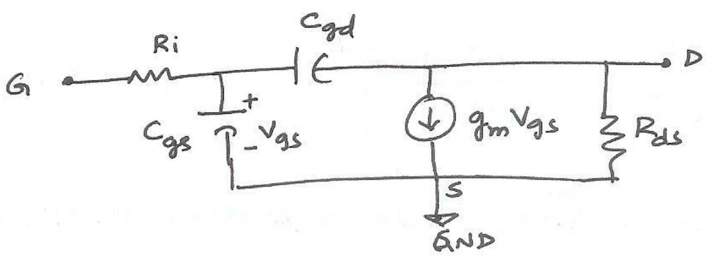
ECE 145A/218A HW#5 SOLUTIONS SARAT GUNDAVARAPU

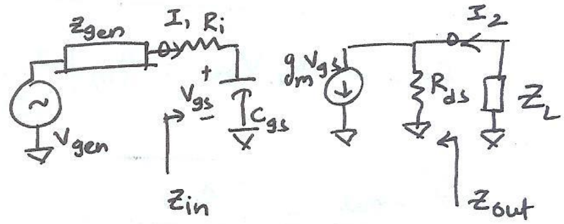
Problem - 1

1(a)



To compute MAG, match both input and o/p ports.

$Z_{gen} = Z_{in}^*$; $Z_L = Z_{out}^*$



$P_{in} = I_{in}^2 R_i$ $\qquad P_{out} = I_{out}^2 R_{ds}$

with $C_{gd} = 0F$

Clearly, $Z_{gen} = R_i - \dfrac{1}{j\omega C_{gs}}$

$$Z_{out} = R_{ds}$$

$P_{out} = I_{out}^2 R_{ds}$; $I_{out} = \dfrac{g_m V_{gs}}{2}$; $V_{gs} = I_{in}\left(\dfrac{1}{j\omega C_{gs}}\right)$

$$= \left[\frac{g_m V_{gs}}{2}\right]^2 R_{ds}$$

$$\frac{P_{out}}{P_{in}} = \left[\frac{g_m I_{in}}{2j\omega C_{gs}}\right]^2 R_{ds} \cdot \frac{1}{I_{in}^2 R_i} = \frac{-g_m^2 R_{ds}}{4\omega^2 C_{gs}^2 R_i}$$

$$MAG = \left|\frac{P_{out}}{P_{in}}\right|_{\substack{Z_{gen} = Z_{in}^* \\ Z_L = Z_{out}^*}} = \frac{g_m^2 R_{ds}}{4\omega^2 C_{gs}^2 R_i}$$

$$\boxed{MAG = \frac{g_m^2 R_{ds}}{4\omega^2 C_{gs}^2 R_i}}$$

$MAG = 1$ @ $f = f_{max} \Rightarrow f_{max} = \left[\dfrac{g_m^2 R_{ds}}{16\pi^2 C_{gs}^2 R_i}\right]^{1/2}$

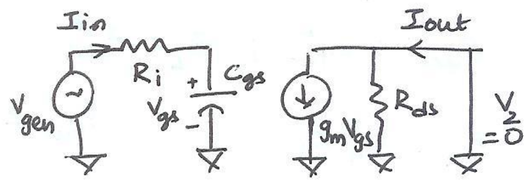
$$\Rightarrow \boxed{f_{max} = \frac{g_m}{4\pi C_{gs}}\left[\frac{R_{ds}}{R_i}\right]^{1/2}}$$

~~MAG~~ $f_{max} = \dfrac{(1.5\ mS/\mu m)\cdot W_g}{4\pi(1.0\ fF/\mu m)\cdot W_g}\left[\dfrac{1}{(1/g_m)\cdot(0.1\ mS/\mu m\cdot W_g)}\right]^{1/2}$

$$= \frac{1.5\times10^{-3}}{4\pi\times10^{-15}}\left[\frac{1.5}{0.1}\right]^{1/2} = 462.3\ GHz$$

$\boxed{f_{max} = 462.3\ GHz}$ (independent of width of gate!)

Short Circuit Current Gain



$$I_{out} = g_m V_{gs} = g_m\left[\frac{I_{in}}{j\omega C_{gs}}\right]$$

$$\Rightarrow \boxed{\frac{I_{out}}{I_{in}} = \left[\frac{g_m}{j\omega C_{gs}}\right]}$$

SC curr Gain $= 1$ @ $f = f_T$

$$\left|\frac{I_{out}}{I_{in}}\right|_{V_2=0} = \frac{g_m}{\omega_T C_{gs}} = 1$$

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

$$= \frac{1.5\ mS/\mu m\cdot W_g}{2\pi\ 1.0\ fF/\mu m\cdot W_g}$$

$$\boxed{f_T = 238.73\ GHz}$$

1 (b)

@ $\frac{f_{max}}{10} = 46.23\,GHz$

$Z_{gen} = Z_{in}^*$

$Z_{out}^* = Z_L = R_{ds}$

$Z_{in}^* = R_i - \frac{1}{j\omega C_{gs}}$

$W_g = 100\mu m$

$R_i = 1/g_m = 6.67\Omega$

$g_m = 1.5mS/\mu m \cdot W_g = 150mS$

$C_{gs} = 1.0fF/\mu m \cdot W_g = 100fF$

$G_{ds} = \frac{1}{R_{ds}} = 0.1mS/\mu m \cdot W_g$

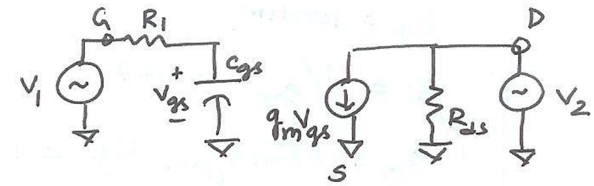
$= 10mS \Rightarrow R_{ds} = 100\Omega$

$j\omega C_{gs} = j0.063S$

$Z_{gen} = 6.67\Omega - \frac{1}{j0.063S} = (6.67 + j15.873)\Omega$

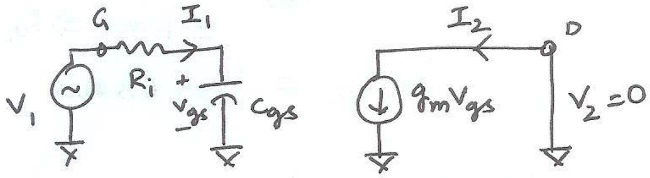
$Z_{out} = 100\Omega$

1(c)



To calculate Y_{11}, Y_{21}
Set $V_2 = 0$

$$Y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2=0} \qquad Y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2=0}$$



R_{ds} is shorted too!

