

Paper Number(s): **E4.18**  
**AM5**

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE  
UNIVERSITY OF LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING  
EXAMINATIONS 2001

MSc and EEE PART IV: M.Eng. and ACGI

**RADIO FREQUENCY ELECTRONICS**

There are SIX questions on this paper.

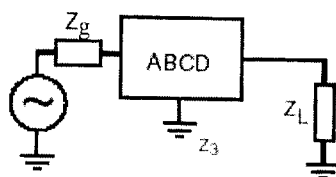
Answer FOUR questions.

Time allowed: 3:00 hours

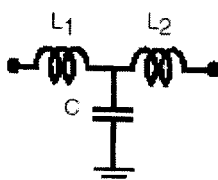
Examiners: Papavassiliou, C. and Payne, A.J.



1. A certain circuit will be used as a filter between a generator of amplitude  $V_g$  and impedance  $Z_g$  and a load  $Z_L$ . This circuit can be represented by an  $ABCD$  matrix.
- a) State the definition of the  $ABCD$  matrix. From this definition directly compute the voltage transfer function  $G=V_L/V_G$  of the circuit of figure 1. in terms of its  $ABCD$  parameters, as well as  $Z_g$  and  $Z_L$ .  
[5 marks]
- b) From the definition of the  $ABCD$  matrix directly compute the current transfer function  $H=I_L/I_G$  of the circuit in figure 1. in terms of its  $ABCD$  parameters, as well as  $Z_g$  and  $Z_L$ .  
[5 marks]
- c) From your answers in questions a) and b) above compute the power gain of this network.  
[5 marks]
- d) Using component  $ABCD$  matrices compute the voltage and current gain of the tee network in fig. 2. Compute its input impedance if it is terminated in a load  $Z_L$ . Show it performs an impedance matching function, but do not compute the component values necessary to implement a particular impedance matching transformer.  
[10 marks]



**Figure 1:** A 2-port network connected as a filter



**Figure 2:** A Tee network filter

2. High speed diodes manufactured on an Integrated Circuit substrate often have one of their terminals, usually the cathode, connected to the substrate. The substrate is, however, also the ground plane for the microstrip lines used for interconnection and impedance matching. We are required to design a monolithic microwave switch using a grounded cathode diode as depicted in figure 3.

a) Describe an impedance transformation approach to make this diode appear in series, so that the switch depicted in figure 4. can be implemented. Implement this impedance transformation approach using microstrip lines. If the phase velocity on a substrate is  $1 \times 10^8$  m/s what is the required physical length of these lines for a 10 GHz operating frequency?

**[5 marks]**

b) The diode must be switched on and off to perform the couple/isolate functions of the switch in figure 4. Design appropriate microstrip networks to supply the necessary bias. Note that your circuit should be such that the supply is completely invisible at signal frequencies.

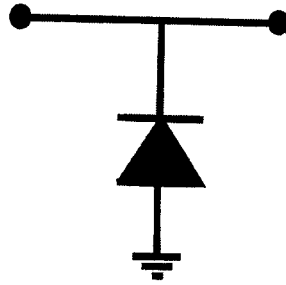
**[7 marks]**

c) With the aid of a diagram show how we can implement DC isolation between the power supply and the external circuits connected to the two terminals of the switch.

**[5 marks]**

d) Compute the insertion loss,  $\left| \frac{1}{S_{21}} \right|^2$  of your switch when used between  $50 \Omega$  lines. Explain how you can minimise the insertion loss of this switch by properly choosing the impedance of your transmission line transformers. What is the minimum insertion loss of this diode in the ON state given that the diode ON resistance is 15 ohms, and the fabrication process permits you to manufacture transmission lines of  $Z_0$  between 20 and 125 ohms?

**[8 marks]**



**Figure 3:** A diode is only available as a shunt connected element



**Figure 4:** Desired connection for the diode

3. A mobile telephone operator needs you to specify the required transmitter power, and physical size of a base station antenna in order to implement error free communications between the base station and mobile terminals. The following specifications are available:

<b>System</b>	
Operating frequency	1.8GHz
Data bandwidth	56 kBit/s
Analogue Bandwidth	10 kHz
Range	10km
<b>Mobile Terminal</b>	
Antenna effective aperture	16.67 cm <sup>2</sup>
Antenna Noise temperature	300 K
Receiver path noise figure	15dB
Transmitter power	10 mW
<b>Base Station</b>	
Antenna temperature	150 K
Receiver path noise figure	5dB
Antenna aperture efficiency	50%
Antenna Electrical efficiency	90%

- a) What is the required  $S/N$  at the end of the receiver path in order to implement error free communications under the system specifications?

[5 marks]

- b) Assume the base station is in receive mode, and that a minimum  $S/N=15\text{dB}$  above the theoretical minimum is required for error free reception. What must the base station antenna effective aperture be to ensure error free reception? What is its physical size? What is its directivity? What is its polar extent, given that its azimuthal extent is 50 degrees?

