Version MJC/3

EGT3
ENGINEERING TRIPOS PART IIB

Tuesday 25th April 2023 9.30 to 11.10

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) (i) Find the ABCD parameter matrix for the two port network shown below in Figure 1. [20%]

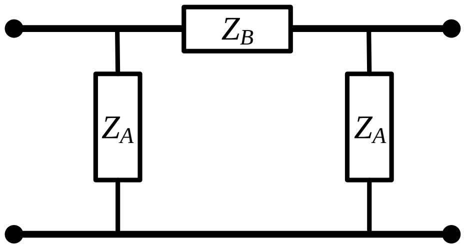

Fig. 1

(ii) Hence find the S_{21} coefficient at a reference impedance of 50 Ω for the cascade if this network is preceded by a transmission line with a characteristic impedance of 75 Ω and a length of $\frac{\lambda}{4}$, and $Z_A = 25\ \Omega, Z_B = 100j\ \Omega$.

The ABCD parameters of a transmission line of length l, characteristic impedance Z_o and propagation constant β are given by:

$$\begin{bmatrix} \cos\beta l & jZ_0 \sin\beta l \\ j\frac{1}{Z_0}\sin\beta l & \cos\beta l \end{bmatrix}$$ [30%]

Note: $S_{21} = \frac{2}{A+\frac{B}{Z_0}+CZ_0+D}$

(b) Using signal flow graphs, for the mismatched 3-port network shown in Figure 2 find:

(i) The input reflection coefficient at P_1 [30%]

(ii) The power gain between ports 1 and 2. [20%]

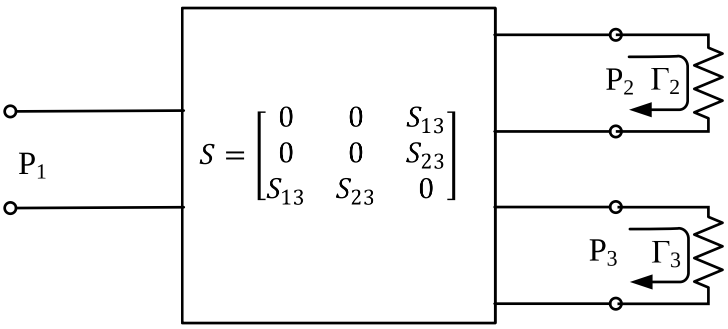

Fig. 2

2 (a) A wideband radio repeater is to be designed with a bandwidth of 900 MHz to 2.5 GHz. Two candidate amplifiers have been identified for this application with gain and linearity parameters given in the table below.

Amplifier	Gain (dB)	OIP2 (dBm)	IIP3 (dBm)
A	20	20	30
B	25	35	20

(i) Discuss with reasons which amplifier would be more appropriate for this application. [20%]

(ii) If amplifier B is used with input signals at 1.050 GHz and 1.5 GHz each with a power of −10 dBm determine the frequencies and amplitudes of the possible spurious signals assuming that no filters are employed other than to limit the bandwidth to cover 0.9-2.5 GHz. [20%]

(iii) It is decided to cascade the amplifiers. Determine the order of amplifiers A and B which is most favourable in terms of worst case IIP3 and find the resulting system IIP3. State your assumptions. [20%]

(iv) The output noise floor for the best cascaded combination is found to be −100 dBm measured over a 100 kHz bandwidth. Find the 3rd order spurious free dynamic range (SFDR) of the cascaded combination. [10%]

(b) A 5G base-station has a receiver front end shown in Figure 3 consisting of a lossy line with a loss $L = 3$ dB and a low noise amplifier (LNA) with a gain, $G = 20$ dB and an equivalent noise temperature $T_e = 350$ K. The operating frequency is 2210-2260 MHz and the physical temperature is 310 K. A noise source with $N_i = -93$ dBm over the operating bandwidth is applied at the input.

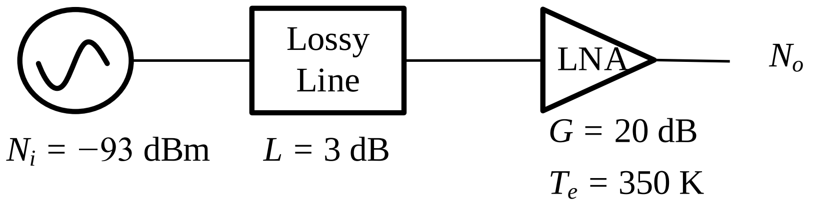

Fig. 3

(i) What is the noise figure in dB of the amplifier? [10%]

(ii) What is the total output noise over the operating bandwidth and the noise figure of the cascaded lossy line and amplifier? [20%]

3 (a) A pulsed radar system is shown in Figure 4. It operates with a carrier frequency of 10 GHz and pulse power of 100 mW into an antenna with a +10 dBi gain.

