Version PAR/4

EGT2
ENGINEERING TRIPOS PART IIA

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Tuesday 26 April 2022 2 to 3.40

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**Module 3B1**

**RADIO FREQUENCY ELECTRONICS**

*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**
Single-sided script paper.

**SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM**
CUED approved calculator allowed.
Supplementary page: Smith Chart (Question 2).
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 space launch vehicle reaches an altitude of 86 km in a test flight and carries a radio data link system to send/receive flight information to/from a ground station below. The space vehicle has a transmitter power of 25 W and operates at a frequency of 920 MHz, using a 75 Ω half-wave dipole antenna made from metal rods. The ground station directional antenna has a gain of 30 dB and 50 Ω impedance.

(a) What is the signal *power density* and magnitude of the radiated *magnetic field* at the ground station, assuming the vehicle antenna has a *radiation efficiency* of 90 %? [20%]

(b) Estimate the *effective aperture* of the space vehicle antenna and hence calculate the amplitude of the signal produced across a 75 Ω matched load when it is used to receive signals from the ground, transmitted with a power of 200 W, assuming optimal alignment. [20%]

(c) What *beam angle* would you expect the directional ground station antenna to have, and hence what distance off-axis at peak altitude could the spacecraft be before the radio signal strength drops significantly ? [20%]

(d) What should be the minimum diameter of the space vehicle antenna rods, if they are made from non-magnetic stainless steel with a resistivity of $6.92 \times 10^{-7}$ Ω m, in order to realise a radiation efficiency of at least 90% ? [15%]

(e) Calculate the ratio of the transmitted voltage signal amplitude to the received signal amplitude expressed in dB, assuming optimal coupling and matched sources/loads, for the following two cases:

(i) transmission from the ground station to the space vehicle, and

(ii) transmission from the space vehicle to the ground station. [25%]

2 (a) The output of a mixer has an impedance of $15 + j30\ \Omega$ at 10 MHz. Design an impedance matching circuit using the Q-method to match the output to 75 Ω with a pair of passive components. [20%]

(b) Draw the circuit diagram for a Colpitts oscillator and calculate the component values for oscillation at 300 MHz, producing an amplitude of a few volts into a high impedance load when powered from a 6 V d.c. source. An inductor with a value of 50 nH and Q-factor of 25 is to be used. [25%]

(c) The input impedance of an RF mixer can be represented by a network of 3 passive components: a 35 Ω resistor in parallel with a 5 pF capacitor, with that pair in series with a 25 nH inductor. The mixer is to be incorporated into a 50 Ω system.

(i) Calculate the complex input impedance at a frequency of 300 MHz and plot this point on the Smith chart. What is the value of $S_{11}$ corresponding to this point? [15%]

(ii) Design an impedance matching circuit using a length of transmission line and a series capacitor to match the input to 50 Ω at a frequency of 300 MHz. If the transmission line comprises a piece of coaxial cable with a capacitance of 78 pF $m^{-1}$, what physical length is required in the matching circuit? [20%]

(iii) With reference to the Smith Chart and appropriate calculation, design an alternative impedance matching circuit comprising two capacitors, to match the mixer input to 50 Ω at a frequency of 300 MHz. [20%]

*A Smith Chart is attached to the back of this paper. It should be detached and handed in with your answers.*

3 A combined signal booster amplifier and power splitter is to be incorporated into the signal path from a 75 Ω TV aerial such that the received signal can be amplified and equally divided to two separate rooms in a house via 75 Ω coaxial cables. The system comprises an RF transistor amplifier with a net gain of 20 dB followed by a Wilkinson divider/coupler, realised in microstrip on a PTFE dielectric PCB, operating at a frequency around 520 MHz.