[10 marks]

- c) Assume the base station is in transmit mode. What is the minimum transmit power which will result in error-free reception at the mobile terminal? You may assume the same, as in part (b),  $S/N$  ratio for error free reception.

[10 marks]

$$(k_B = 1.38 \cdot 10^{-23} \text{ J/K})$$

4. An ideal transconductor is defined by the following equations:

$$I_1 = 0$$

$$I_2 = g V_1$$

a) Write the **Y** matrix for an ideal transconductor.

[2 marks]

b) Write the **Y** matrix for the circuit in fig. 5a, where two transconductors, of transconductance  $g$  and  $-g$  are connected so that the input of one is the output of the other. This circuit is one of many possible implementations of a gyrator, which we will symbolise as  $K$  ( $K=1/g$ ) (fig 5b). From the **Y** matrix derive the **ABCD** matrix for this gyrator. What is its bandwidth?

[4 marks]

c) Derive the **ABCD** matrix for a cascade of two gyrators,  $K_1$  and  $K_2$ . From your answer draw and clearly label an equivalent circuit for this configuration.

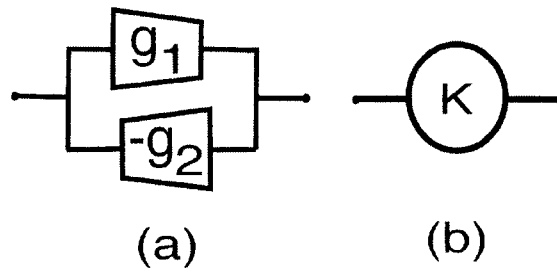
[5 marks]

d) Derive the **ABCD** matrices, and draw and clearly label equivalent circuits for each of the networks in figure 6.

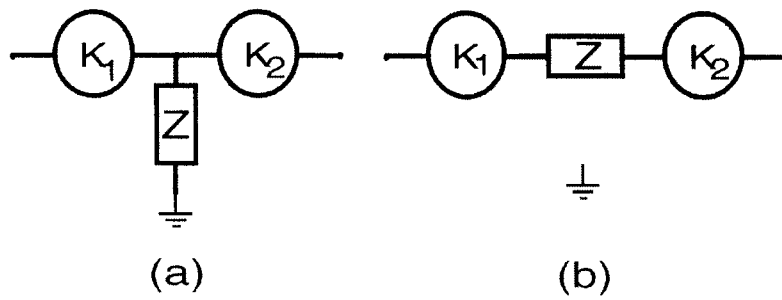
[8 marks]

e) Deduce, draw and clearly label equivalent circuits for a series **LC** network substituted for **Z** in fig 6a, and a parallel **LC** network substituted for **Z** in fig 6b, both terminated at  $Z_T$ .

[6 marks]



**Figure 5** A gyrator (a) implementation, (b) symbol



**Figure 6** Gyrated circuit elements (a) shunt, (b) series



5) In an RF application we need to isolate our circuit from microwave oven interference, and thus decide to use a 2.45 GHz band reject filter with 100 MHz bandwidth. We will base the design on the 3<sup>rd</sup> order 1dB Chebyshev normalised lowpass prototype of figure 7.

a) Using this prototype design a 2.45 GHz lumped band reject filter with a stop band of 100 MHz to operate between 50 Ohm source and load.

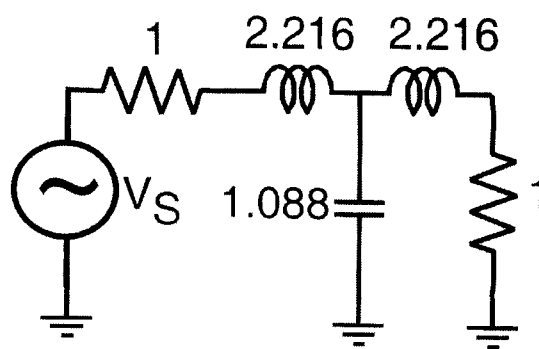
**[10 marks]**

b) How can the filter components be implemented using transmission lines? Assume you are working with balanced lines so that both series and shunt connections are allowed. Write equations for these components in terms of the line segment impedances and lengths. Draw a schematic for the filter clearly illustrating the appearance of the filter if made using balanced lines.

**[5 marks]**

c) Implement the filter using only microstrip resonators and microstrip lines. Write expressions for, but do not compute line lengths and impedances.

**[10 marks]**



**Figure 7:** Filter prototype of question 5.

6) The network in figure 8 is often used as an impedance matching transformer between real impedances  $R$  and  $R_{in}$ .

a) Derive expressions for the components of the impedance matching network in figure 8. You are given the terminating resistances, the frequency of operation, and the desired fractional 3dB bandwidth of the match.

