVE AMPLIFIER

FANCY NAME BUT A VERY SIMPLE CONCEPT...



- ASSUME IDEAL TRANSISTORS WITH NO PARASITICS

$$i_d = g_m V_{gs}$$

→ GATE & DRAIN DO NOT LOAD LINES

- NOW EXCITE A WAVE ON THE GATE LINE (SINUSOID OR NON-SINUSOID)

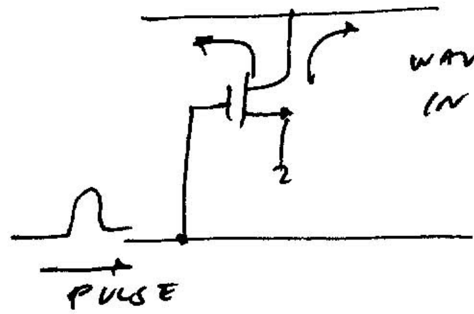
- THE GATE LINE IS TERMINATED IN ITS CHAR IMP Z_g & THE INPUT IS DRIVEN WITH A GENERATOR OF IMPEDANCE Z_g
  → SAME AT OUTPUT (Z_d)

- IDEAL TEM TRANSMISSION LINE HAS A INFINITE CUTOFF FREQ

- ASSUME GATE AND DRAIN LINE HAVE EQUAL PROPAGATION VELOCITY $\beta_g = \beta_d$ AND ZERO LOSS $\alpha = 0$

$$v_g(z) = e^{-j\beta z}\,\frac{V_s}{2} \qquad V_{gn} = \frac{V_s}{2}\, e^{-(n-1)j\beta_g \ell_g}$$

$n=1$ "NO DELAY FIRST GUY"



WAVE LAUNCHED IN BOTH DIRECTIONS

$$v_o = I_d Z_d$$

$$I_d = + \frac{1}{2} \sum_{n=1}^{N} i_{dn}\, e^{-(N-n)j\beta_d \ell_d}$$

$n=N \Rightarrow$ NO DELAY "LAST" GUY

$$i_{dn} = -g_m v_{gs}$$

$$I_d = -\frac{g_m V_s}{4} \sum_{n=1}^{N} e^{-(n-1)j\beta_g \ell_g} \cdot e^{-(N-n)j\beta_d \ell_d}$$

$$= -\frac{g_m}{4} V_s\, e^{-Nj\beta_d \ell_d}\, e^{j\beta_g \ell_g} \sum_{n=1}^{N} e^{-nj(\beta_g \ell_g - \beta_d \ell_d)}$$

ENFORCE SYNCHRONIZATION

$$\rightarrow \beta_g \ell_g = \beta_d \ell_d = \beta \ell$$

$$I_d = -\frac{g_m}{4} V_s\, e^{-Nj\beta\ell}\, e^{j\beta\ell} \cdot N$$

CURRENT SUM IN PHASE

$$G = \frac{P_{out}}{P_{in}} = \frac{\frac{1}{2}|I_d|^2 Z_d}{\frac{1}{8}|V_s|^2 / Z_g} = \frac{g_m^2 Z_d Z_g N^2}{4}$$

FOR THIS SIMPLE CASE THE GAIN INCREASES LIKE N^2 AND THE BW IS <u>INFINITE</u>!

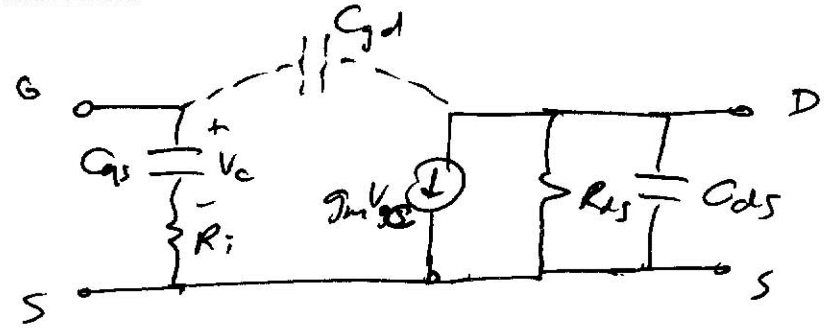
THIS IS AN ENCOURAGING START ...

