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AO6

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2003

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

**RADIO FREQUENCY ELECTRONICS**

Wednesday, 7 May 10:00 am

Time allowed: 3:00 hours

**There are SIX questions on this paper.**

**Answer FOUR questions.**

**Corrected Copy**

**Any special instructions for invigilators and information for candidates are on page 1.**

Examiners responsible First Marker(s) : S. Lucyszyn
Second Marker(s) : C. Papavassiliou

Special Information for Invigilators: none.

Information for Candidates: Filter tables and filter curves will be supplied

# The Questions

1. A lossless coaxial cable has a distributed capacitance of 50 pF/m and distributed inductance of 280 nH/m.

   (a) At an operational frequency of 1.8 GHz, calculate the following transmission line parameters:
   (i) Characteristic impedance [1]
   (ii) Propagation constant [2]
   (iii) Guided wavelength [2]
   (iv) Phase velocity [2]

   (b) Given the electric and magnetic field intensities between the inner and outer conductors, show that the power flux density at the surface of a conductor is equal to the surface power density given in terms of the surface current and impedance variables. Illustrate all the vector variables.
   [6]

   (c) For the coaxial cable in 1(a), if the electric field intensity between the conductors is 1 V/m and the conductors are made from copper (having a bulk DC conductivity of $\sigma_o$ = 5.8 x$10^7$ S/m), determine the following surface parameters at 1.8 GHz ($\mu_o$ = 4x$\pi$ x$10^{-7}$ S/m):
   (i) Surface current density [2]
   (ii) Surface impedance [3]
   (iii) Surface power density [2]

2. A short transmission line is used to transform an arbitrary termination impedance, $Z = R + jX$, to the reference impedance, $Zo$. The impedance looking into the transformer is given by the following expression:

$$z_{IN} = \frac{z + jz_{TX}\tan\theta}{z_{TX} + jz\tan\theta} \qquad (2.1)$$

   the normalised variables used have their usual meanings

   (a) Using equation (2.1), derive the equations for the characteristic impedance of the transmission line, $Z_{TX}$, and the corresponding electrical length, $\theta$.
   [10]

   (b) From the expressions derived in 2(a), what are the mathematical limits for the resistive and reactive values of the termination impedance that can be mapped into the input impedance of the short transmission line transformer?
   [3]

   (c) A load termination consisting of a 20 pF capacitance in series with a 2 Ω resistance must be matched at 900 MHz to a 50 Ω reference impedance using a short transmission line transformer. Using expressions derived in 2(a) and 2(b), calculate $Z_{TX}$ and $\vartheta$ for the short transmission line transformer.
   [5]

   (d) Comment on the suitability, or otherwise, of implementing the short transmission line transformer calculated in 2(c) using conventional microstrip and thin-film microstrip technologies.
   [2]

3.

(a) What are the levels of insertion loss and return loss at the -3 dB cut-off frequency for a lossless filter? You are asked to design a filter with a maximum pass band return loss level of -6.868 dB. What will be the worst-case pass band insertion loss ripple for a lossless filter?

[5]

(b) Using the worst-case pass band insertion loss level calculated in 3(a), design a lumped-element L-C band stop filter to meet the following specifications:

| | |
|---|---|
| Lower pass band -3 dB cut-off frequency: | 540 MHz |
| Upper pass band -3 dB cut-off frequency: | 660 MHz |
| Stop band bandwidth: | 60 MHz |
| Band stop attenuation: | > 45 dB |
| Source impedance, $Zs$: | 50 Ω |
| Load impedance, $Z_L$: | 100 Ω |

[10]

(c) Define group delay and explain the general relationship between its frequency response and that of sharp cut-off insertion loss characteristics.

[5]

4.

(a) Using a signal flow graph or otherwise, derive an expression for the input voltage wave reflection coefficient for a 2-port network that is terminated with a load impedance $Z_L$.

[5]

(b) From the expression derived in 4(a), describe how stability circles can be created on the Smith chart. What does this stability circle represent when it encompasses the impedance matched, $z_o$, point on the Smith chart and when it does not encompass this point?

[5]

(c) Given a 2-port network with the following S-parameters:

$$[S]=\begin{bmatrix}0.5 & 0.5\\ 10 & 0.5\end{bmatrix} \qquad (4.1)$$

What is the input voltage wave reflection coefficient if the output port is terminated with a load impedance $Z_L$ = -5 Ω and a reference impedance $Zo$ = 50 Ω?