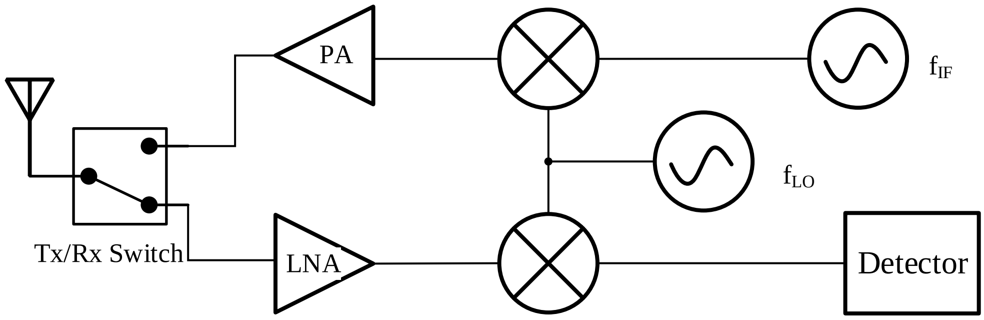

Fig. 4

The Tx/Rx Switch has a deadtime of 20 ns when no signals are passed as it switches from transmit to receive. It produces 50 ns pulses with a pulse repetition interval of 1 μs. The detector has a maximum sensitivity of −100 dBm measured at the antenna connector.

(i) Determine the maximum and minimum unambiguous range to a transponder which consists of an antenna with a gain of +25 dBi terminated into an open circuit. State any assumptions made. [40%]

(ii) It is proposed to eliminate the deadtime of the switch by replacing with a circulator and modulating pulses with the power amplifier (PA). If the circulator has perfect isolation and no loss, estimate the maximum antenna S_{11} if the leakage into the receiver should be 10 dB lower than the desired signal at maximum range. [10%]

(b) A frequency modulated continuous wave (FMCW) radar is proposed instead. It makes use of a sawtooth frequency modulation as shown in Figure 5:

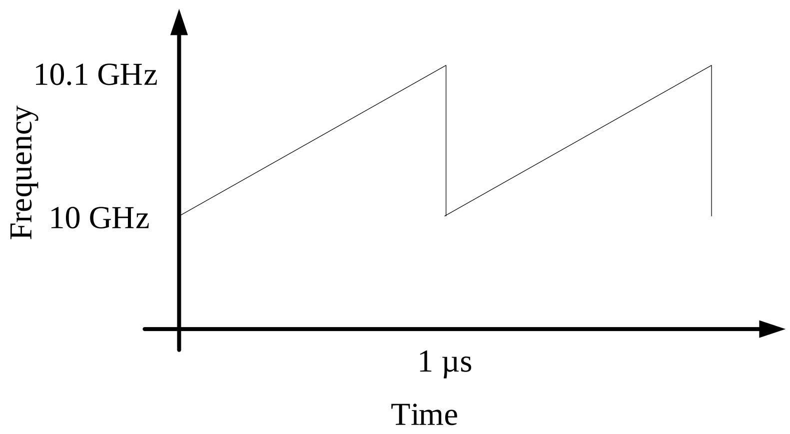

Fig. 5

(i) Sketch a schematic of the FMCW radar. [10%]

(ii) What frequency would be detected for a target at a range of 10 m? What is the maximum unambiguous range? [10%]

(iii) Explain how isolation between the transmitted and received signals is achieved, and how the effect of imperfect isolation can be minimised. [15%]

(d) A radio system operates on a carrier frequency of 915 MHz with an intermediate frequency (IF) of 955 kHz and a channel bandwidth of 100 kHz. An interfering signal exists 0.5 MHz from the carrier with a level 20 dB above that of the wanted signal. Calculate the maximum local oscillator phase noise and frequency offset which should be specified if the selectivity should be 50 dB. [15%].

4 (a) An amplifier has S parameters $S_{11} = -2.29$ dB $\angle\, 101°$, $S_{12} = -29$ dB $\angle 55°$, $S_{21} = 8.32$ dB $\angle 57°$, $S_{22} = -0.57$ dB $\angle -58.36°$, $\Gamma_{opt} = 0.6\,\angle 156.8°$, $R_N = 1.35\,\Omega$ and $F_{min} = 1.68$ dB measured at 1 GHz with a 50 Ω reference impedance.