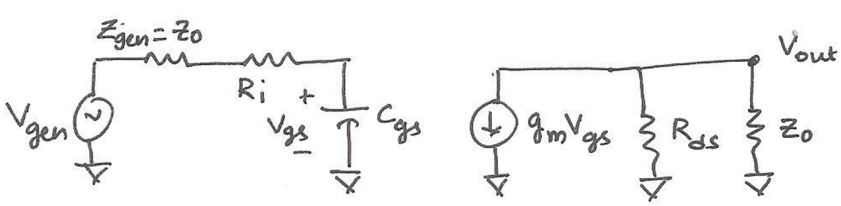
$$\cancel{Y_{11}} I_1 = \frac{V_1}{R_i + (1/j\omega C_{gs})} \Rightarrow Y_{11} = \frac{1}{R_i + (1/j\omega C_{gs})} = \frac{j\omega C_{gs}}{1 + j\omega R_i C_{gs}}$$

$$\boxed{Y_{11} = \frac{j\omega C_{gs}}{1 + j\omega R_i C_{gs}}}$$

$$I_2 = g_m V_{gs} \; ; \quad V_{gs} = \frac{V_1 \,(1/j\omega C_{gs})}{R_i + (1/j\omega C_{gs})} = \frac{V_1}{1 + j\omega R_i C_{gs}}$$

$$\Rightarrow \boxed{Y_{21} = \frac{g_m}{1 + j\omega R_i C_{gs}}}$$

$\underline{S_{21}}$; $\quad Z_{gen} = Z_L = Z_0$; $\quad S_{21} = \dfrac{2V_{out}}{V_{gen}}$



$$V_{out} = -g_m V_{gs}\left[R_{ds} \| Z_0\right]$$

$$V_{gs} = \frac{V_{gen}\left(1/j\omega C_{gs}\right)}{(Z_0 + R_i) + \left(\frac{1}{j\omega C_{gs}}\right)} = \frac{V_{gen}}{1 + j\omega C_{gs}(R_i + Z_0)}$$

$$\Rightarrow V_{out} = \frac{-g_m V_{gen} \cdot R_{ds} Z_0}{\left[1 + j\omega C_{gs}(R_i + Z_0)\right]} \frac{1}{\left[R_{ds} + Z_0\right]}$$

$$\boxed{\frac{2V_{out}}{V_{gen}} = S_{21} = \frac{-2g_m}{1 + j\omega C_{gs}(R_i + Z_0)} \cdot \left[R_{ds} \| Z_0\right]}$$

1(d) $f = 100\,\text{GHz}$; $g_m = 1.5\,\text{mS}/\mu\text{m} \cdot W_g = 0.15\,\text{S} = 150\,\text{mS}$

$W_g = 100\,\mu\text{m}$; $R_i = 6.67\,\Omega$

$Z_0 = 50\,\Omega$; $C_{gs} = 1\,\text{fF}/\mu\text{m} \cdot W_g = 100\,\text{fF}$

f - $G_{ds} = 0.1\,\text{mS}/\mu\text{m} \cdot W_g = 10\,\text{mS} \Rightarrow R_{ds} = \frac{1}{10\,\text{mS}} = 100\,\Omega$

$j\omega C_{gs} = j0.063\,\text{S}$

(i) Insertion Power gain: $G_i \|S_{21}\|^2$ Gain with 50Ω source, Load Impedance

$$S_{21} = \frac{-2 \times 0.15\,\text{S}}{1 + j0.063(56.67)} \cdot \left[100\Omega \| 50\Omega\right] \quad \{\text{from } 1(c)\}$$

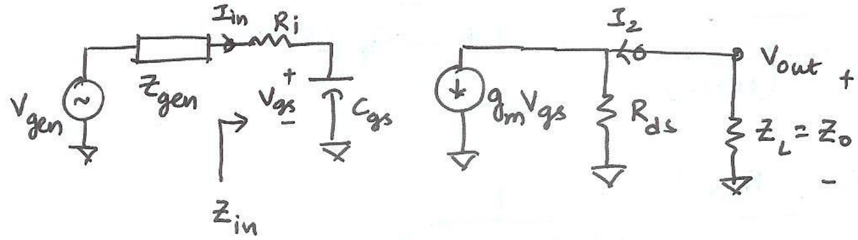
$$= \frac{-0.3 \times \left(\frac{100}{3}\right)}{1 + j3.56} = \frac{-10}{1 + j3.56}$$

$$\|S_{21}\|^2 = \left[\frac{10}{\sqrt{1 + (3.56)^2}}\right]^2 = \frac{100}{1 + 12.678} = 7.31$$

$$10 \cdot \log \|S_{21}\|^2 \approx \boxed{8.64\,\text{dB} = G_i}$$

(ii) Operating power gain : G_p : Gain w/ input matched.

$$Z_{gen} = Z_{in}^{*} \quad ; \quad Z_L = Z_0 = 50\Omega$$



As in pr #1, $P_{in} = |I_{in}^2 R_i|$ and $I_{in} = V_{gs}(j\omega C_{gs})$

$$\Rightarrow P_{in} = \omega^2 C_{gs}^2 V_{gs}^2 R_i$$

$$P_{out} = I_{out}^2 Z_L = \Bigg[g_m V_{gs} \cdot \underbrace{\frac{R_{ds}}{R_{ds} + Z_0}}_{\text{current Divider}} \Bigg]^2 \times Z_0$$

$$G_p = \frac{P_{out}}{P_{in}} = \frac{g_m^2 V_{gs}^2 R_{ds}^2 Z_0}{(R_{ds}+Z_0)^2 \omega^2 C_{gs}^2 V_{gs}^2 R_i}$$

$$\boxed{G_p = \left[\frac{g_m R_{ds}}{(R_{ds}+Z_0)\omega C_{gs}} \right]^2 \times \frac{Z_0}{R_i}}$$

@ 100GHz $\quad G_p = \left[\dfrac{0.15 \times 100}{150 \times 0.063} \right]^2 \times \dfrac{50}{6.67} = 18.89$