[5]

(d) For the 2-port network given in 4(c) the Rollett's stability factor is 2.3. Comment on the apparent contradiction between the Rollett's stability factor and the input voltage wave reflection coefficient found in 4(c). What is the maximum gain that can be achieved with a passive load impedance termination?

[5]

5. Draw the topology of a double-balanced amplifier.

(a) If 3 dB quadrature couplers are used in conjunction with identical non-ideal single-ended amplifiers, use S-parameter analysis to determine expressions for the overall insertion gain and input return loss. Assume the couplers are perfectly matched to the reference impedance, $Zo$, and the interconnections between the main components are ideal.

[10]

(b) For the topology in 5(a), if the working single-ended amplifiers have a forward voltage wave transmission coefficient of $S_{21} = |10|\angle 35°$, determine the overall insertion gain and input return loss if one of the amplifiers fails, such that $S_{21} = 0$. Assume that there is no change in the input or output impedances of the failed transistor. What is the main application of this topology and what are its advantages and disadvantages when compared to a single-ended amplifier?

[10]

6.

(a) Describe a scalar network analyser and draw the simplified block diagram for a vector network analyser (VNA), clearly identifying all blocks. Explain how transmission measurements are performed with the VNA and list some of the advantages and disadvantages of both instruments.

[8]

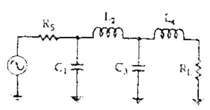
(b) Compare and contrast test-fixture measurements with on-wafer probing.

[4]

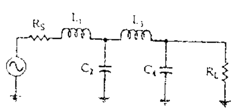
(c) Briefly explain the basic principles by which a VNA can perform synthetic-pulse time domain reflectometry. Sketch the measured reflection response in the time domain for a slightly mismatched MMIC through-line embedded within a non-ideal test fixture. Describe how the frequency response of $|S_{11}|$ can be emphasised for the embedded MMIC. Is this 'de-embedding' process needed with on-wafer probing?

[8]

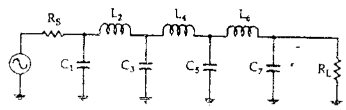
Butterworth Low-Pass Prototype Element Values



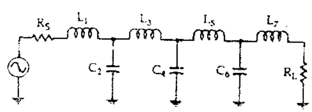

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ |
|---|---|---|---|---|---|
| 2 | 1.111 | 1.035 | 1.835 | | |
| | 1.250 | 0.849 | 2.121 | | |
| | 1.429 | 0.697 | 2.439 | | |
| | 1.667 | 0.566 | 2.828 | | |
| | 2.000 | 0.448 | 3.346 | | |
| | 2.500 | 0.342 | 4.095 | | |
| | 3.333 | 0.245 | 5.313 | | |
| | 5.000 | 0.156 | 7.707 | | |
| | 10.000 | 0.074 | 14.814 | | |
| | ∞ | 1.414 | 0.707 | | |
| 3 | 0.900 | 0.808 | 1.633 | 1.599 | |
| | 0.800 | 0.844 | 1.384 | 1.926 | |
| | 0.700 | 0.915 | 1.165 | 2.277 | |
| | 0.600 | 1.023 | 0.965 | 2.702 | |
| | 0.500 | 1.181 | 0.779 | 3.261 | |
| | 0.400 | 1.425 | 0.604 | 4.064 | |
| | 0.300 | 1.838 | 0.440 | 5.363 | |
| | 0.200 | 2.669 | 0.284 | 7.910 | |
| | 0.100 | 5.187 | 0.136 | 15.455 | |
| | ∞ | 1.500 | 1.333 | 0.500 | |
| 4 | 1.111 | 0.466 | 1.592 | 1.744 | 1.469 |
| | 1.250 | 0.388 | 1.695 | 1.511 | 1.811 |
| | 1.429 | 0.325 | 1.862 | 1.291 | 2.175 |
| | 1.667 | 0.269 | 2.103 | 1.082 | 2.613 |
| | 2.000 | 0.218 | 2.452 | 0.883 | 3.187 |
| | 2.500 | 0.169 | 2.986 | 0.691 | 4.009 |
| | 3.333 | 0.124 | 3.883 | 0.507 | 5.338 |
| | 5.000 | 0.080 | 5.684 | 0.331 | 7.940 |
| | 10.000 | 0.039 | 11.094 | 0.162 | 15.642 |
| | ∞ | 1.531 | 1.577 | 1.082 | 0.383 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ |



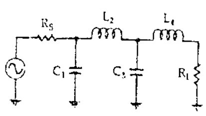

Butterworth Low-Pass Prototype Element Values



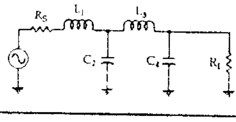

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ | $C_5$ | $L_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.900 | 0.442 | 1.027 | 1.910 | 1.756 | 1.389 | | |
| | 0.800 | 0.470 | 0.866 | 2.061 | 1.544 | 1.738 | | |
| | 0.700 | 0.517 | 0.731 | 2.285 | 1.333 | 2.108 | | |
| | 0.600 | 0.586 | 0.609 | 2.600 | 1.126 | 2.552 | | |
| | 0.500 | 0.686 | 0.496 | 3.051 | 0.924 | 3.133 | | |
| | 0.400 | 0.838 | 0.388 | 3.736 | 0.727 | 3.965 | | |
| | 0.300 | 1.094 | 0.285 | 4.884 | 0.537 | 5.307 | | |
| | 0.200 | 1.608 | 0.186 | 7.185 | 0.352 | 7.935 | | |
| | 0.100 | 3.512 | 0.091 | 14.095 | 0.173 | 15.710 | | |
| | ∞ | 1.545 | 1.694 | 1.382 | 0.894 | 0.309 | | |
| 6 | 1.111 | 0.289 | 1.040 | 1.322 | 2.054 | 1.744 | 1.335 | |
| | 1.250 | 0.245 | 1.116 | 1.126 | 2.239 | 1.550 | 1.688 | |
| | 1.429 | 0.207 | 1.236 | 0.957 | 2.499 | 1.346 | 2.062 | |
| | 1.667 | 0.173 | 1.407 | 0.801 | 2.858 | 1.143 | 2.509 | |
| | 2.000 | 0.141 | 1.653 | 0.654 | 3.369 | 0.942 | 3.094 | |
| | 2.500 | 0.111 | 2.028 | 0.514 | 4.141 | 0.745 | 3.931 | |
| | 3.333 | 0.082 | 2.656 | 0.379 | 5.433 | 0.552 | 5.280 | |
| | 5.000 | 0.054 | 3.917 | 0.248 | 8.020 | 0.363 | 7.922 | |
| | 10.000 | 0.026 | 7.705 | 0.122 | 15.786 | 0.179 | 15.738 | |
| | ∞ | 1.553 | 1.759 | 1.553 | 1.202 | 0.758 | 0.259 | |
| 7 | 0.900 | 0.299 | 0.711 | 1.404 | 1.489 | 2.125 | 1.727 | 1.296 |
| | 0.800 | 0.322 | 0.606 | 1.517 | 1.278 | 2.334 | 1.546 | 1.652 |
| | 0.700 | 0.357 | 0.515 | 1.688 | 1.091 | 2.618 | 1.350 | 2.028 |
| | 0.600 | 0.408 | 0.432 | 1.928 | 0.917 | 3.005 | 1.150 | 2.477 |
| | 0.500 | 0.480 | 0.354 | 2.273 | 0.751 | 3.553 | 0.951 | 3.064 |
| | 0.400 | 0.590 | 0.278 | 2.795 | 0.592 | 4.380 | 0.754 | 3.904 |
| | 0.300 | 0.775 | 0.206 | 3.671 | 0.437 | 5.761 | 0.560 | 5.258 |
| | 0.200 | 1.145 | 0.135 | 5.427 | 0.287 | 8.526 | 0.369 | 7.908 |
| | 0.100 | 2.257 | 0.067 | 10.700 | 0.142 | 16.822 | 0.182 | 15.748 |
| | ∞ | 1.558 | 1.799 | 1.659 | 1.397 | 1.055 | 0.656 | 0.223 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ | $L_5$ | $C_6$ | $L_7$ |