(a) Draw the schematic circuit diagram of a suitable transistor amplifier and briefly describe the architecture of a Wilkinson divider/coupler. [25%]

(b) Calculate the values of passive components in the amplifier circuit to meet the performance characteristics required. You may assume that a suitable transistor is available for which $h_{fe} = 250$ and that the circuit is powered from a 9 V d.c. supply. [20%]

(c) The booster amplifier transistor has the following properties: $h_{fe} = 250$, $f_t = 18$ GHz, $c_{cb} = 0.22$ pF, $c_{oe} = 0.15$pF. Calculate the maximum frequency at which the amplifier circuit could operate before the gain drops by 3 dB from its peak value. [30%]

(d) If the PCB material has a relative permittivity, $\varepsilon_r$ , of 2.2 and a thickness of 1.2 mm calculate the track width and length of the microstrip sections comprising the Wilkinson divider and give the value of any further components required. [25%]

4 (a) A motion detector to automatically open a supermarket door uses a Doppler radar module to detect people approaching. The module transmits a microwave beam at 24 GHz and the reflected signal received back is mixed with a reference signal from the transmitter. The frequency of the mixer output is twice the microwave frequency, multiplied by the motion velocity, divided by the speed of light.

(i) Design a Voltage Controlled Voltage Source (VCVS) band-pass filter circuit employing a pair of 2-pole cascaded filters to pass signals from the mixer corresponding to a person moving at a speed of between 0.5 m $s^{-1}$ and 5 m $s^{-1}$. Use 10 kΩ resistors where appropriate and give the values of other passive components used. Justify your choice of filter type. A 2-pole VCVS filter design table is given below in Table 1. [25%]

(ii) In order to prevent spurious operation from small objects such as birds and insects, and to prevent the detection of distant movements, small signals from the mixer are to be ignored. Design a suitable circuit to activate a 12 V d.c. relay only in response to a mixer output signal within the right frequency range and above 10 mV in amplitude. [20%]

(b) A Phase Locked Loop (PLL) comprises an XOR logic gate as a phase detector with an output of 5 V for 180° phase difference, a low-pass filter comprising an inverting operational amplifier circuit with a 10 kΩ input resistor to the inverting node and a resistor and capacitor in parallel in the feedback path, and a voltage-controller oscillator (VCO) with an output frequency of 1.2 MHz per volt at its input. Draw the block diagram of the PLL, derive the loop characteristic equation, and calculate the filter resistor and capacitor values required to realise a loop natural frequency of 20 kHz and a step response overshoot of 15%. [55%]

Table 1. 2-pole VCVS filter design table

| Bessel | | Butterworth | | Chebyshev (0.5 dB) | |
|---|---|---|---|---|---|
| $f_n$ | $A$ | $f_n$ | $A$ | $f_n$ | $A$ |
| 1.274 | 1.268 | 1 | 1.586 | 1.231 | 1.842 |