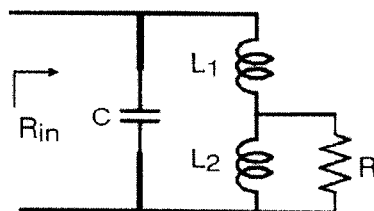
[10 marks]

b) What is the range of ratios between  $R$  and  $R_{in}$  that you can achieve with this transformer ?

[10 marks]

c) How do you need to modify the component values you calculated in (a) to accommodate complex terminating impedances?

[5 marks]



**Figure 8:** An impedance matching circuit.

RF

Question 1

$$2) \begin{bmatrix} \bar{V}_1 \\ \bar{I}_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \bar{V}_2 \\ -\bar{I}_2 \end{bmatrix}$$

$$V_1 = V_g - Z_s I_1 \Rightarrow I_1 = \frac{V_g - V_1}{Z_s} \quad (1)$$

$$V_2 = -Z_L I_2 \Rightarrow I_2 = -\frac{V_2}{Z_L} \quad (2)$$

$$V_1 = A V_2 - B I_2 = A V_2 + B \frac{V_2}{Z_L} \quad (3)$$

$$I_1 = C V_2 - D I_2 \Rightarrow \frac{V_g - V_1}{Z_s} = C V_2 + D \frac{V_2}{Z_L} \Rightarrow$$

$$\frac{V_g}{Z_s} = \frac{A V_2}{Z_s} + \frac{B V_2}{Z_s Z_L} + C V_2 + \frac{D V_2}{Z_L} \Rightarrow$$

$$V_g = V_2 \cdot \left( A + \frac{B}{Z_L} + C Z_s + D \frac{Z_s}{Z_L} \right) \Rightarrow$$

$$\frac{V_2}{V_g} = \left( A + \frac{B}{Z_L} + C Z_s + D \frac{Z_s}{Z_L} \right)^{-1} = G \quad [S]$$

(b) The current gain is just from the second eq. in the ABCD definition:

$$I_1 = C V_2 - D I_2 = C Z_L I_2 - D I_2 \Rightarrow$$

$$I_1 = I_2 (-C Z_L - D) \Rightarrow \frac{I_2}{I_1} = -\frac{1}{C Z_L + D} = H \quad [S]$$

$$(c) G_p = \frac{P_{out}}{P_{in}} = \frac{-V_2 I_2}{V_1 I_1} = -GH \text{ (and substitute)} [S]$$

(2)

$$d) X_{ser L} = \begin{bmatrix} 1 & j\omega L \\ 0 & 1 \end{bmatrix}$$

$$X_{shunt C} = \begin{bmatrix} 1 & 0 \\ j\omega C & 1 \end{bmatrix}$$

$$\text{then } X_{filter} = \begin{bmatrix} 1 & j\omega L_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\omega C & 1 \end{bmatrix} \begin{bmatrix} 1 & j\omega L_2 \\ 0 & 1 \end{bmatrix} =$$

$$= \begin{bmatrix} 1 - \omega^2 L_1 C & j\omega L_1 \\ j\omega C & 1 \end{bmatrix} \begin{bmatrix} 1 & j\omega L_2 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 - \omega^2 L_1 C & j\omega(L_1 + L_2) - j\omega^3 L_1 L_2 C \\ j\omega C & 1 - \omega^2 L_2 C \end{bmatrix}$$

$$G = \left( \frac{A+B}{R_L} + CR_s + D \frac{R_s}{R_L} \right)^{-1} =$$

$$= \left( 1 - \omega^2 L_1 C + j\omega \frac{(L_1 + L_2)}{R_L} - \frac{j\omega^3 L_1 L_2 C}{R_L} + \right.$$

$$\left. j\omega R_s C + (1 - \omega^2 L_2 C) \frac{R_s}{R_L} \right)^{-1}$$

$$H = -(CR_L + D)^{-1} = -(j\omega R_L C + (1 - \omega^2 L_2 C))^{-1}$$

An impedance matching network would

present  $Z_{in} = Z_s^*$

$$Z_{in} = \frac{V_1}{I_1} = \frac{AZ_L + B}{CZ_L + D} = \frac{(1 - \omega^2 L_1 C)Z_L + j\omega(L_1 + L_2) - j\omega^3 L_1 L_2 C}{j\omega Z_L C + (1 - \omega^2 L_2 C)}$$

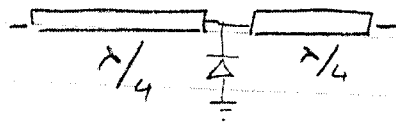
$\begin{bmatrix} 1 & 0 \end{bmatrix}$

(3)

Question 2

a) Place it between two gyrators.