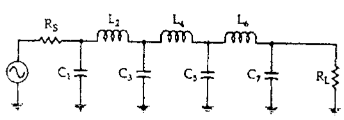

Chebyshev Low-Pass Element Values for 0.01-dB Ripple



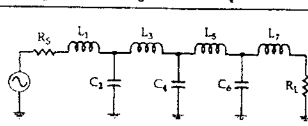

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ |
|---|---|---|---|---|---|
| 2 | 1.101 | 1.347 | 1.483 | | |
| | 1.111 | 1.247 | 1.595 | | |
| | 1.250 | 0.943 | 1.997 | | |
| | 1.429 | 0.759 | 2.344 | | |
| | 1.667 | 0.609 | 2.750 | | |
| | 2.000 | 0.479 | 3.277 | | |
| | 2.500 | 0.363 | 4.033 | | |
| | 3.333 | 0.259 | 5.255 | | |
| | 5.000 | 0.164 | 7.650 | | |
| | 10.000 | 0.078 | 14.749 | | |
| | ∞ | 1.412 | 0.742 | | |
| 3 | 1.000 | 1.181 | 1.821 | 1.181 | |
| | 0.900 | 1.092 | 1.660 | 1.480 | |
| | 0.800 | 1.097 | 1.443 | 1.806 | |
| | 0.700 | 1.160 | 1.228 | 2.165 | |
| | 0.600 | 1.274 | 1.024 | 2.598 | |
| | 0.500 | 1.452 | 0.829 | 3.164 | |
| | 0.400 | 1.734 | 0.645 | 3.974 | |
| | 0.300 | 2.216 | 0.470 | 5.280 | |
| | 0.200 | 3.193 | 0.305 | 7.834 | |
| | 0.100 | 6.141 | 0.148 | 15.390 | |
| | ∞ | 1.501 | 1.433 | 0.591 | |
| 4 | 1.100 | 0.950 | 1.938 | 1.761 | 1.046 |
| | 1.111 | 0.854 | 1.946 | 1.744 | 1.165 |
| | 1.250 | 0.618 | 2.075 | 1.542 | 1.617 |
| | 1.429 | 0.495 | 2.279 | 1.334 | 2.008 |
| | 1.667 | 0.398 | 2.571 | 1.128 | 2.461 |
| | 2.000 | 0.316 | 2.994 | 0.926 | 3.045 |
| | 2.500 | 0.242 | 3.641 | 0.729 | 3.875 |
| | 3.333 | 0.174 | 4.727 | 0.538 | 5.209 |
| | 5.000 | 0.112 | 6.910 | 0.352 | 7.813 |
| | 10.000 | 0.054 | 13.469 | 0.173 | 15.510 |
| | ∞ | 1.529 | 1.691 | 1.312 | 0.523 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ |




Chebyshev Low-Pass Element Values for 0.01-dB Ripple




| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ | $C_5$ | $L_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.000 | 0.977 | 1.685 | 2.037 | 1.685 | 0.977 | | |
| | 0.900 | 0.880 | 1.456 | 2.174 | 1.641 | 1.274 | | |
| | 0.800 | 0.877 | 1.235 | 2.379 | 1.499 | 1.607 | | |
| | 0.700 | 0.926 | 1.040 | 2.658 | 1.323 | 1.977 | | |
| | 0.600 | 1.019 | 0.863 | 3.041 | 1.135 | 2.424 | | |
| | 0.500 | 1.166 | 0.699 | 3.584 | 0.942 | 3.009 | | |
| | 0.400 | 1.398 | 0.544 | 4.403 | 0.749 | 3.845 | | |
| | 0.300 | 1.797 | 0.398 | 5.772 | 0.557 | 5.193 | | |
| | 0.200 | 2.604 | 0.259 | 8.514 | 0.368 | 7.826 | | |
| | 0.100 | 5.041 | 0.127 | 16.741 | 0.182 | 15.613 | | |
| | ∞ | 1.547 | 1.795 | 1.645 | 1.237 | 0.488 | | |
| 6 | 1.101 | 0.851 | 1.796 | 1.841 | 2.027 | 1.631 | 0.937 | |
| | 1.111 | 0.760 | 1.782 | 1.775 | 2.094 | 1.638 | 1.053 | |
| | 1.250 | 0.545 | 1.864 | 1.489 | 2.403 | 1.507 | 1.504 | |
| | 1.429 | 0.436 | 2.038 | 1.266 | 2.735 | 1.332 | 1.899 | |
| | 1.667 | 0.351 | 2.298 | 1.061 | 3.167 | 1.145 | 2.357 | |
| | 2.000 | 0.279 | 2.678 | 0.867 | 3.768 | 0.954 | 2.948 | |
| | 2.500 | 0.214 | 3.261 | 0.682 | 4.667 | 0.761 | 3.790 | |
| | 3.333 | 0.155 | 4.245 | 0.503 | 6.163 | 0.568 | 5.143 | |
| | 5.000 | 0.100 | 6.223 | 0.330 | 9.151 | 0.376 | 7.785 | |
| | 10.000 | 0.048 | 12.171 | 0.162 | 18.105 | 0.187 | 15.595 | |
| | ∞ | 1.551 | 1.847 | 1.790 | 1.598 | 1.190 | 0.469 | |
| 7 | 1.000 | 0.913 | 1.595 | 2.002 | 1.870 | 2.002 | 1.595 | 0.913 |
| | 0.900 | 0.816 | 1.362 | 2.089 | 1.722 | 2.202 | 1.581 | 1.206 |
| | 0.800 | 0.811 | 1.150 | 2.262 | 1.525 | 2.465 | 1.464 | 1.538 |
| | 0.700 | 0.857 | 0.967 | 2.516 | 1.323 | 2.802 | 1.307 | 1.910 |
| | 0.600 | 0.943 | 0.803 | 2.872 | 1.124 | 3.250 | 1.131 | 2.359 |
| | 0.500 | 1.080 | 0.650 | 3.382 | 0.928 | 3.875 | 0.947 | 2.948 |
| | 0.400 | 1.297 | 0.507 | 4.156 | 0.735 | 4.812 | 0.758 | 3.790 |
| | 0.300 | 1.669 | 0.372 | 5.454 | 0.546 | 6.370 | 0.568 | 5.148 |
| | 0.200 | 2.242 | 0.242 | 8.057 | 0.360 | 9.484 | 0.378 | 7.802 |
| | 0.100 | 4.701 | 0.119 | 15.872 | 0.178 | 18.818 | 0.188 | 15.652 |
| | ∞ | 1.559 | 1.867 | 1.866 | 1.765 | 1.563 | 1.161 | 0.456 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ | $L_5$ | $C_6$ | $L_7$ |