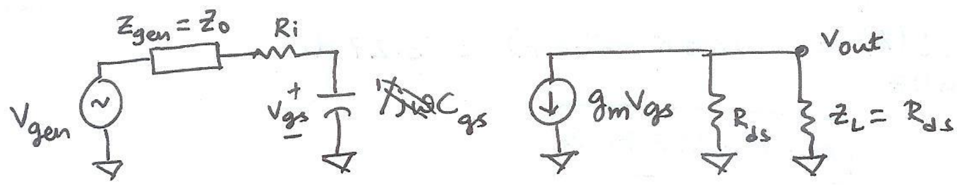
$$10 \log_{10}(G_P) = 12.76\ dB \qquad \boxed{G_P = 12.76 dB}$$

(iii) Available power gain : G_a : Gain w/ output matched $= \dfrac{P_{av,amp}}{P_{av,gen}}$

$$P_{out} = \frac{1}{4} g_m^2 V_{gs}^2 R_{ds} \quad \left[\begin{array}{c}\text{same as MAG's } P_{out} \\ \text{see 1(a)}\end{array}\right]$$

$$V_{gs} = I_{in} / j\omega C$$

$$I_{in} = \frac{V_{gen}}{Z_{gen} + Z_{in}} = \frac{V_{gen}}{Z_0 + R_i + \frac{1}{j\omega C}}$$



$$\Rightarrow V_{gs} = \frac{V_{gen}}{1 + j\omega C\,(R_i + Z_0)}$$

and $$P_{out} = \frac{\frac{1}{4} g_m^2 V_{gen}^2 R_{ds}}{\left(1 + j\omega C\,(R_i + Z_0)\right)^2}$$

$$P_{in} = P_{av,gen} = \frac{1}{4}\frac{V_{gen}^2}{Z_0}$$

$$G_a = \frac{P_{out}}{P_{in}} = \frac{\frac{1}{4} g_m^2 V_{gen}^2 R_{ds} Z_0}{\frac{1}{4} V_{gen}^2 \left[\left(1 + j\omega C(R_i + Z_0)\right)\right]^2}$$

$$G_a = \frac{g_m^2 R_{ds} Z_0}{\left[1 + j\omega(R_i + Z_0)C\right]^2}$$

$$@\,100\,\text{GHz},\ |G_a| = \frac{0.15 \times 100 \times 50 \times 0.15}{1 + (\omega C_{gs})^2 (R_i + Z_0)^2}$$

$$= \frac{750 \times 0.15}{1 + [0.063 \times 56.67]^2}$$

$$= \frac{750 \times 0.15}{13.678} = \cancel{54.83}\ 8.2245$$

$$G_a|_{dB} = 10\log_{10}\left(\frac{8.2245}{\cancel{54.83}}\right) = \cancel{17.939\,dB}\ \ 9.151$$

$$\boxed{\cancel{G_a} = \cancel{17.93}\,dB} \qquad \boxed{G_a = 9.151\,dB}$$

(iv) From 1(a), MAG @ 100 GHz $= \dfrac{g_m^2 R_{ds}}{4\omega^2 C_{gs}^2 R_i} = \dfrac{0.15 \times 0.15 \times 100}{4\,(0.063)^2 \times 6.67} = 21.24$

$$MAG\Big|_{f=100GHz} (dB) = 10\log 10\,(21.24) = 13.27\,dB$$

$$\boxed{MAG = 13.27\,dB}$$

All the calculated values match well with simulated values.

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2. $S_{11} = 0.5$

$S_{22} = 0.7071$

$S_{12} = 0$

$S_{21} = 10$

(a) $Z_{gen} = 50\Omega$

$P_{av,gen} = 1mW$

$Z_L = Z_0 = 50\Omega$

$$\underset{(Z_s = Z_L = Z_0)}{\text{Insertion Gain}} = \left\| S_{21} \right\|^2 = \frac{\text{Power Delivered to } Z_0 \text{ Load}}{\text{Power available from } Z_0 \text{ generator}}$$

Power Delivered to Z_0 load $= \underline{0.1\,W}$

(b) $Z_{gen} = 75\Omega$; $Z_L = 25\Omega$

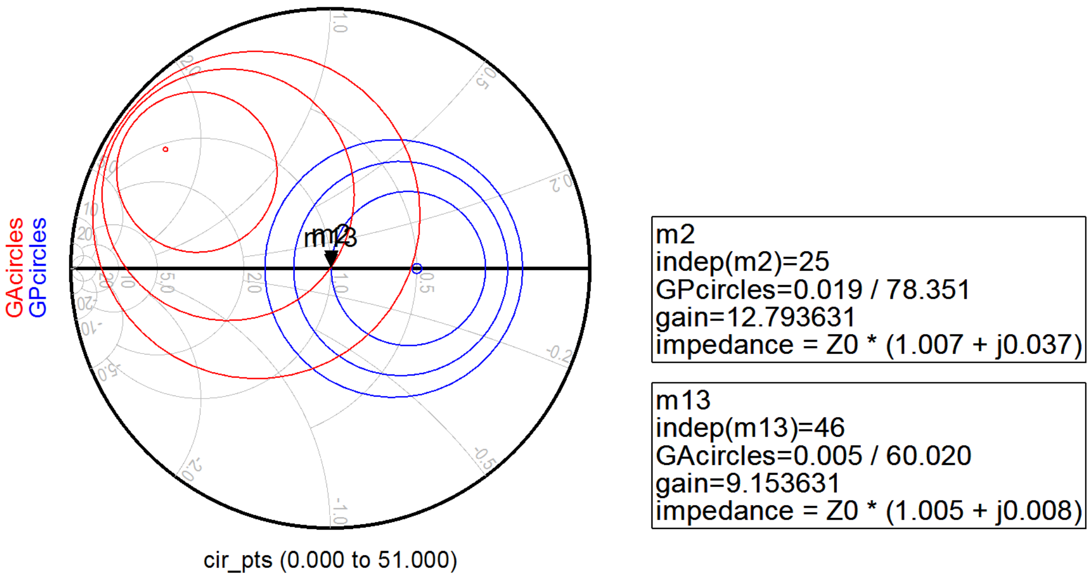
$$\Gamma_s = \frac{75-50}{75+50} = \frac{1}{5} \qquad \Gamma_L = \frac{25-50}{25+50} = \frac{-1}{3} \qquad G_T = \frac{|S_{21}|^2 (1-|\Gamma_s|^2)(1-|\Gamma_L|^2)}{|(1-\Gamma_s S_{11})(1-\Gamma_L S_{22}) - S_{21} S_{12} \Gamma_s \Gamma_L|^2}$$

