Version MJC/3

EGT3
ENGINEERING TRIPOS PART IIB

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Tuesday 23 April 2024 9.30 to 11.10

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**Module 4B24**

**RADIO FREQUENCY SYSTEMS**

*Answer not more than* ***three*** *questions.*

*All questions carry the same number of marks.*

*The* ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number* ***not*** *your name on the cover sheet.*

**STATIONERY REQUIREMENTS**
Write on single-sided paper.

**SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM**
CUED approved calculator allowed.
Attachment: 4B24 Radio Frequency Systems data sheet (2 pages).
Supplementary Page: Two copies of a Smith Chart (Question 4).
Engineering Data Book.

**10 minutes reading time is allowed for this paper at the start of the exam.**

**You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.**

**You may not remove any stationery from the Examination Room.**

1 (a) A 2-port device has an S-parameter matrix with a 50 Ω reference impedance given by:

$$\begin{bmatrix} 0.79\angle -41^\circ & S_{12} \\ S_{21} & 0.79\angle 6^\circ \end{bmatrix}$$

(i) What is the impedance presented by Ports 1 and 2 when the other port is terminated with 50 Ω? [20%]

(ii) If the device is lossless and reciprocal determine the values of $S_{12}$ and $S_{21}$. [30%]

(iii) Determine the load applied to Port 2 which results in a perfect impedance match to 50 Ω at Port 1. [20%]

(b) It is desired to produce a lumped element equivalent circuit of the device in part (a) at a frequency of 3 GHz with a topology shown in Fig. 1.

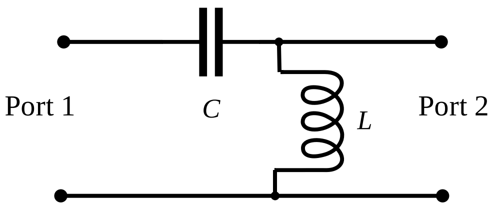


Fig. 1

Find the Z-parameter matrix of the network and hence find suitable component values. [30%]

Note:

$$S_{11} = \frac{(Z_{11} - Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}}{\Delta Z}$$
$$S_{12} = \frac{2Z_{12}Z_0}{\Delta Z}$$
$$S_{21} = \frac{2Z_{21}Z_0}{\Delta Z}$$
$$S_{22} = \frac{(Z_{11} + Z_0)(Z_{22} - Z_0) - Z_{12}Z_{21}}{\Delta Z}$$

where $\Delta Z = (Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}$.

2 An amplifier with 30 dB gain and a noise figure of 3 dB is proceeded by a 4 dB attenuator to reduce distortion as shown in Fig. 2.

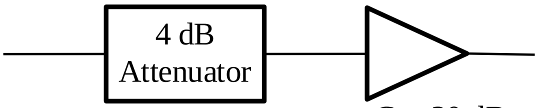


Fig. 2

(a) Find the noise figure and gain of the cascade at a temperature of 290 K. [10%]

(b) Recalculate the noise figure if the temperature of the attenuator is increased by 50 °C. [20%]

(c) A 2-tone test is conducted on the attenuator-amplifier cascade resulting in the frequency spectrum shown in Fig. 3.

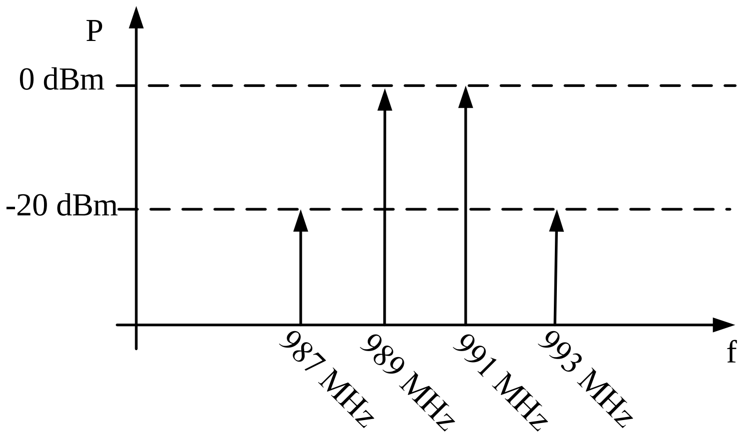


Fig. 3

(i) Find the IIP3 for the amplifier. State any assumptions. [20%]