[1]



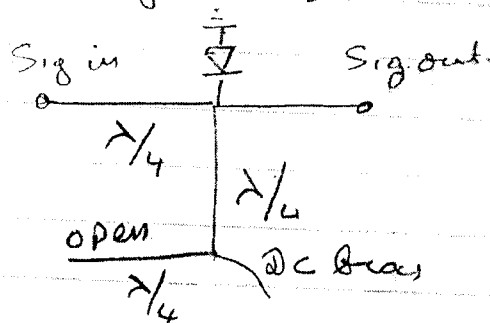
[2]

$$\left. \begin{array}{l} f = 10^{10} \text{ Hz} \\ c = 10^{10} \text{ cm/sec} \end{array} \right\} \Rightarrow \lambda = 1/\text{cm} \Rightarrow l = \lambda/4 = 2.5 \text{ mm}$$

[2]

b) Need to supply DC bias through a  $\lambda/4$

Piece of line:



$\lambda/4$  for DC bias

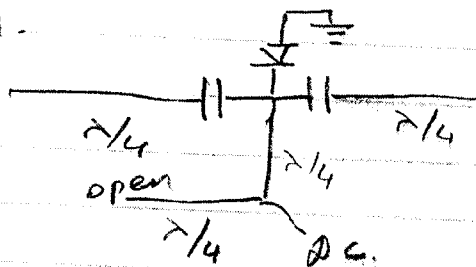
[4]

$\lambda/4$  open to establish DC ground

[3]

c) Need to introduce two capacitors,

eg.



[5]

(4)

d) if the diode appears as:



when on, then

$$\begin{array}{c} Z_0 \\ \hline Z_T \\ \hline \begin{array}{c} \swarrow \quad \downarrow \quad \searrow \\ \frac{1}{4} \quad \frac{1}{4} \quad \frac{1}{4} \\ \hline \frac{1}{4} Z_0 \frac{1}{4} \\ \hline \end{array} \\ \hline Z_0 \end{array} \equiv \frac{Z_T^2}{Z_0} \parallel Z_0$$

or, in reduced units it is

$$Z = \frac{Z_T^2}{Z_0 Z_0} = \frac{1}{4}$$

A series impedance has a  $Y$  matrix (in red. units)

$$Y = \begin{pmatrix} Y & -Y \\ -Y & Y \end{pmatrix} \quad \text{and the } S_{21} \text{ element is:}$$

$$\text{is: } S_{21} = \frac{-2Y_{21}}{1 + Y_{11} + Y_{22} - \Delta Y} = \frac{2Y}{1 + 2Y + 2Y^2} = \left| \frac{1}{S_{21}} \right|^2 = \left( \frac{1 + 2Y + 2Y^2}{2Y} \right)^2$$

since  $Y = \frac{Z_0 Z_0}{Z_T^2}$  to minimise the <sup>avg</sup> loss

$$\begin{aligned} \text{to minimise } L = \frac{1}{|S_{21}|} &\Rightarrow \frac{dL}{dY} = \frac{Y(2+2Y) - 1 - 2Y - 2Y^2}{Y^2} \cdot 2L \\ &= -\frac{1}{Y^2} \cdot 2L \text{ i.e. } L \text{ is monotonically decreasing} \end{aligned}$$

with  $Y$ . Then we need to use the minimum

possible  $Z_T$  for the generators,  $Z_T = 20\Omega$

(5)

then 
$$\gamma = \frac{10 \times 50}{(20)^2} = 1.25$$

and 
$$L = \left( \frac{1 + 2\gamma + 2\gamma^2}{2\gamma} \right)^2 = 17.0225 = 8.46 \text{ dB}$$

(6)

Question 3.

a). From the Shannon theorem, if  $C$  is the capacity:

$$C = B \ln\left(\frac{S}{N} + 1\right) \Rightarrow \frac{S}{N} = 2^{\frac{C}{B}} - 1$$

it is given:  $C = 56 \times 10^3$   
 $B = 10^4$

$$\Rightarrow \frac{S}{N} = 47.5 = 16.85 \text{ dB}$$

[5]

b) By the Friis formula,

$$P_{\text{rec}} = P_{\text{T}} \cdot \frac{A_{\text{effT}} A_{\text{effR}}}{R^2 \lambda^2}$$

$$\lambda = \frac{c}{1.8 \text{ GHz}} = 0.167 \text{ m}$$

the range is given as  $R = 10^4 \text{ m}$ .