GAIN INC IS <u>MILD</u>; CASCADE GIVES G_0^N

PRACTICAL CASE: – TRANSISTOR HAS LOSSES

– TRANSMISSION LINE HAS LOSSES

<u>SIMPLE TRANSISTOR MODEL</u>

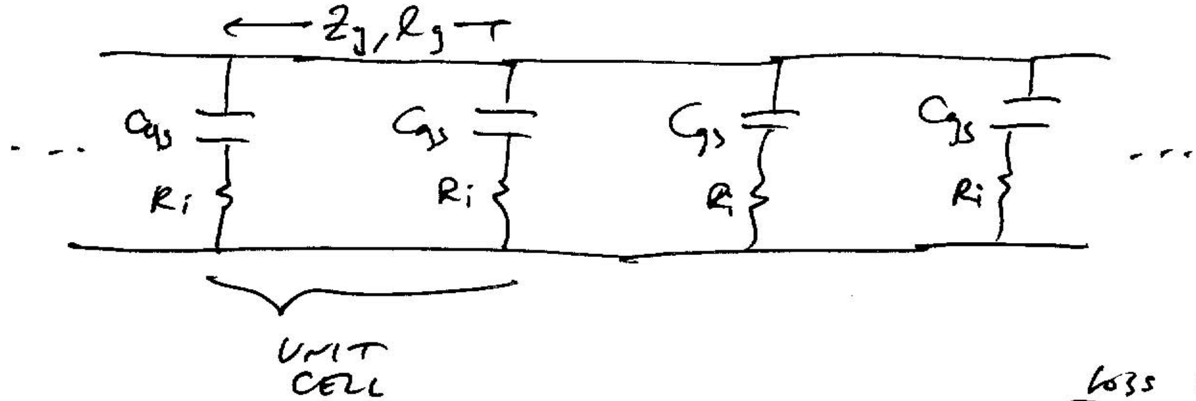


→ TRANSISTOR WILL <u>LOAD</u> LINE

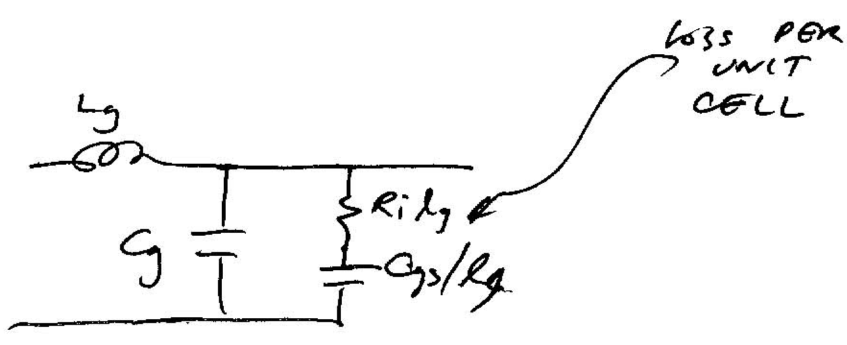
→ LOSSES WILL INCREASE T-LINE LOSSES

ASSUME TRANSISTOR IS UNILATERAL $C_{gd} = 0$

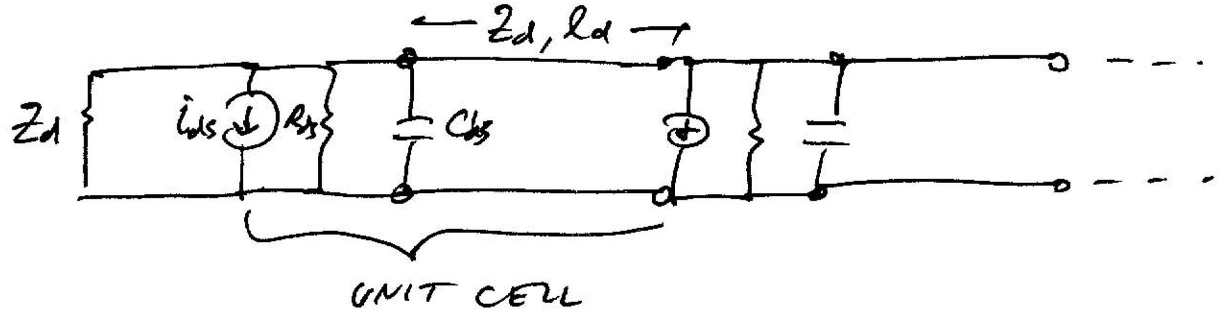
GATE LINE:



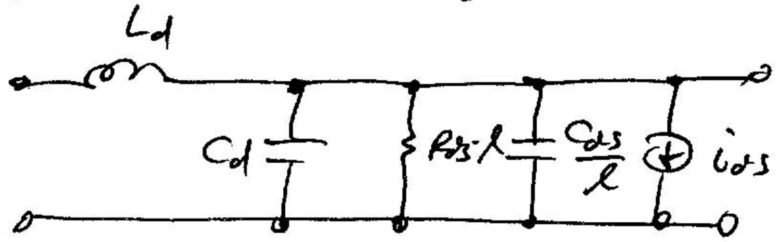
EQ CIRCUIT



DRAIN LINE



DIST EQ^V CIRCUIT OF UNIT CELL



GATE

$$Z = j\omega L_g$$

$$Y = j\omega C_g + \frac{j\omega C_{gs}/\ell_g}{1 + j\omega R_i C_{gs}}$$

$$Z_g = \sqrt{\frac{Z}{Y}} \cong \sqrt{\frac{L_g}{C_g + C_{gs}/\ell_g}}$$

Low loss

$$\gamma_g = \alpha_g + j\beta_g = \sqrt{ZY}$$

$$= \sqrt{j\omega L_g \left(j\omega C_g + \frac{j\omega C_{gs}/\ell_g}{1 + j\omega R_i C_{gs}} \right)}$$

$$\simeq \sqrt{-\omega^2 L_g \left(C_g + C_{gs}(1 - j\omega R_i C_{gs})/\ell_g \right)}$$

DRAIN

$$Z = j\omega L_d$$

$$Y = \frac{1}{R_{ds} l_d} + j\omega\left(C_d + C_{ds}/l_d\right)$$

$$Z_0 = \sqrt{\frac{Z}{Y}} \cong \sqrt{\frac{L_d}{C_d + C_{ds}/l}}$$

$$\gamma_d = \alpha_d + j\beta_d = \sqrt{(j\omega L_d)\left(\frac{1}{R_{ds} l_d} + \underbrace{j\omega(C_d + C_{ds}/l_d)}_{\text{DOMINATES}}\right)}$$

$$\cong \frac{Z_d}{2R_{ds} l_d} + j\omega\sqrt{L_d(C_d + C_{ds}/l_d)}$$

REDO GAIN CALC

$$v_{gs\,n} = \frac{v_s}{2} e^{-(n-1)\gamma_g l_g} \underbrace{\left(\frac{1}{1 + j\omega R_i C_{gs}}\right)}_{\text{VOLTAGE DIV} \approx 1}$$

$$I_d = -\frac{g_m v_s}{4} e^{-N\gamma_d l_d} e^{\gamma_g l_g} \underbrace{\sum_{n=1}^{N} e^{-n(\gamma_g l_g - \gamma_d l_d)}}_{\text{SUM}}$$

$$I_d = -\frac{g_m v_s}{4} \frac{e^{-N\gamma_g l_g} - e^{-N\gamma_d l_d}}{e^{-\gamma_g l_g} - e^{-\gamma_d l_d}}$$

$$G = \frac{g_m^2 Z_d Z_g}{4} \frac{\left(e^{-N\alpha_g l_g} - e^{-N\alpha_d l_d}\right)^2}{\left(\underbrace{e^{-\alpha_g l_g} - e^{-\alpha_d l_d}}_{\approx\, \alpha_g l_g - \alpha_d l_d}\right)^2}$$

GAIN IS NO LONGER A MONOTONIC FUNC OF N
BUT PEAKS AT A FINITE N

PHYSICAL EXPLANATION: ADDING AN EXTRA STAGE WILL ONLY IMPROVE GAIN IF THE PRODUCT OF

$$\underbrace{\frac{g_m V_{gs}(N+1)\, Z_d}{2}}_{\text{EXTRA GAIN}} > \underbrace{\left|e^{\gamma_d l_d}\right|}_{\text{ATTEN ON DRAIN LINE}}$$

DECREASING EXP.

EVENTUALLY THE POLYNOMIAL INC IN GAIN DUE TO EXTRA STAGE WILL NOT OUTWEIGH THE EXPONENTIAL LOSS!