(ii) Find the SFDR of the cascade if the order of the amplifier and attenuator are switched such that the amplifier proceeds the attenuator and an input noise of −185 dBm $Hz^{-1}$ is present. [20%]

(d) Rather than use a passive attenuator to reduce the signal into the amplifier, it is proposed to use an impedance mis-match instead to reduce the input by 4 dB compared to the matched case. Find the noise figure at 290 K for this arrangement. [30%]

3 (a) An antenna array operating at 5 GHz with a gain of 12 dB and linear polarisation is pointed towards a region of the sky with a background temperature of 7 K. A noise temperature of 105 K is measured at the output of the antenna.

(i) If the physical antenna temperature is 290 K, what is the antenna radiation efficiency? State any assumptions made. [20%]

(ii) If the same antenna is used for a transmit-receive pair, calculate the power loss between a matched source feeding the transmitter and a matched load at the receive antenna if the antennas are pointed directly at one another, separated by 100 m in free space, but misaligned in polarisation by 20°. [20%]

(iii) It is found experimentally that the received power is greater than that predicted by the free space model, but decreases smoothly as the 4$^{th}$ power of antenna separation as separation increases. Explain how this could arise. [10%]

(b) A direct conversion radio receiver for QPSK signals is shown in Fig. 4.

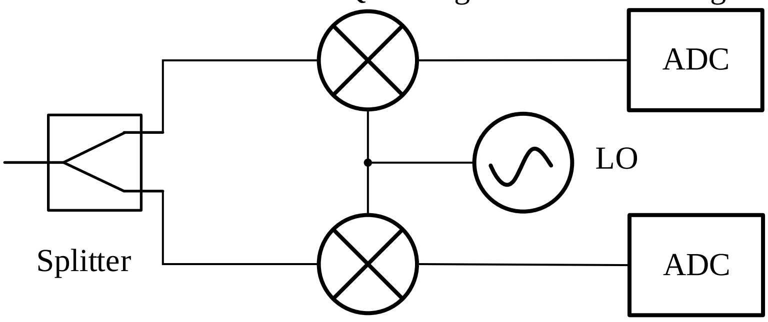


Fig. 4

(i) Briefly explain the advantages of this approach compared to a superheterodyne receiver. What problem might occur if the mixers are imperfect and mismatch appears at the input? [20%]

(ii) The splitter has S-parameters:

$$\begin{bmatrix} 0 & 0.5\angle 5° & 0.4\angle 100° \\ 0.5\angle 5° & 0 & 0 \\ 0.4\angle 100° & 0 & 0 \end{bmatrix}$$

Describe the nature of the imperfections in the splitter. Explain qualitatively the impact compared to an ideal splitter with a sketch of the QPSK signal detected at the ADCs. How could this be compensated? [30%]

4 (a) A FET has the following scattering and noise parameters at 6 GHz ($Z_0$=50 Ω): $S_{11} = 0.8\angle -160°,\ S_{12} = 0.04\angle -10°,\ S_{21} = 5\angle 60°,\ S_{22} = 0.3\angle -180°$, $F_{min} = 2\text{dB},\ \Gamma_{opt} = 0.4\angle -120°,\ R_N = 20\ \Omega$. The source and load impedances are 50 Ω.

(i) Determine the stability of the amplifier and draw the stability circle if required for the input side. [20%]

(ii) Find the minimum noise figure which can be achieved, the impedance to be presented on the input side to achieve this and the resulting available gain. State any assumptions or approximations. [15%]

(iii) Using a shorted transmission line stub design the input impedance matching network. [20%]

(b) A hybrid amplifier is shown in Fig. 5. Each of the amplifiers has the parameters provided in part (a), and is configured to maximise bandwidth.