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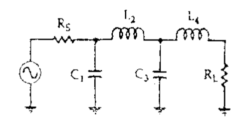
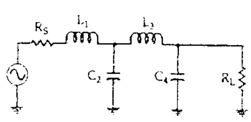
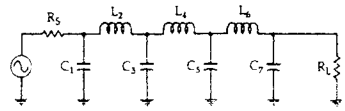
Chebyshev Low-Pass Prototype Element Values for 0.1-dB Ripple



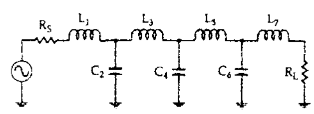

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ |
|---|---|---|---|---|---|
| 2 | 1.355 | 1.209 | 1.638 | | |
| | 1.429 | 0.977 | 1.982 | | |
| | 1.667 | 0.733 | 2.489 | | |
| | 2.000 | 0.560 | 3.054 | | |
| | 2.500 | 0.417 | 3.827 | | |
| | 3.333 | 0.293 | 5.050 | | |
| | 5.000 | 0.184 | 7.426 | | |
| | 10.000 | 0.087 | 14.433 | | |
| | ∞ | 1.391 | 0.819 | | |
| 3 | 1.000 | 1.433 | 1.594 | 1.433 | |
| | 0.900 | 1.426 | 1.494 | 1.622 | |
| | 0.800 | 1.451 | 1.356 | 1.871 | |
| | 0.700 | 1.521 | 1.193 | 2.190 | |
| | 0.600 | 1.648 | 1.017 | 2.603 | |
| | 0.500 | 1.853 | 0.838 | 3.159 | |
| | 0.400 | 2.186 | 0.660 | 3.968 | |
| | 0.300 | 2.763 | 0.486 | 5.279 | |
| | 0.200 | 3.942 | 0.317 | 7.850 | |
| | 0.100 | 7.512 | 0.155 | 15.466 | |
| | ∞ | 1.513 | 1.510 | 0.716 | |
| 4 | 1.355 | 0.992 | 2.148 | 1.585 | 1.341 |
| | 1.429 | 0.779 | 2.348 | 1.429 | 1.700 |
| | 1.667 | 0.576 | 2.730 | 1.185 | 2.243 |
| | 2.000 | 0.440 | 3.227 | 0.967 | 2.856 |
| | 2.500 | 0.329 | 3.961 | 0.760 | 3.698 |
| | 3.333 | 0.233 | 5.178 | 0.560 | 5.030 |
| | 5.000 | 0.148 | 7.607 | 0.367 | 7.614 |
| | 10.000 | 0.070 | 14.887 | 0.180 | 15.230 |
| | ∞ | 1.511 | 1.768 | 1.455 | 0.673 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ |



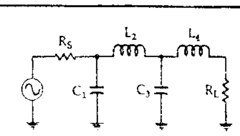

Chebyshev Low-Pass Prototype Element Values for 0.1-dB Ripple



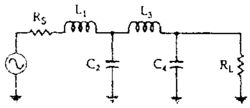

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ | $C_5$ | $L_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.000 | 1.301 | 1.556 | 2.241 | 1.556 | 1.301 | | |
| | 0.900 | 1.285 | 1.433 | 2.380 | 1.488 | 1.488 | | |
| | 0.800 | 1.300 | 1.282 | 2.582 | 1.382 | 1.738 | | |
| | 0.700 | 1.358 | 1.117 | 2.868 | 1.244 | 2.062 | | |
| | 0.600 | 1.470 | 0.947 | 3.269 | 1.085 | 2.484 | | |
| | 0.500 | 1.654 | 0.778 | 3.845 | 0.913 | 3.055 | | |
| | 0.400 | 1.954 | 0.612 | 4.720 | 0.733 | 3.886 | | |
| | 0.300 | 2.477 | 0.451 | 6.196 | 0.550 | 5.237 | | |
| | 0.200 | 3.546 | 0.295 | 9.127 | 0.366 | 7.889 | | |
| | 0.100 | 6.787 | 0.115 | 17.957 | 0.182 | 15.745 | | |
| | ∞ | 1.561 | 1.807 | 1.766 | 1.417 | 0.651 | | |
| 6 | 1.355 | 0.942 | 2.080 | 1.659 | 2.247 | 1.534 | 1.277 | |
| | 1.429 | 0.735 | 2.249 | 1.454 | 2.544 | 1.405 | 1.629 | |
| | 1.667 | 0.542 | 2.600 | 1.183 | 3.064 | 1.185 | 2.174 | |
| | 2.000 | 0.414 | 3.068 | 0.958 | 3.712 | 0.979 | 2.794 | |
| | 2.500 | 0.310 | 3.765 | 0.749 | 4.651 | 0.778 | 3.645 | |
| | 3.333 | 0.220 | 4.927 | 0.551 | 6.195 | 0.580 | 4.996 | |
| | 5.000 | 0.139 | 7.250 | 0.361 | 9.261 | 0.384 | 7.618 | |
| | 10.000 | 0.067 | 14.220 | 0.178 | 18.427 | 0.190 | 15.350 | |
| | ∞ | 1.534 | 1.884 | 1.831 | 1.749 | 1.394 | 0.638 | |
| 7 | 1.000 | 1.262 | 1.520 | 2.239 | 1.680 | 2.239 | 1.520 | 1.262 |
| | 0.900 | 1.242 | 1.395 | 2.361 | 1.578 | 2.397 | 1.459 | 1.447 |
| | 0.800 | 1.255 | 1.245 | 2.548 | 1.443 | 2.624 | 1.362 | 1.697 |
| | 0.700 | 1.310 | 1.083 | 2.819 | 1.283 | 2.942 | 1.233 | 2.021 |
| | 0.600 | 1.417 | 0.917 | 3.205 | 1.209 | 3.384 | 1.081 | 2.444 |
| | 0.500 | 1.595 | 0.753 | 3.764 | 0.928 | 4.015 | 0.914 | 3.018 |
| | 0.400 | 1.885 | 0.593 | 4.618 | 0.742 | 4.970 | 0.738 | 3.855 |
| | 0.300 | 2.392 | 0.437 | 6.054 | 0.556 | 6.569 | 0.557 | 5.217 |
| | 0.200 | 3.428 | 0.286 | 8.937 | 0.369 | 9.770 | 0.372 | 7.890 |
| | 0.100 | 6.570 | 0.141 | 17.603 | 0.184 | 19.376 | 0.186 | 15.813 |
| | ∞ | 1.575 | 1.858 | 1.921 | 1.827 | 1.734 | 1.379 | 0.631 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ | $L_5$ | $C_6$ | $L_7$ |