Substituting the values,

$$G_T = \frac{(10)^2 \left(1-\frac{1}{25}\right)\left(1-\frac{1}{9}\right)}{\left|\left(1-\left(\frac{1}{5}\right)(0.5)\right)\left(1-\left(\frac{-1}{3}\right)\left(\frac{1}{\sqrt{2}}\right)\right)\right|^2} = 69.25$$

Power delivered to load $\rightarrow$ 69.25 mW

Problem 1(d)



Eqn GAstep_size=2.07

Eqn num_GAcircles=3

Eqn GPstep_size=0.5

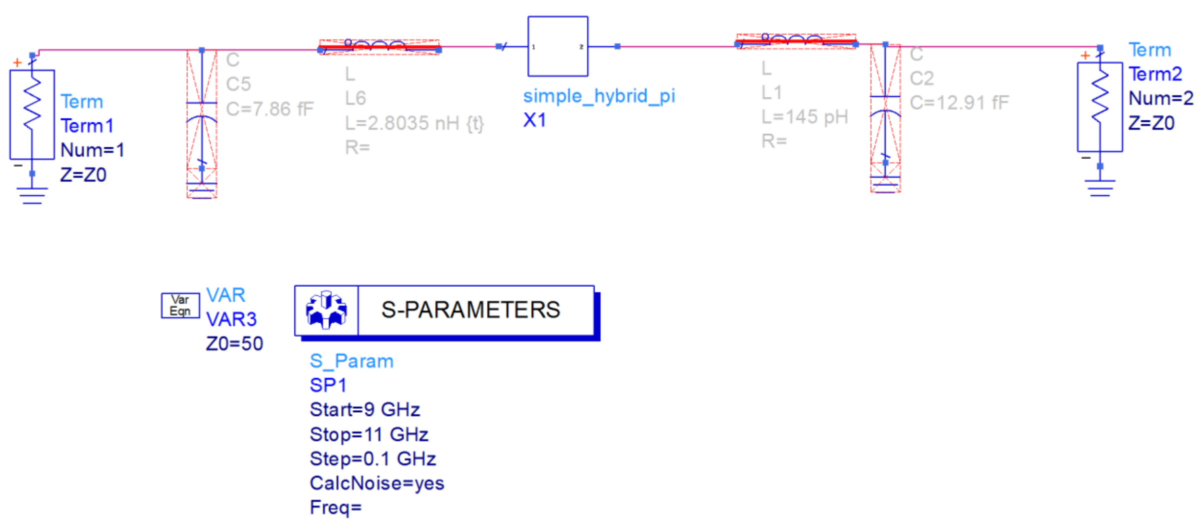
Eqn num_GPcircles=3

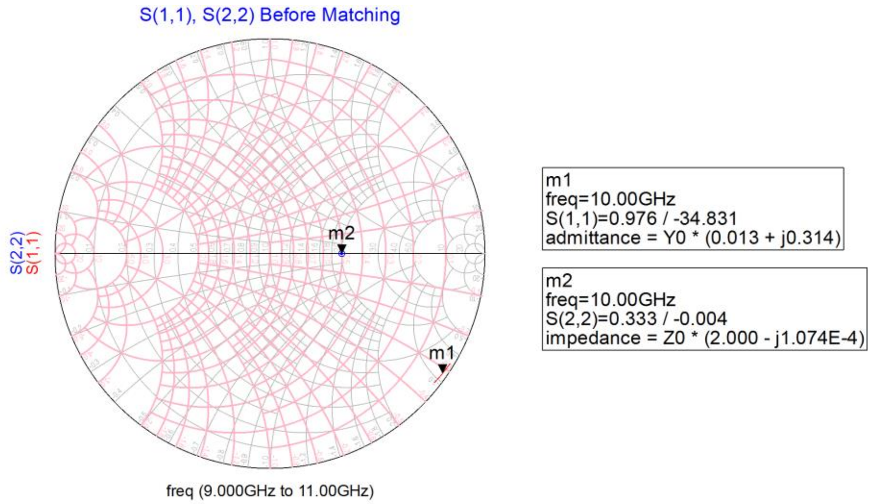
Eqn InsertionGain= mag(S(2,1))**2

Eqn InsertionGaindB = 10*log10(InsertionGain)

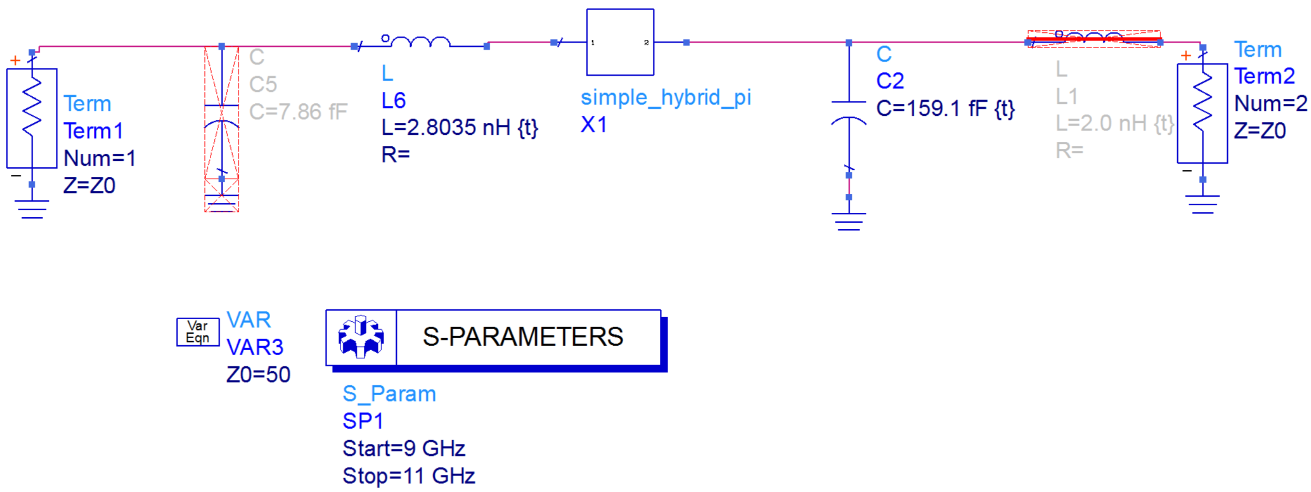
freq	InsertionGain	InsertionGaindB	MaxGain
100.0 GHz	7.310	8.639	13.296