The mobile terminal power is  $1 \text{ W}$

and the antenna aperture is  $16.67 \times 10^{-4} \text{ m}^2$ .

$$\begin{aligned} \text{then } P_{\text{rec}} &= \frac{10^{-2} \times 16.67 \times 10^{-4} \cdot A_{\text{effR.S.}}}{10^8 \times (0.167)^2} = \\ &= A_{\text{effR.S.}} \cdot 5.977 \times 10^{-12} \text{ (W)} \end{aligned}$$

The noise power received is just.  $P_N = k T_A B =$   
 $= 1.38 \times 10^{-23} \times 150 \times 10^4 = 2.07 \times 10^{-17}$



(7)

therefore, the required <sup>minimum</sup> signal power is:

$$P_{sig} = P_N \cdot \overset{\times 10^{-12}}{S/N} \cdot NF \cdot SNR = 2.07 \times 10^{-17} \times 47.5 \times 3.16 \times 31.6 = 9.82 \times 10^{-14} \text{ W}$$

then, the base station effective aperture is:

$$A_{eff} \times 5.977 \times 10^{-12} = 9.82 \times 10^{-14} \Rightarrow A_{eff} = 0.164 \text{ m}^2$$

Since  $A_{eff} = A_{phys} \cdot \eta_A \Rightarrow A_{phys} = \frac{0.164 \text{ m}^2}{0.5} = 0.328 \text{ m}^2$

The directivity is:  $G = \eta_{ee} \cdot D$  where  $G$  is the gain

and  $G = \frac{4\pi A_{eff}}{\lambda^2} \Rightarrow D = \frac{1}{\eta_{ee}} \cdot \frac{4\pi A_{eff}}{\lambda^2} = \frac{1}{0.9} \cdot \frac{4\pi \times 0.164}{(0.167)^2}$

then  $D = 83.6$

In terms of the angular extent the directivity

is:

$$D \approx \frac{41000}{\theta^2} \text{ if } \theta = 90,$$

$$\theta = \frac{41000}{80 \times 83.6} = 10^\circ$$

[10]

(8)

c) Once again, the received power is

$$P_{rec} = P_t \cdot \frac{A_{effT} A_{effR}}{R^2 \lambda^2}$$

to simplify calculation, we already know

$P_{rec}$  for this system, for 10mW:

$$P_{rec} = \frac{P_{trans}}{10^{-2}} \times 9.82 \times 10^{-14} \text{ W.}$$

the required received power is:

$$P_{rec} = k T_{ANT} B \cdot \left. \frac{S}{N} \right|_{rec} \cdot SNR_{MIN} = 0.00 = 20 \times P_{rec_{BS}}$$

then the transmitter power is  $P_T = 200 \text{ mW}$

LSI

(8)

## Question 4

$$a) \quad Y = \begin{pmatrix} 0 & 0 \\ g & 0 \end{pmatrix}$$

$$\left( Y_{11} = \frac{\partial I_1}{\partial V_1} \Big|_{V_2=0}, Y_{12} = \frac{\partial I_1}{\partial V_2} \Big|_{V_1=0}, Y_{21} = \frac{\partial I_2}{\partial V_1} \Big|_{V_2=0}, Y_{22} = \frac{\partial I_2}{\partial V_2} \Big|_{V_1=0} \right) \quad [2]$$

b)  $Y = \begin{pmatrix} 0 & g \\ g & 0 \end{pmatrix}$  (since the two nets are connected opposite to each other, add the  $Y$  matrices).

derivation of ABCD from  $Y$ :

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_2 \\ -I_2 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 & 0 \\ Y_{11} & Y_{12} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -Y_{21} & -Y_{22} \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \frac{1}{Y_{21}} \begin{pmatrix} 1 & 0 \\ Y_{11} & Y_{12} \end{pmatrix} \begin{pmatrix} -Y_{22} & -1 \\ Y_{21} & 0 \end{pmatrix} = \frac{1}{Y_{21}} \begin{pmatrix} -Y_{22} & -1 \\ -\Delta & -Y_{11} \end{pmatrix}$$

for the gyrator:  $\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \frac{1}{g} \begin{pmatrix} 0 & -1 \\ -g^2 & 0 \end{pmatrix} = \begin{pmatrix} 0 & -1/g \\ -g & 0 \end{pmatrix}$

the bandwidth is clearly infinite. [4]

c)  $\text{---} \textcircled{K_1} \text{---} \textcircled{K_2} \text{---}$   $\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 0 & -1/g_1 \\ -g_1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1/g_2 \\ -g_2 & 0 \end{pmatrix} = \begin{pmatrix} g_2/g_1 & 0 \\ 0 & g_1/g_2 \end{pmatrix}$

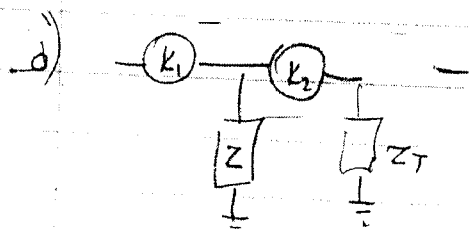
then  $V_1 = g_2/g_1 V_2$   
 $I_1 = -g_1/g_2 I_2$

$\downarrow$   
 $Z_{\text{eff}} = \frac{V_1}{I_1} = \frac{g_2^2}{g_1^2} Z_T$

So it is a simultaneous voltage and current transformer.