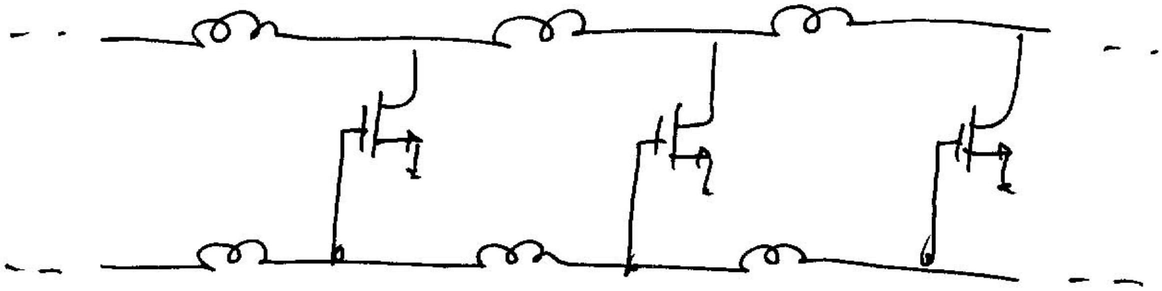
→ TAKE DERIVATIVE

$$N_{opt} = \frac{\ln(\alpha_g l_g / \alpha_d l_d)}{\alpha_g l_g - \alpha_d l_d}$$

GAIN IS <u>NOT FLAT</u> WITH FREQ DUE FREQ DEPENDENCE OF α_g & α_d

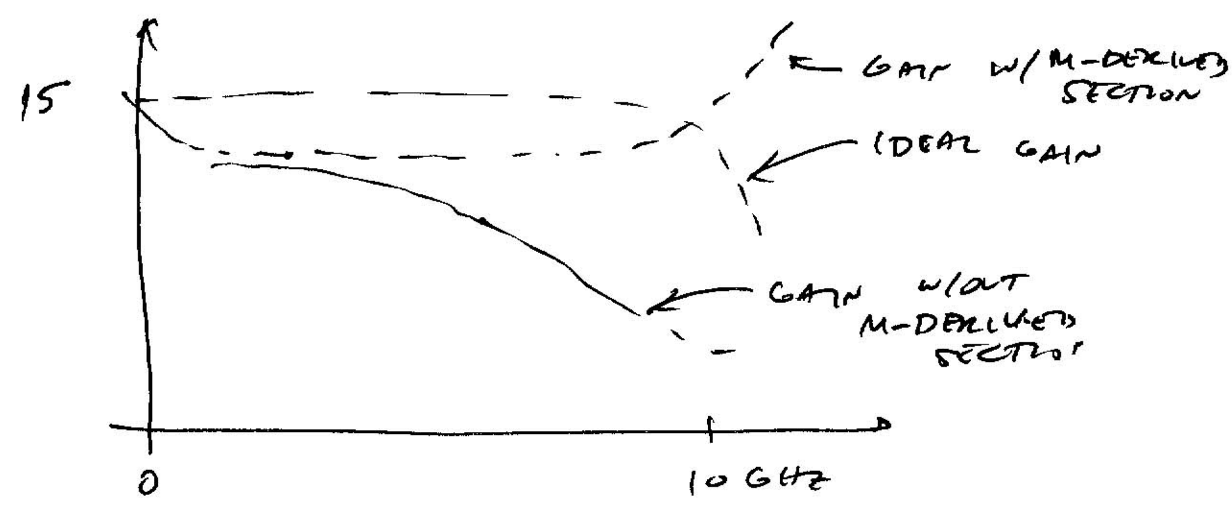
MORE DETAILED CALC... (MY CLASS PROJECT)

- ANALYZE CIRCUIT AS AN ARTIFICIAL TRANSMISSION LINE USING IMAGE PARAMETER METHOD
- TAKE INTO ACCOUNT LOSSES IN LUMPED INDUCTORS



- USE BISECTED-π M-DERIVED MATCHING NETWORKS TO COMPENSATE FOR FREQ DEP OF T-LINE

$$G = \frac{Re(Z'_{id})}{Re(Z'_{ig})} |Z_{ig}|^2 \frac{g_m^2 |\delta|^2 \sinh^2\left[\frac{n}{2}(\alpha_d - \alpha_g)\right] e^{-n(\alpha_d + \alpha_g)}}{4\left(1 + \left(\frac{\omega}{\omega_g}\right)^2\right) \sinh^2\left(\frac{1}{2}(\alpha_d - \alpha_g)\right)}$$