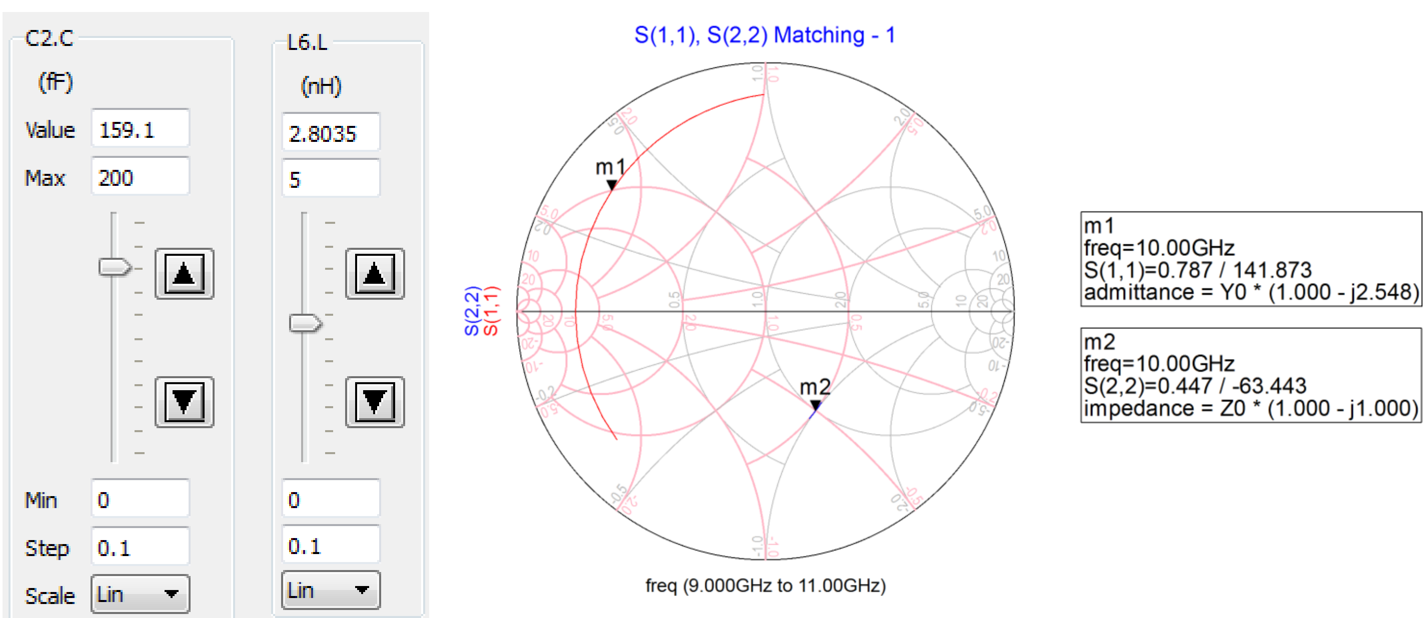
Problem 1(e)



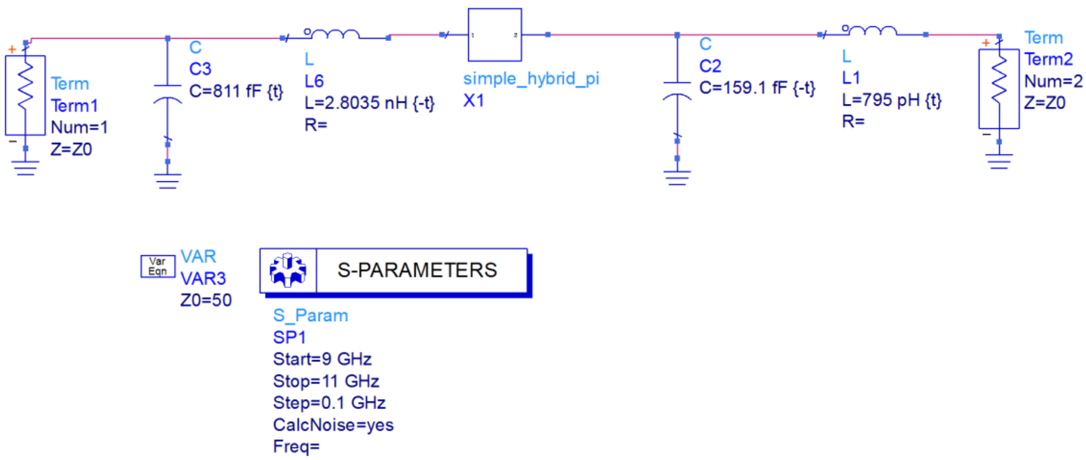


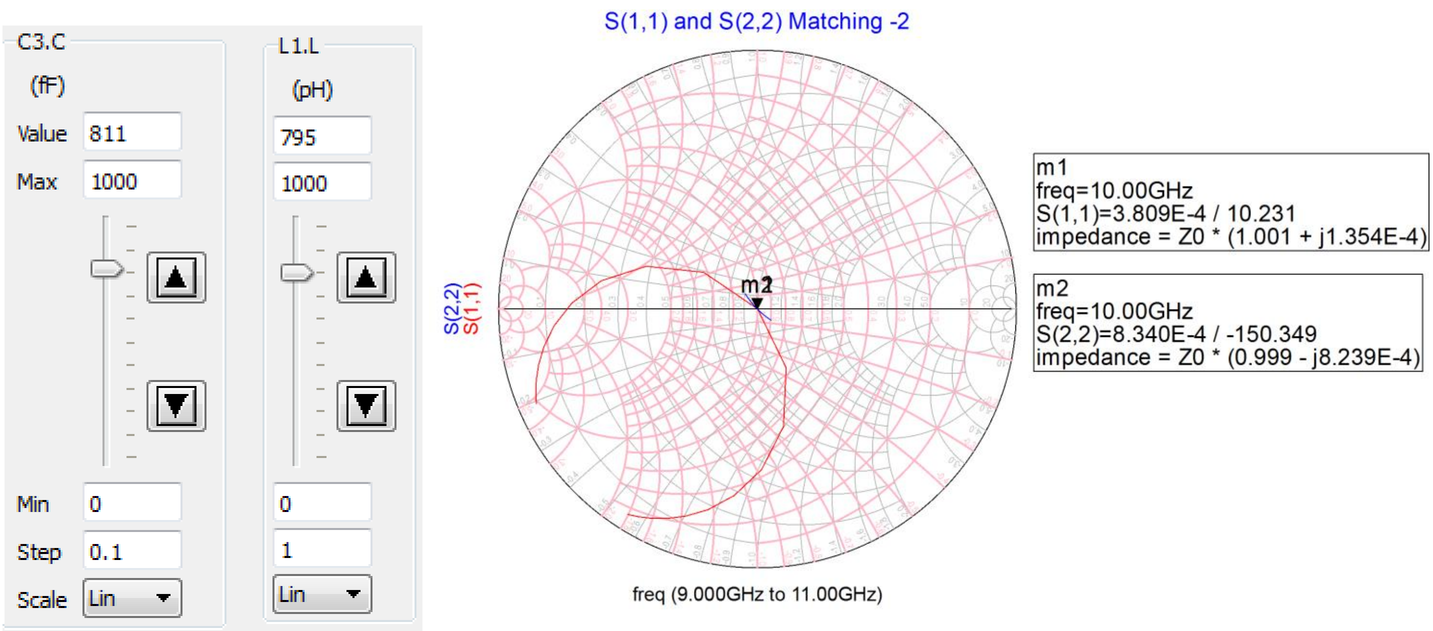
MATCHING PART – 1:

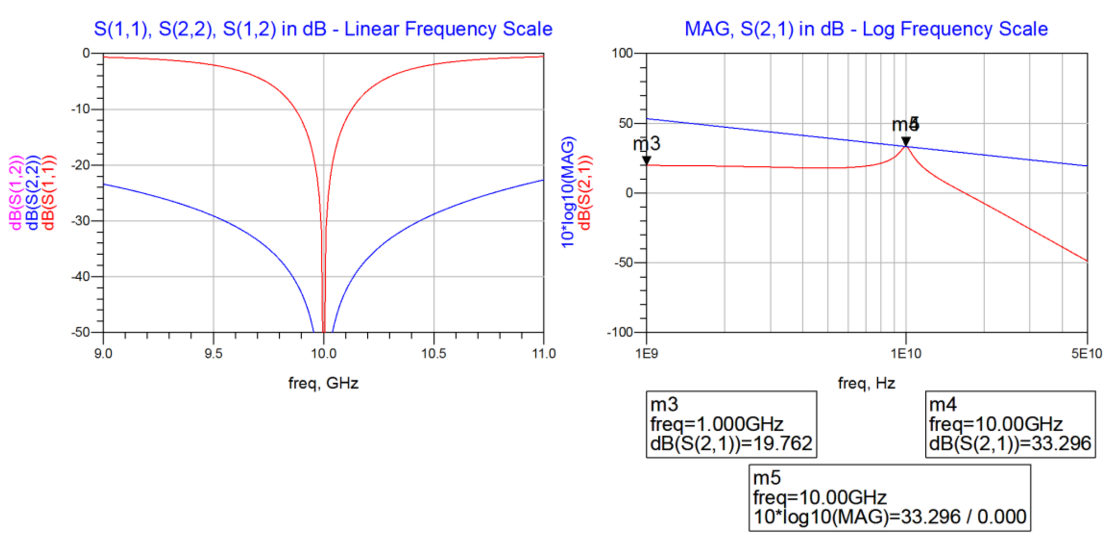




MATCHING PART – 2:







Eqn MAG=(StabFact1-sqrt(StabFact1**2 - 1))*mag(S(2,1))/mag(S(1,2))

2(c) Gain w/input matched, $\Rightarrow$ operating power gain, G_P

$$G_P = \frac{1}{1-\Gamma_{in}^2} \cdot |S_{21}|^2 \frac{1-|\Gamma_L|^2}{|1-\Gamma_L S_{22}|^2}$$

$\because$ the device is unilateral, i.e, $S_{12}=0$,

① $$\Gamma_{in} = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1-S_{22}\Gamma_L} = S_{11} = 0.5$$

$$\left[\text{and } \Gamma_{out} = S_{22} + \frac{S_{21}S_{12}\Gamma_S}{1-S_{11}\Gamma_S} = S_{22} = 0.707\right]$$

② $$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{30-50}{30+50} = -0.25$$

$$\Rightarrow G_P = \frac{1}{1-0.25} \cdot 100 \cdot \frac{1-(-0.25)^2}{|1-(-0.25)(0.707)|^2}$$

$$= \frac{4}{3} \cdot 100 \cdot \frac{\left(1-\frac{1}{16}\right)}{\left(1+\frac{1}{4\sqrt{2}}\right)^2} = \frac{\frac{400 \times \cancel{15}^{5}}{\cancel{16} \times \cancel{3}}}{\frac{(4\sqrt{2}+1)^2}{\cancel{16} \times 2}} = \frac{4000}{1+32+8\sqrt{2}}$$

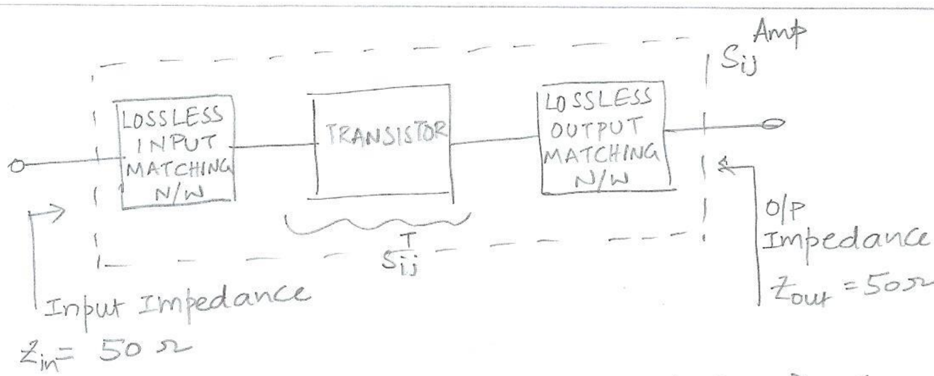
$$= \frac{4000}{33+8\sqrt{2}}$$

$$G_P = 103.476$$

$\Rightarrow$ O/p Power = 103.476 mW

$$\boxed{P_{out} \approx 0.103 W}$$

2(d)



We will find S-params of this n/w & use them to find P_{out} for given Z_{gen}, Z_L

Since the transistor is already matched at the input and output to 50Ω, the input and output reflection coefficients of the total network. $S_{11}^{Amp} = S_{22}^{Amp} = 0$. Since the network is unilateral, $S_{12}^{Amp} = 0$, We need to find S_{21}^{Amp}.