[5]

(10)



$$(ABCD) = \begin{pmatrix} 0 & -1/g_1 \\ -g_1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ Y & 1 \end{pmatrix} \begin{pmatrix} 0 & -1/g_2 \\ -g_2 & 0 \end{pmatrix} =$$

$$= \begin{pmatrix} -Y/g_1 & -1/g_1 \\ -g_1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -1/g_2 \\ -g_2 & 0 \end{pmatrix} = \begin{pmatrix} g_2/g_1 & Y/g_2 g_1 \\ 0 & g_1/g_2 \end{pmatrix}$$

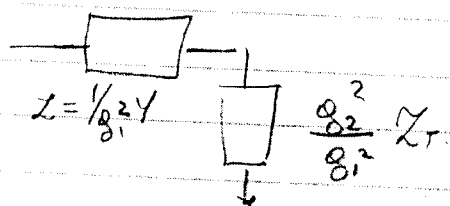
if it is terminated in  $Z_T$ , then

$$-V_2 = -Z_T i_2 \quad \text{and} \quad i_1 = -\frac{g_1}{g_2} i_2$$

$$V_1 = \frac{g_2}{g_1} V_2 - \frac{Y}{g_2 g_1} i_2 = -\frac{g_2}{g_1} Z_T i_2 - \frac{Y}{g_2 g_1} i_2 =$$

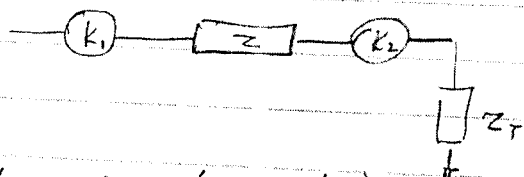
$$= + \frac{g_2^2}{g_1^2} i_1 Z_T + \frac{1}{g_1^2} Y i_1$$

and the equivalent circuit is:



if  $g_1 = g_2$  it reduces to

[4].



$$(ABCD) = \begin{pmatrix} 0 & -1/g_1 \\ -g_1 & 0 \end{pmatrix} \begin{pmatrix} 1 & Z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & -1/g_2 \\ -g_2 & 0 \end{pmatrix} =$$

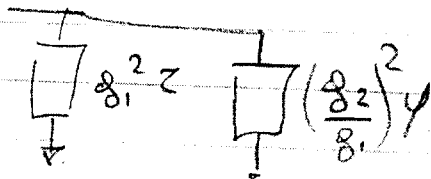
(11)

$$= \begin{pmatrix} 0 & -1/g_1 \\ -g_1 & -g_1 Z \end{pmatrix} \begin{pmatrix} 0 & -1/g_2 \\ -g_2 & 0 \end{pmatrix} = \begin{pmatrix} g_2/g_1 & 0 \\ g_1 g_2 Z & g_1/g_2 \end{pmatrix}$$

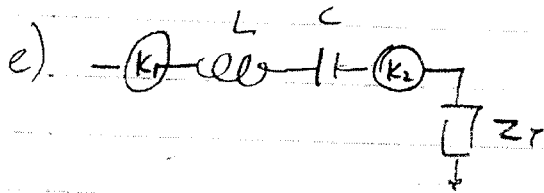
then  $V_1 = g_2/g_1 V_2$ ,  $V_2 = -Z_T i_2$

and  $i_1 = g_1 g_2 V_2 Z - \frac{g_1}{g_2} i_2 = \left( g_1 g_2 Z + \frac{g_1}{g_2} \frac{1}{Z_T} \right) \frac{g_1}{g_2} V_1$

$$= g_1^2 Z + \left( \frac{g_1^2}{g_2^2} \right) \frac{1}{Z_T}$$



[4]



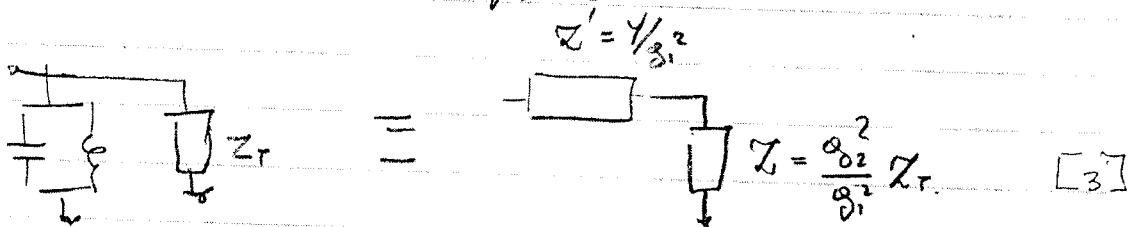
$$= Y_1 = g_1^2 Z(L) \quad \text{and} \quad Z = \frac{g_2^2}{g_1^2} Z_T$$

[3]

$$Z(LC) = j\omega L + \frac{1}{j\omega C} \Rightarrow Y_1 = g_1^2 j\omega L + \frac{g_1^2}{j\omega C}$$

is a parallel LC,  $L' = \frac{C}{g_1^2}$ ,  $C' = g_1^2 L$

the parallel LC maps to.