**END OF PAPER**

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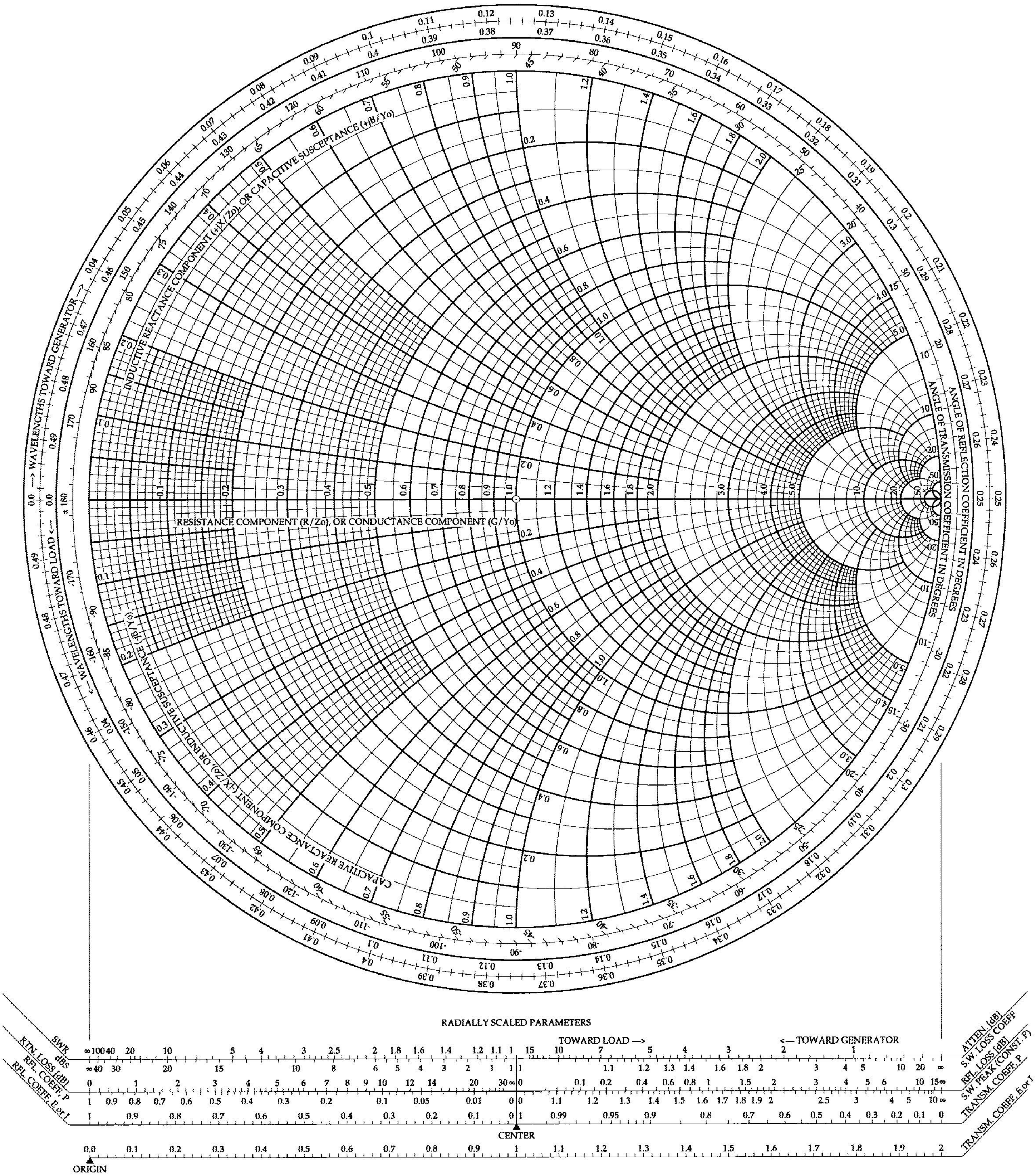
EGT2

ENGINEERING TRIPOS PART IIA

Tuesday 26 April 2022, Module 3B1, Question 2

Candidate No.

Smith Chart for Question 2 – to be detached and handed in with script.



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**Module 3B1**

**RADIO FREQUENCY ELECTRONICS**

NUMERICAL ANSWERS

1 (a) $3.63\times10^{-10}$ W m$^{-2}$ ; $1.39\times10^{-6}$ A m$^{-1}$
(b) 0.0114 m$^2$ ; 3.83 mV (p-p)
(c) 7.2º ; 5.4 km
(d) 0.32 mm
(e) (i) 97.3 dB
(ii) 100.9 dB

2 (a) $L$ = 59.7 μH ; $C$ = 265 pF
(b) Coupling capacitor ~ 10 nF ; $C$ = 2.81 pF ; $R_3 = R_d$ = 390 Ω ; $R_1$ = 22 kΩ ; $R_2$ = 33 kΩ
(c) (i) $Z$ = 31.5 + j36.7 Ω ; $\underline{S}_{11} = 0.46\angle 93^\circ$
(ii) 10.2 pF ; 36 mm
(iii) $C_s$ = 42.4 pF ; $C_p$ = 8.06 pF

3 (b) $R_1$ ~ 880 Ω ; $R_2$ ~ 100 Ω ; $R_3$ = 3.3 Ω ; $R_4$ = 75 Ω ; $C$ ~ 10 nF
(c) 852 MHz
(d) $l$ = 97.2 mm ; $w$ = 1.44 mm

4 (a) (i) Chebyshev ; 245 nF ; 16.2 nF
(b) 10 kΩ ; 105 Ω ; 76 nF