For a unilateral device,
$$G_{Max}^{Trans} = \frac{1}{1-|S_{11}^{Trans}|^2} \left|S_{21}^{Trans}\right|^2 \frac{1}{1-|S_{22}^{Trans}|^2}$$

$$= \frac{1}{1-(0.5)^2} \cdot (10)^2 \frac{1}{1-\left(\frac{1}{\sqrt{2}}\right)^2}$$

$$G_{Max}^{Trans} = \frac{4}{3} \times 100 \times 2$$

$$= 100\left[\frac{8}{3}\right]$$

By definition, $G_{Max}^{Trans} = G_{Max}^{Amp}$

So, $$\frac{1}{1-|S_{11}^{Amp}|^2} \cdot \left|S_{21}^{Amp}\right|^2 \frac{1}{1-|S_{22}^{Amp}|^2} = 100\left(\frac{8}{3}\right)$$

$$\because S_{11}^{Amp} = S_{22}^{Amp} = 0 \Rightarrow S_{21}^{Amp} = 10\sqrt{\frac{8}{3}}$$

$$\Rightarrow [S]^{Amp} = \begin{bmatrix} 0 & 0 \\ 10\sqrt{\frac{8}{3}} & 0 \end{bmatrix}$$

Now, with $Z_{gen} = 25\Omega$, $\Gamma_S = \frac{25-50}{25+50} = \frac{-1}{3}$

and $Z_L = 100\Omega$, $\Gamma_L = \frac{100-50}{100+50} = \frac{1}{3}$

$$\Rightarrow G_T^{Amp} = \frac{\left|S_{21}^{Amp}\right|^2 \left[1-|\Gamma_S|^2\right]\left[1-|\Gamma_L|^2\right]}{\left|\left(1-\Gamma_S S_{11}^{Amp}\right)\left(1-\Gamma_L S_{22}^{Amp}\right) - S_{21}^{Amp} S_{12}^{Amp}\Gamma_S\Gamma_L\right|^2}$$

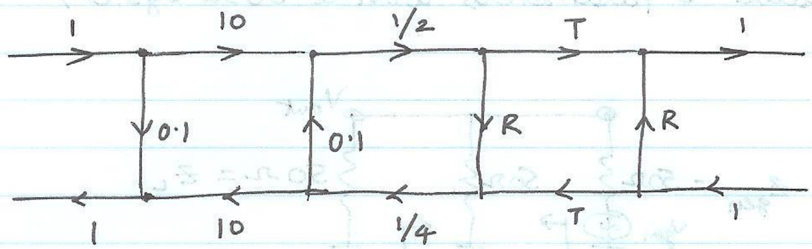
$$= 100\cdot\left(\frac{8}{3}\right)\cdot\left(1-\frac{1}{9}\right)^2 \quad \left\{\because S_{11}^{Amp} = S_{22}^{Amp} = S_{12}^{Amp} = 0\right\}$$

$$= 100 \cdot \frac{8}{3} \cdot \frac{64}{81} \approx 210.7 \Rightarrow \boxed{P_{Load} = 210.7\,mW} = 0.21\,W$$

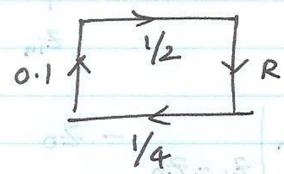
Pr-4:

$$[S]_{laser} = \begin{bmatrix} 0.1 & 10 \\ 10 & 0.1 \end{bmatrix} ; \quad [S]_{iso} = \begin{bmatrix} 0 & 0.25 \\ 0.\cancel{7}5 & 0 \end{bmatrix} ; \quad [S]_{att} = \begin{bmatrix} R & T \\ T & R \end{bmatrix}$$

Drawing the signal flow graph,



Only 1 loop in the path,



Loop Gain $= \frac{R}{80}$

$$\rightarrow S_{21} = \frac{\text{Forward Gain}}{1 - \text{Loop Gain}} = \frac{[1 * 10 * \frac{1}{2} * T * 1]}{1 - \frac{R}{80}} = \frac{5T}{1 - \frac{R}{80}}$$

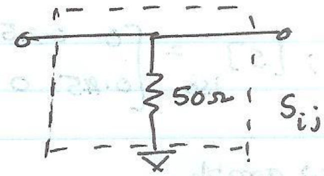
$\rightarrow S_{11}$ = Sum of 2 reflection paths

$$= 0.1 + \left[\frac{10 \times \frac{1}{2} \times R \times \frac{1}{4} \times 10}{1 - \frac{R}{80}} \right] = 0.1 + \frac{100R/8}{1 - \frac{R}{80}}$$

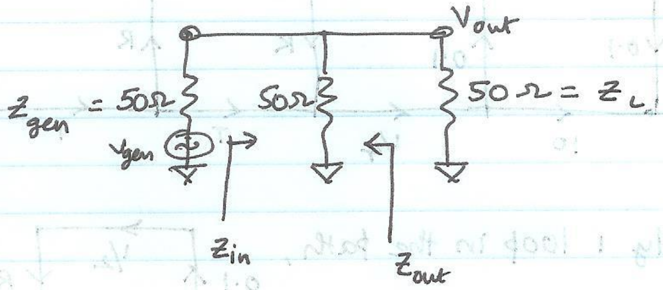
$$\rightarrow S_{22} = R + \left[\frac{T \times \frac{1}{4} \times 0.1 \times \frac{1}{2} \times T}{1 - \frac{R}{80}} \right] = R + \frac{T^2/80}{1 - R/80}$$

$$\rightarrow S_{12} = \frac{T \times \frac{1}{4} \times 10}{1 - R/80} = \frac{2.5T}{1 - R/80}$$

Pr-3 (a)