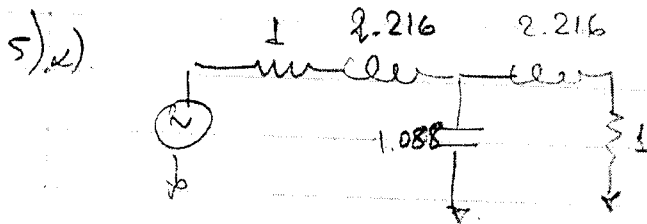


Since  $Y(LC) = j\omega C + \frac{1}{j\omega L}$ ,  $Z' = 1/g_1^2 j\omega C + 1/g_2^2 1/j\omega$

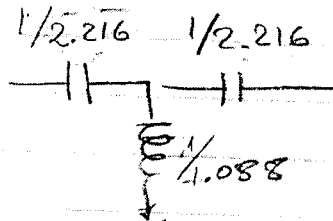
(12)

and the equivalent circuit is a series LC with

$$L' = \frac{C}{g^2}, \quad C' = g^2 L.$$



high pass prototype:



scale for  $X$  and <sup>centre</sup> frequency.

$$C'_1 = C'_3 = \frac{C_1}{50 \omega_0} = \frac{1}{2.216} \cdot \frac{1}{50} \cdot \frac{1}{2\pi \times 10^8} = 14.3 \text{ pF}$$

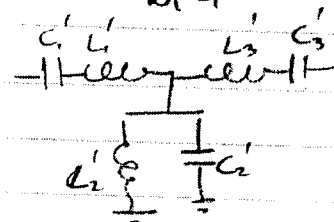
$$L'_2 = \frac{L_2 \omega_0}{50} = \frac{50}{1.088 \times 2\pi \times 10^8} = 289.5 \text{ pH}$$

to make it band reject, resonate these

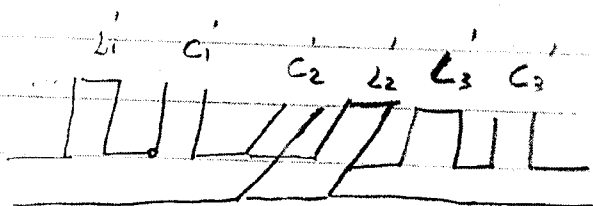
with  $L'_1, C'_2, L'_3$  so that  $\omega_0^2 = \frac{1}{L'_1 C'_2}$

$$\Rightarrow L'_1 = \frac{1}{\omega_0^2 C'_2} = 293 \text{ pH} = L'_3$$

$$C'_2 = \frac{1}{\omega_0^2 L'_1} = 14.4 \text{ pF}$$



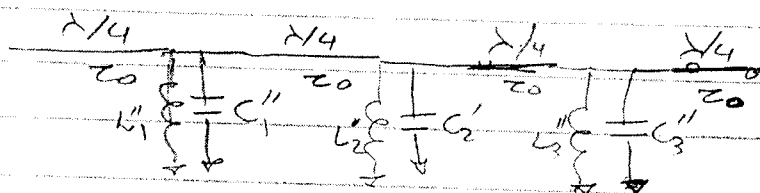
- b) an inductor can be a shorted stub of length less than  $\lambda/4$  and a capacitor an open stub of length less than  $\lambda/4$ . then the filter becomes:



Since  $Z_{open} = \frac{Z_0}{j \tan \beta l} \approx \frac{Z_0}{j \frac{\omega}{c} l} \Rightarrow C_{eff} = \frac{l}{Z_0 c}$

and  $Z_{short} = j Z_0 \tan \beta l \approx Z_0 j \frac{\omega}{c} l \Rightarrow L_{eff} = \frac{Z_0 l}{c}$  [10]