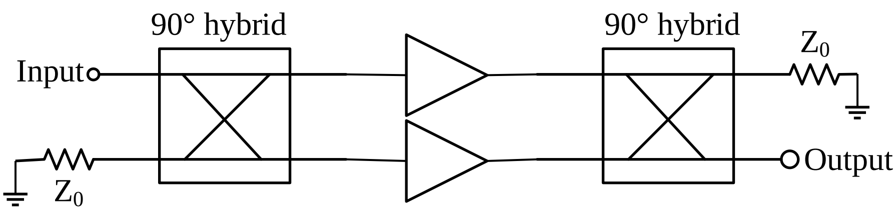


Fig. 5

(i) Explain how this configuration can improve the bandwidth. How would the gain, linearity, efficiency and noise figure compare to the amplifier as matched in part (a) and a single unmatched amplifier? [20%]

(ii) Find the resulting system input reflection coefficient and gain if the 90° hybrids are not ideal and each has S-parameters

$$\frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1\angle 10° & 1\angle 90° & 0 \\ 1\angle 10° & 0 & 0 & 1\angle 90° \\ 1\angle 90° & 0 & 0 & 1\angle 10° \\ 0 & 1\angle 90° & 1\angle 10° & 0 \end{bmatrix}$$

and the source and load impedances are both 50 Ω. [25%]

*Two Smith Charts are attached at the end of the question paper. They should be detached and handed in with your answers.*

**END OF PAPER**

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# 4B24 RF Systems Datasheet

## Noise

Y-factor Noise measurement:

$Y = \left(\frac{N_1}{N_2}\right)$ $\qquad$ $T_e = \frac{T_1 - YT_2}{Y-1}$

Noise figure Circles:

centre $C_F = \frac{\Gamma_{opt}}{N+1}$ and radius $R_F = \frac{\sqrt{N(N+1-|\Gamma_{opt}|^2)}}{N+1}$

where $N = \frac{|\Gamma_S - \Gamma_{opt}|^2}{1-|\Gamma_S|^2} = \frac{F-F_{min}}{4R_N/Z_0}\ |1+\Gamma_{opt}|^2$

## Distortion

Cascaded OIP3

$$OIP_3 = \left[\frac{1}{G_2^2(OIP_3')^2} + \frac{1}{(OIP_3'')^2}\right]^{-\frac{1}{2}}$$

## Stability

$K - \Delta$ test, unconditionally stable if and only if

$K = \frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2}{2|S_{12}S_{21}|} > 1$ $\qquad$ and $\qquad$ $|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1$

Stability Circles:

$C_L = \frac{(S_{22}-\Delta S_{11}^*)^*}{|S_{22}|^2-|\Delta|^2} R_L = \left|\frac{S_{12}S_{21}}{|S_{22}|^2-|\Delta|^2}\right|$

$C_S = \frac{(S_{11}-\Delta S_{22}^*)^*}{|S_{11}|^2-|\Delta|^2}, R_S = \left|\frac{S_{12}S_{21}}{|S_{11}|^2-|\Delta|^2}\right|$

## Amplifier Design for Specific Gain

$C_S = \frac{g_S S_{11}^*}{1-(1-g_S)|S_{11}|^2}, C_L = \frac{g_L S_{22}^*}{1-(1-g_L)|S_{22}|^2}$

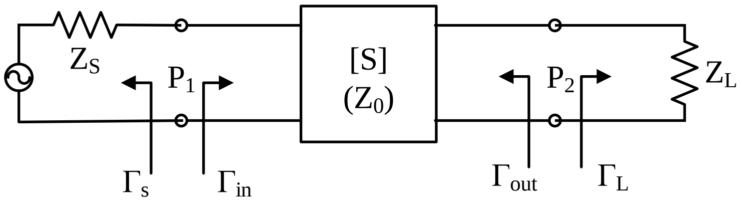
$R_S = \frac{\sqrt{1-g_S}(1-|S_{11}|^2)}{1-(1-g_S)|S_{11}|^2}, R_L = \frac{\sqrt{1-g_L}(1-|S_{22}|^2)}{1-(1-g_L)|S_{22}|^2}$

Where:

$g_S = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2}(1-|S_{11}|^2)$

$g_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2}(1-|S_{22}|^2)$

# Amplifier Gain




Power gain:

$$G = \frac{|S_{21}|^2(1-|\Gamma_L|^2)}{(1-|\Gamma_{in}|^2)|1-S_{22}\Gamma_L|^2}$$

Available gain

$$G_A = \frac{|S_{21}|^2(1-|\Gamma_S|^2)}{|1-S_{11}\Gamma_S|^2(1-|\Gamma_{out}|^2)}$$