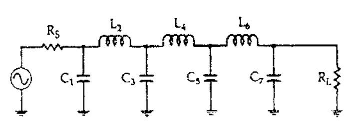

Chebyshev Low-Pass Prototype Element Values for 0.5-dB Ripple



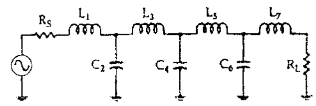

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ |
|---|---|---|---|---|---|
| 2 | 1.984 | 0.983 | 1.950 | | |
| | 2.000 | 0.909 | 2.103 | | |
| | 2.500 | 0.564 | 3.165 | | |
| | 3.333 | 0.375 | 4.411 | | |
| | 5.000 | 0.228 | 6.700 | | |
| | 10.000 | 0.105 | 13.322 | | |
| | ∞ | 1.307 | 0.975 | | |
| 3 | 1.000 | 1.864 | 1.280 | 1.834 | |
| | 0.900 | 1.918 | 1.209 | 2.026 | |
| | 0.800 | 1.997 | 1.120 | 2.237 | |
| | 0.700 | 2.114 | 1.015 | 2.517 | |
| | 0.500 | 2.557 | 0.759 | 3.436 | |
| | 0.400 | 2.985 | 0.615 | 4.242 | |
| | 0.300 | 3.729 | 0.463 | 5.576 | |
| | 0.200 | 5.254 | 0.309 | 8.225 | |
| | 0.100 | 9.890 | 0.153 | 16.118 | |
| | ∞ | 1.572 | 1.518 | 0.932 | |
| 4 | 1.984 | 0.920 | 2.586 | 1.304 | 1.826 |
| | 2.000 | 0.845 | 2.720 | 1.238 | 1.985 |
| | 2.500 | 0.516 | 3.766 | 0.869 | 3.121 |
| | 3.333 | 0.344 | 5.120 | 0.621 | 4.480 |
| | 5.000 | 0.210 | 7.708 | 0.400 | 6.987 |
| | 10.000 | 0.098 | 15.352 | 0.194 | 14.262 |
| | ∞ | 1.436 | 1.889 | 1.521 | 0.913 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ |



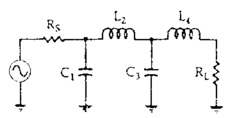

Chebyshev Low-Pass Prototype Element Values for 0.5-dB Ripple



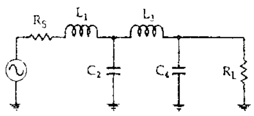

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ | $C_5$ | $L_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.000 | 1.807 | 1.303 | 2.691 | 1.303 | 1.807 | | |
| | 0.900 | 1.854 | 1.222 | 2.849 | 1.238 | 1.970 | | |
| | 0.800 | 1.926 | 1.126 | 3.060 | 1.157 | 2.185 | | |
| | 0.700 | 2.035 | 1.015 | 3.353 | 1.058 | 2.470 | | |
| | 0.600 | 2.200 | 0.890 | 3.765 | 0.942 | 2.861 | | |
| | 0.500 | 2.457 | 0.754 | 4.367 | 0.810 | 3.414 | | |
| | 0.400 | 2.870 | 0.609 | 5.296 | 0.664 | 4.245 | | |
| | 0.300 | 3.588 | 0.459 | 6.871 | 0.508 | 5.625 | | |
| | 0.200 | 5.064 | 0.306 | 10.054 | 0.343 | 8.367 | | |
| | 0.100 | 9.556 | 0.153 | 19.647 | 0.173 | 16.574 | | |
| | ∞ | 1.630 | 1.740 | 1.922 | 1.514 | 0.903 | | |
| 6 | 1.984 | 0.905 | 2.577 | 1.368 | 2.713 | 1.299 | 1.796 | |
| | 2.000 | 0.830 | 2.704 | 1.291 | 2.872 | 1.237 | 1.956 | |
| | 2.500 | 0.506 | 3.722 | 0.890 | 4.109 | 0.881 | 3.103 | |
| | 3.333 | 0.337 | 5.055 | 0.632 | 5.699 | 0.635 | 4.481 | |
| | 5.000 | 0.206 | 7.615 | 0.406 | 8.732 | 0.412 | 7.031 | |
| | 10.000 | 0.096 | 15.186 | 0.197 | 17.681 | 0.202 | 14.433 | |
| 7 | 1.000 | 1.790 | 1.296 | 2.718 | 1.385 | 2.718 | 1.296 | 1.790 |
| | 0.900 | 1.835 | 1.215 | 2.869 | 1.308 | 2.883 | 1.234 | 1.953 |
| | 0.800 | 1.905 | 1.118 | 3.076 | 1.215 | 3.107 | 1.155 | 2.168 |
| | 0.700 | 2.011 | 1.007 | 3.364 | 1.105 | 3.416 | 1.058 | 2.455 |
| | 0.600 | 2.174 | 0.882 | 3.772 | 0.979 | 3.852 | 0.944 | 2.848 |
| | 0.500 | 2.428 | 0.747 | 4.370 | 0.838 | 2.289 | 0.814 | 3.405 |
| | 0.400 | 2.835 | 0.604 | 5.295 | 0.685 | 5.470 | 0.669 | 4.243 |
| | 0.300 | 3.546 | 0.455 | 6.867 | 0.522 | 7.134 | 0.513 | 5.635 |
| | 0.200 | 5.007 | 0.303 | 10.049 | 0.352 | 10.496 | 0.348 | 8.404 |
| | 0.100 | 9.456 | 0.151 | 19.649 | 0.178 | 20.631 | 0.176 | 16.665 |
| | ∞ | 1.646 | 1.777 | 2.031 | 1.789 | 1.924 | 1.503 | 0.895 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ | $L_5$ | $C_6$ | $L_7$ |