(i) Determine the stability of the amplifier at 1 GHz. [10%]

(ii) Find the noise figure and maximum gain which can be achieved with no matching on the input. [20%]

(iii) Find the *transducer gain, available gain* and *power gain* of the amplifier in this configuration. What would be the measured S_{21} using a Vector Network Analyser (VNA) if the device under test is the amplifier with the output impedance matching circuit? [15%]

(iv) Estimate how much the gain can be increased if the noise figure is maintained at the same value, but impedance matching is used on the input. [20%]

(v) Design an impedance matching network with the maximum bandwidth using a single open or short circuit shunt stub for the input matching network. Explain how your solution maximises bandwidth. [20%]

(b) An antenna which can be modelled as a voltage source v_s in series with 25−32.5j Ω is connected to a receiver with an input impedance of 150 Ω using a 50 Ω transmission line. Find the electrical length of transmission line which maximises the power delivered to the receiver. [15%]

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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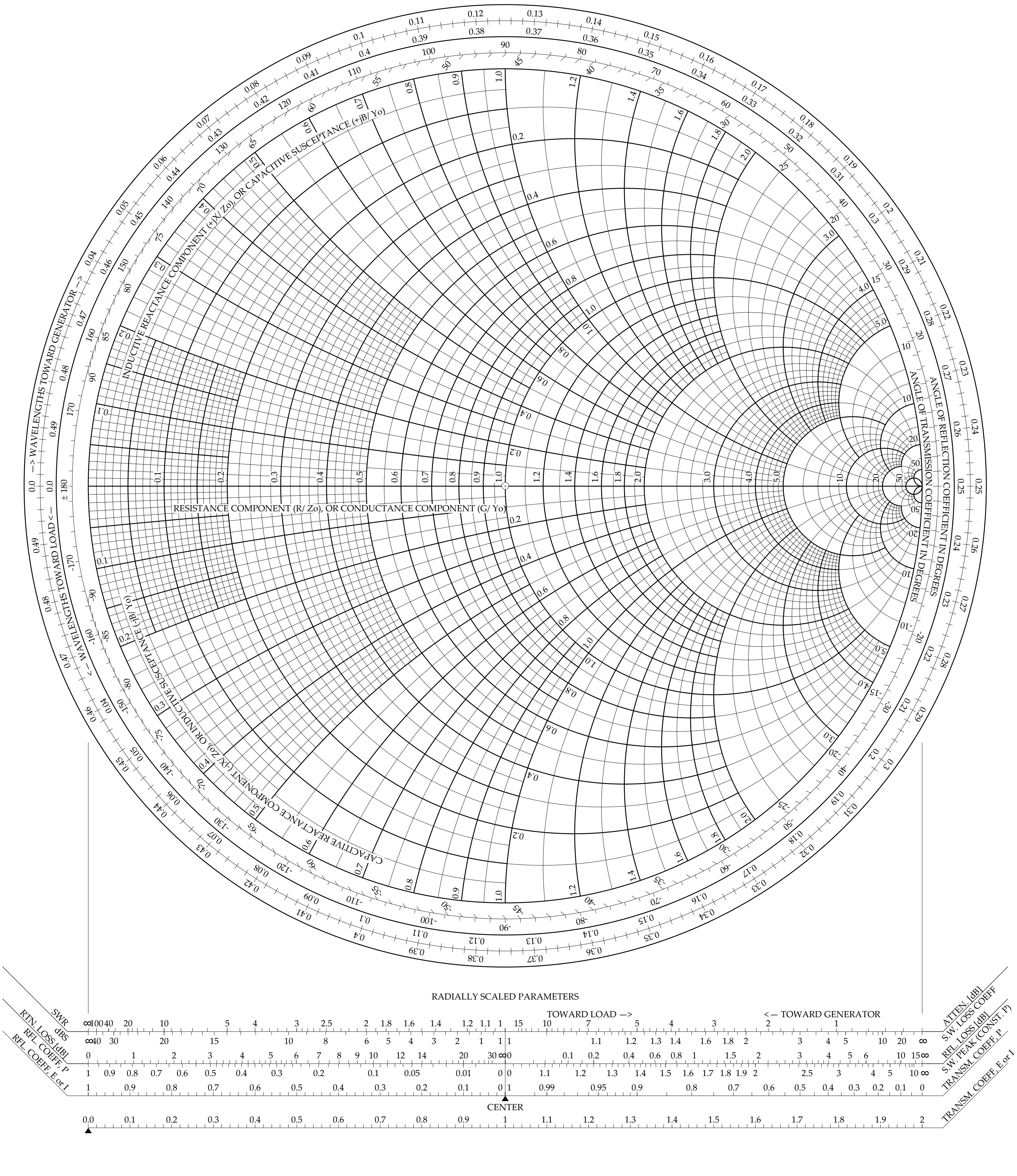
Module 4B24 Supplementary Page
Tuesday 25th April, Question 4

Candidate No.