- c) We can use  $\lambda/4$  transformers as gyrators to turn the filter into:



then,  $L_1'' = Z_0^2 C_1' = L_3''$

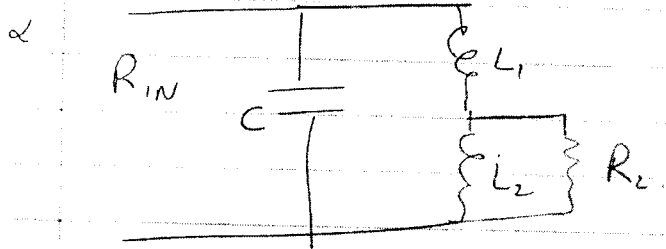
$$C_1'' = \frac{L_1''}{Z_0^2} = C_3''$$

The parallel LC's can be implemented as open  $\lambda/4$  stubs with

$$L = \pi Z_0 \quad \text{and} \quad C = \frac{1}{\pi Z_0}$$



## Question 6.



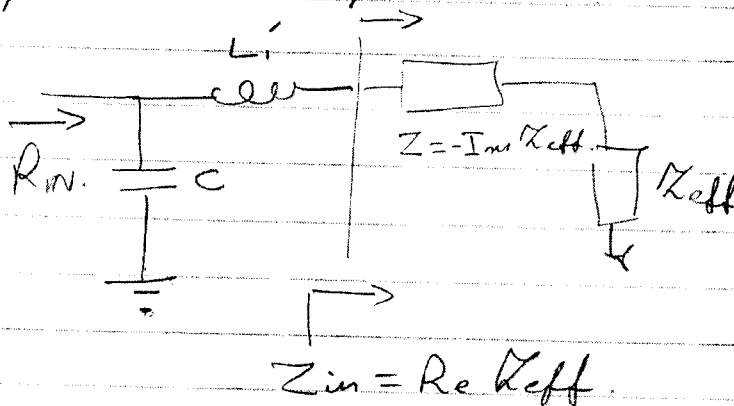
2) Lump  $L_2, R_L$  into  $Z_{eff} = \frac{j\omega L_2 R_L}{j\omega L_2 + R_L}$

then  $Z_{eff} = \frac{j\omega L_2}{1 + j\omega \frac{L_2}{R_L}} = R_L \frac{j\omega \pi}{1 + j\omega \pi} \quad \pi = \frac{L_2}{R_L}$

$\text{Re } Z_{eff} = R_L \frac{\omega^2 \pi^2}{1 + \omega^2 \pi^2} = R_{eff}$

$\text{Im } Z_{eff} = R_L \frac{\omega \pi}{1 + \omega^2 \pi^2}$

this converts to a simple impedance match problem: (step down!)



(16)

If  $Q$  is specified,

$$Q^2 = \frac{R_{in}}{R_{eff}} - 1 \Rightarrow Q^2 R_{eff} = R_{in} - R_{eff} \Rightarrow$$

$$(Q^2 + 1) R_{eff} = R_{in}$$

$$\text{But } R_{eff} = R_L \frac{\xi^2}{1 + \xi^2} \quad \left( \xi = \omega L = \frac{\omega L_2}{R_L} \right)$$

$$\Rightarrow (Q^2 + 1) \frac{\xi^2}{1 + \xi^2} R_L = R_{in} \Rightarrow (Q^2 + 1) \frac{\xi^2}{1 + \xi^2} \rho = 1$$

$$\Rightarrow \xi^2 [(Q^2 + 1)\rho - 1] = 1 \Rightarrow \frac{\omega^2 L_2^2}{R_L^2} = \frac{1}{[(Q^2 + 1)\rho - 1]} = \xi^2$$

this defines  $L_2$ .

The std. impedance matching with  $L$  network

gives:

$$Q R_{eff} = \omega L_1 \Rightarrow Q R_L \frac{\xi^2}{1 + \xi^2} = \omega L_1'$$

$$\Rightarrow L_1' = \frac{Q R_L}{\omega} \frac{\xi^2}{1 + \xi^2}$$

then

$$\omega L_1 = \omega L_1' - \text{Im } Z_{eff} = \omega L_1' - R_L \frac{\xi}{1 + \xi^2} =$$

$$= Q R_L \frac{\xi^2}{1 + \xi^2} - R_L \frac{\xi}{1 + \xi^2} = R_L \frac{Q \xi (\xi - 1)}{1 + \xi^2}$$

$$\text{and } Q = \frac{R_{in}}{R_L}$$

b) By the derivation of  $L_2$  we have:

$$\frac{\omega^2 L_2^2}{R_L^2} = \frac{1}{(Q^2+1)\rho-1}$$

The constraint on  $\rho = \frac{R_{in}}{R_L}$  is

$$(Q^2+1)\rho \geq 1 \quad \rho \geq \frac{1}{1+Q^2}$$

also, since  $L_1$  needs to be an inductor

it follows  $\xi > 1 \Rightarrow \xi^2 > 1 \Rightarrow$

$$\frac{1}{(Q^2+1)\rho-1} > 1 \Rightarrow 1 > (Q^2+1)\rho-1 \Rightarrow$$

$$(Q^2+1)\rho < 2 \Rightarrow \rho < \frac{2}{1+Q^2}$$

$$\Rightarrow \frac{1}{1+Q^2} < \rho < \frac{2}{1+Q^2}$$

[10]

c) By adding the negative of the imaginary part of the respective impedances.

[5]