Transducer Gain

$$G_T = \frac{|S_{21}|^2(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-\Gamma_S\Gamma_{in}|^2|1-S_{22}\Gamma_L|^2}$$

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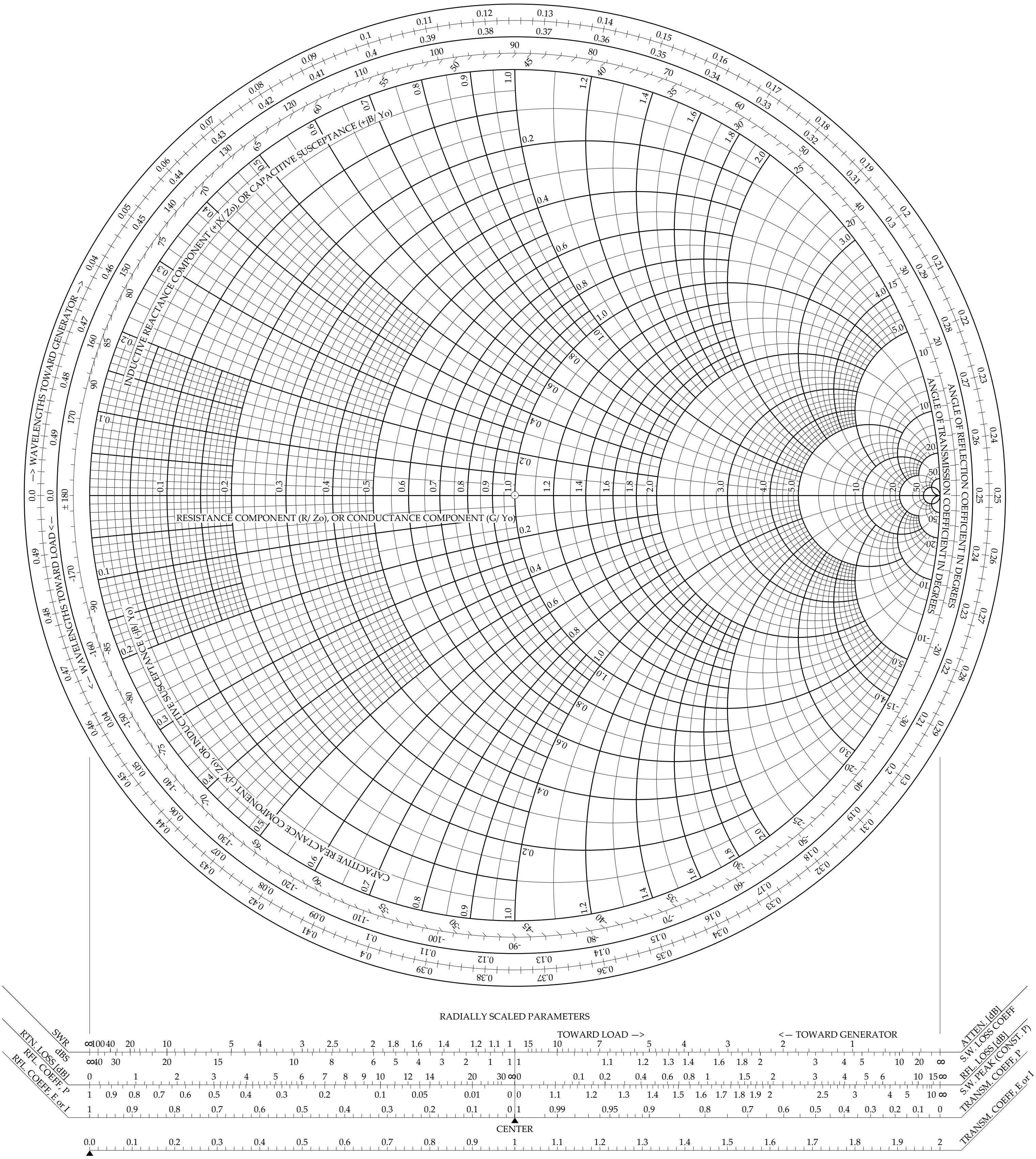
Candidate No.

Smith Chart for Question 4 to be detached and handed in with script



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