ZERO LOSS ATTENUATION FACTOR

$$Z_i = \sqrt{\frac{L}{C}\left(1-\left(\frac{\omega}{\omega_c}\right)^2\right)}$$

$$e^{\gamma} = 1 - \frac{2\omega^2}{\omega_c^2} + \frac{2\omega}{\omega_c}\sqrt{\frac{\omega^2}{\omega_c^2} - 1}$$

$$\omega_c = \frac{2}{\sqrt{LC}}$$

ω_c IS CUTOFF FREQ OF ARTIFICIAL LINE

"BEYER" DESIGN METH. FOR LOW LOSS

$$\alpha_g = \frac{2a\,X_k^2}{n\sqrt{1+\left(\frac{4a^2}{n^2}-1\right)X_k^2}}$$

$$\alpha_d = \frac{2b}{n\sqrt{1-X_k^2}}$$

$$\omega_g = \frac{1}{R_i C_{gs}}$$

$$\omega_d = \frac{1}{C_{ds} R_{ds}}$$

$$X_k = \frac{\omega}{\omega_c}$$

$$a = \frac{n\,\omega_c}{2\omega_g}$$

$$b = \frac{n\,\omega_d}{2\omega_c}$$

NORMAL PARAM

$$A_N = \frac{\sinh\left(\frac{b}{n}\right) e^{b} \sinh \eta_- \, e^{-\eta_+}}{\sinh(b)\left(1+\frac{4a^2}{n^2}X_k^2\right)^{1/2}\sqrt{1-X_k^2}\,\sinh \frac{1}{n}\eta_-}$$

$$\eta_\pm = \frac{b}{\sqrt{1-X_k^2}} \pm \frac{a\,X_k^2}{\sqrt{1+\left(\frac{4a^2}{n^2}-1\right)X_k^2}}$$

$$A_0 = \text{LF GAIN} = \frac{g_m \sqrt{R_{01} R_{02}} \sinh b \, e^{-b}}{2 \sinh\left(\frac{b}{n}\right)}$$

$\Rightarrow$ THREE PARAM DETERMINE PERF: a, b, n

$$\frac{A_0 f_c}{4 f_{max}} = \sqrt{ab}\, e^{-b} = K$$

$$A_0 f_c = 4K X f_{max} \qquad f_{max} \cong \frac{g_m}{4\pi C_{gs}} \sqrt{\frac{R_{ds}}{R_i}}$$

$$X = \frac{f_{-1dB}}{f_c} \quad \text{FRAC BANDWIDTH}$$

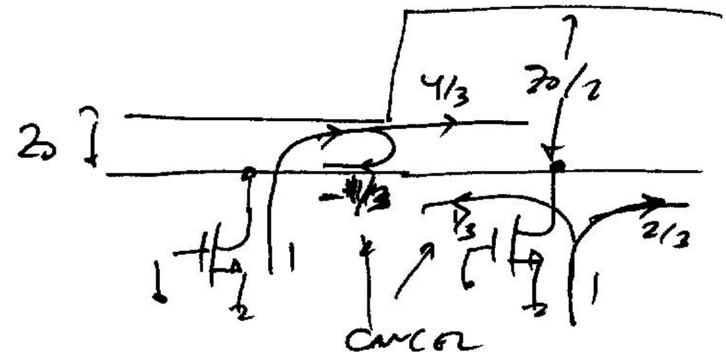
KX IS GAIN BW PRODUCT NORMALIZED TO $4 f_{max}$

$KX \simeq 0.2 \quad \Rightarrow \quad A_0 f_{1dB} \simeq 0.8 f_{max}$

LIMIT ON BROADBAND DESIGN!

$$A_0 = 10 \quad \Rightarrow \quad \underbrace{f_{1dB} = 0.08 \underbrace{f_{max}}_{100\,GHz}}_{8\,GHz}$$

TAPERED DRAIN LINE $\frac{1}{2}$ OF POWER ON DRAIN LINE IS WASTED INTO TERMINATION RESISTANCE, BY TAPERING LINE WE CAN REDUCE CURRENT IN "BACKWARD" DIRECTION



$$\frac{Z_0}{Z_0/2+Z_0} = \frac{2}{3}$$

$$\frac{Z_0/2-Z_0}{Z_0/2+Z_0} = \frac{2-1}{2+1} = -\frac{1}{3}$$

DESIGN SO ALL CURRENT GOING INTO Z_0 CANCEL $\Rightarrow$ EACH SECTION HAS IMPEDANCE Z_0/K