Calculate S-parameters with a 50Ω system



$$S_{11} = \frac{Z_{in}\big|_{Z_L = Z_0} - Z_0}{Z_{in}\big|_{Z_L = Z_0} + Z_0} \quad ; \quad Z_{in}\big|_{Z_L = Z_0} = 25\,\Omega$$

$$= \frac{-25}{75} = -0.33 \qquad \boxed{S_{11} = -0.33}$$

Similarly,

$$S_{22} = \frac{Z_{out}\big|_{Z_{gen} = Z_0} - Z_0}{Z_{out}\big|_{Z_{gen} = Z_0} - Z_0} \quad ; \quad Z_{out}\big|_{Z_{gen} = Z_0} = 25\,\Omega$$

$$\boxed{S_{22} = -0.33}$$

$$S_{21} = \frac{2V_{out}}{V_{gen}}\bigg|_{Z_L = Z_{gen} = Z_0}$$

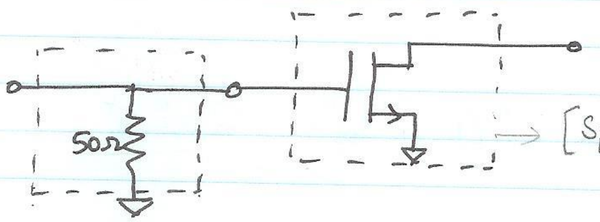
$$V_{out} = \frac{V_{gen}\,[50 \| 50]\,\Omega}{(50 + [50 \| 50])\,\Omega} = \frac{V_{gen}}{3}$$

$$\Rightarrow S_{21} = \frac{2}{3} = 0.67 \qquad \boxed{S_{21} = 0.67}$$

$S_{12} \rightarrow$ Circuit is symmetrical $\Rightarrow S_{12} = S_{21} = \frac{2}{3} = 0.67$

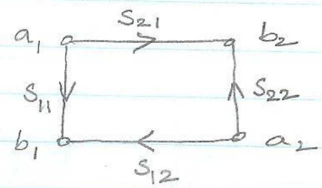
$$\underset{(Res)}{[S]_{ij}} = \begin{bmatrix} -0.33 & 0.67 \\ 0.67 & -0.33 \end{bmatrix}$$

(b) Resistor is connected b/w FET input and GND. Find s-parameter of Combined N/W

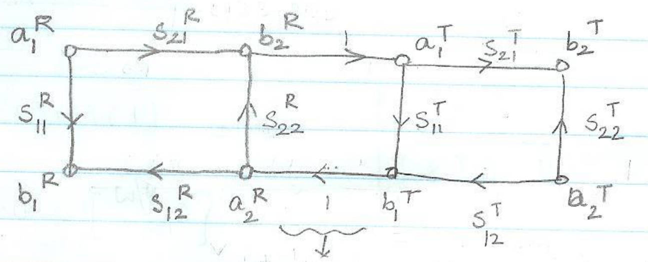


$$\rightarrow [S_{ij}]^T = \begin{bmatrix} 0.25 & 1 \\ 10 & 0.125 \end{bmatrix}$$

SAMPLE SIGNAL FLOW GRAPH FOR A 2-PORT N/W

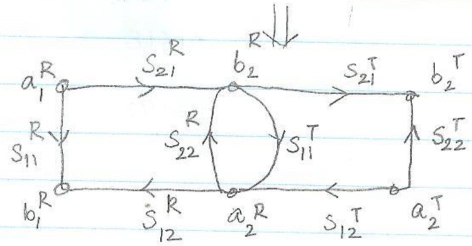


COMBINED N/W OF THE RESISTOR AND TRANSISTOR



Indicating Direct Connections (NO DELAYS!)

$\Downarrow$



$S_{11} = \dfrac{b_1^R}{a_1^R}$ | $S_{12} = \dfrac{b_1^R}{a_2^T}$

$S_{22} = \dfrac{b_2^T}{a_2^T}$ | $S_{21} = \dfrac{b_2^T}{a_1^R}$

Use Mason's GAIN RULE,
$$\frac{P_1[1 - \Sigma L^1(1) + \Sigma L^1(2) + \cdots] + P_2[1 - \Sigma L^2(1) + \Sigma L^2(2) \cdots] + \cdots}{1 - \Sigma L(1) + \Sigma L(2) - \Sigma L(3)}$$

EASE OF CALCULATION: ONLY ONE LOOP $\dfrac{1}{1-S_{22}^{R}S_{11}^{T}} \rightarrow \dfrac{1}{1-\left(-\frac{1}{3}\right)\left(\frac{1}{4}\right)} = \dfrac{12}{13} = \underline{0.923}$

Using the above rule, S-parameters of the new N/W will be computed.

S_{11}

$$S_{11} = \frac{S_{11}^{R}\left[1-S_{22}^{R}S_{11}^{T}\right] + S_{21}^{R}S_{11}^{T}S_{12}^{R}}{1-S_{22}^{R}S_{11}^{T}}$$

$$\boxed{S_{11} = S_{11}^{R} + \frac{S_{21}^{R}S_{11}^{T}S_{12}^{R}}{1-S_{22}^{R}S_{11}^{T}}} = -0.33 + (0.67)(0.25)(0.67)(0.923)$$

$$\boxed{S_{11}^{N/W} = -0.225}$$

$S_{22} \rightarrow$

$$S_{22} = \frac{S_{22}^{T}\left[1-S_{11}^{T}S_{22}^{R}\right] + S_{12}^{T}S_{22}^{R}S_{21}^{T}}{1-S_{11}^{T}S_{22}^{R}}$$

$$\boxed{S_{22} = S_{22}^{T} + \frac{S_{12}^{T}S_{22}^{R}S_{21}^{T}}{1-S_{11}^{T}S_{22}^{R}}} = (0.125) + (1)(-0.33)(10)(0.923)$$

$$\boxed{S_{22}^{N/W} = -2.92}$$

S_{21}

$$\boxed{S_{21} = \frac{S_{21}^{R}S_{21}^{T}}{1-S_{11}^{T}S_{22}^{R}}} = (0.67)(10)(0.923)$$

$$\boxed{S_{21}^{N/W} = 6.18}$$

S_{12} –

$$\boxed{S_{12} = \frac{S_{12}^{T}S_{12}^{R}}{1-S_{11}^{T}S_{22}^{R}}} = (1)(0.67)(0.923)$$

$$\left[S_{12}^{N/W}\right] = 0.618$$

$$\boxed{\left[S_{ij}\right]^{N/W} = \begin{pmatrix} -0.225 & 0.618 \\ 6.18 & -2.92 \end{pmatrix}}$$