Smith Chart to be detached and handed in with script if required



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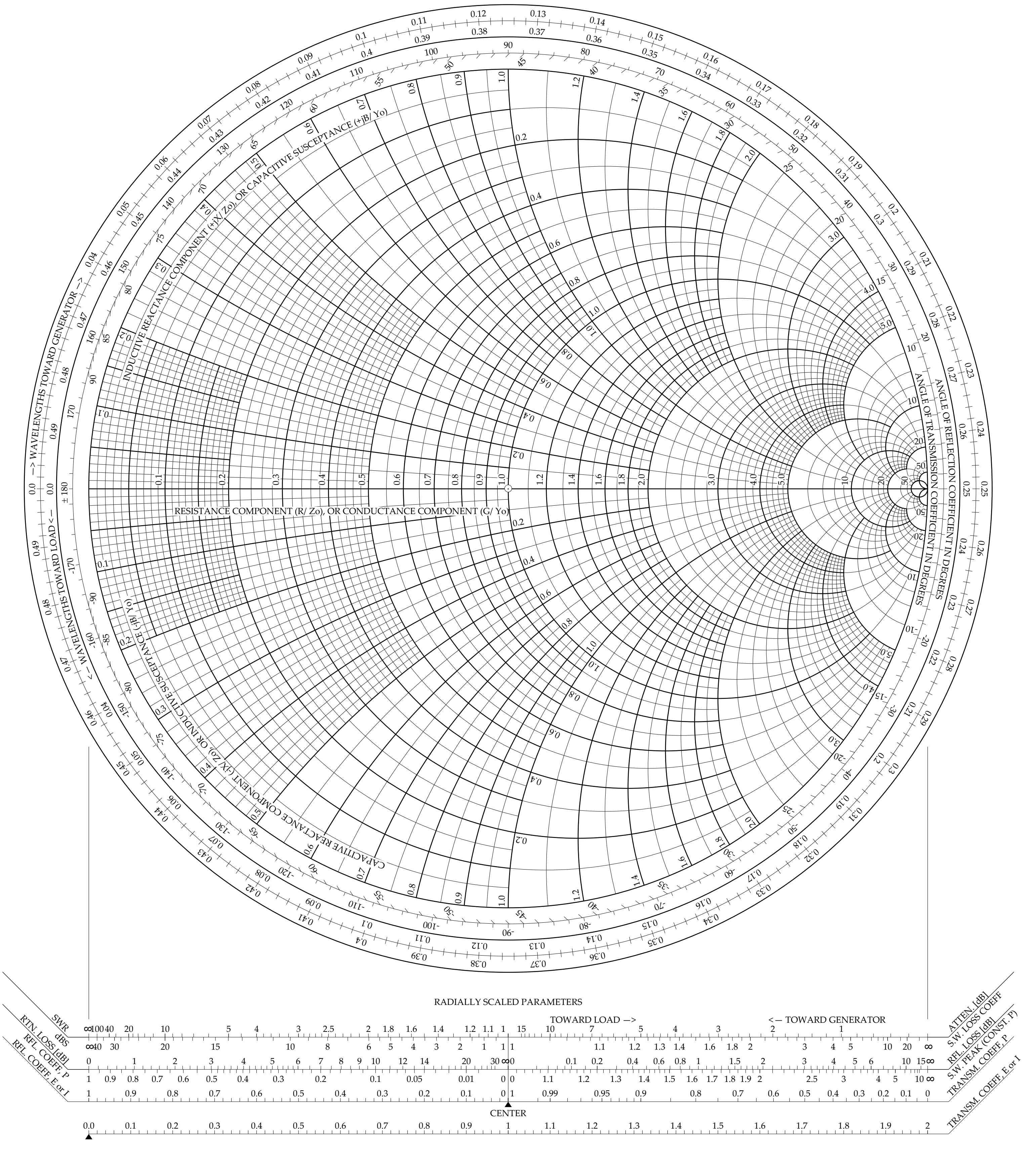


4B24 RF Systems Datasheet

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

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

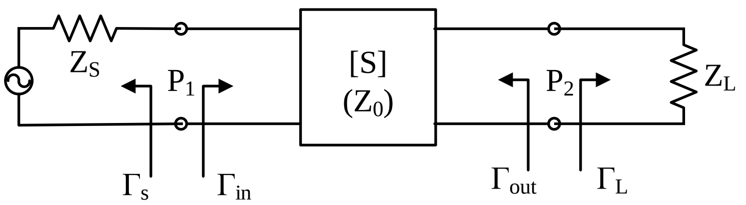
$R_S = \frac{\sqrt{1-g_S}(1-|S_{11}|^2)}{1-(1-g_S)|S_{11}|^2}$, $R_L = \frac{\sqrt{1-g_L}(1-|S_{22}|^2)}{1-(1-g_L)|S_{22}|^2}$

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

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