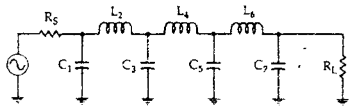
**Chebyshev Low-Pass Prototype Element Values for 1.0-dB Ripple**



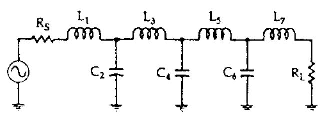

| $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ |
|---|---|---|---|---|
| 3.000 | 0.572 | 3.132 | | |
| 4.000 | 0.365 | 4.600 | | |
| 8.000 | 0.157 | 9.658 | | |
| ∞ | 1.213 | 1.109 | | |
| 1.000 | 2.216 | 1.088 | 2.216 | |
| 0.500 | 4.431 | 0.817 | 2.216 | |
| 0.333 | 6.647 | 0.726 | 2.216 | |
| 0.250 | 8.862 | 0.680 | 2.216 | |
| 0.125 | 17.725 | 0.612 | 2.216 | |
| ∞ | 1.652 | 1.460 | 1.108 | |
| 3.000 | 0.653 | 4.411 | 0.814 | 2.535 |
| 4.000 | 0.452 | 7.083 | 0.612 | 2.848 |
| 8.000 | 0.209 | 17.164 | 0.428 | 3.281 |
| ∞ | 1.350 | 2.010 | 1.488 | 1.106 |
| $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ |



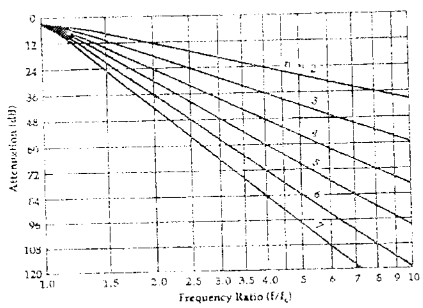

**Chebyshev Low-Pass Prototype Element Values for 1.0-dB Ripple**



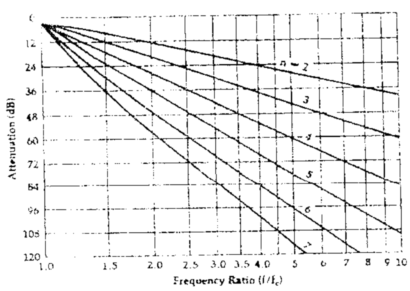

| $n$ | $R_S/R_L$ | $C_1$ | $L_2$ | $C_3$ | $L_4$ | $C_5$ | $L_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|---|
| 5 | 1.000 | 2.207 | 1.128 | 3.103 | 1.128 | 2.207 | | |
| | 0.500 | 4.414 | 0.565 | 4.653 | 1.128 | 2.207 | | |
| | 0.333 | 6.622 | 0.376 | 6.205 | 1.128 | 2.207 | | |
| | 0.250 | 8.829 | 0.282 | 7.756 | 1.128 | 2.207 | | |
| | 0.125 | 17.657 | 0.141 | 13.961 | 1.128 | 2.207 | | |
| | ∞ | 1.721 | 1.645 | 2.061 | 1.493 | 1.103 | | |
| 6 | 3.000 | 0.679 | 3.873 | 0.771 | 4.711 | 0.969 | 2.406 | |
| | 4.000 | 0.481 | 5.644 | 0.476 | 7.351 | 0.849 | 2.582 | |
| | 8.000 | 0.227 | 12.310 | 0.198 | 16.740 | 0.726 | 2.800 | |
| | ∞ | 1.378 | 2.097 | 1.690 | 2.074 | 1.494 | 1.102 | |
| 7 | 1.000 | 2.204 | 1.131 | 3.147 | 1.194 | 3.147 | 1.131 | 2.204 |
| | 0.500 | 4.408 | 0.566 | 6.293 | 0.895 | 3.147 | 1.131 | 2.204 |
| | 0.333 | 6.612 | 0.377 | 9.441 | 0.796 | 3.147 | 1.131 | 2.204 |
| | 0.250 | 8.815 | 0.283 | 12.588 | 0.747 | 3.147 | 1.131 | 2.204 |
| | 0.125 | 17.631 | 0.141 | 25.175 | 0.671 | 3.147 | 1.131 | 2.204 |
| | ∞ | 1.741 | 1.677 | 2.155 | 1.703 | 2.079 | 1.494 | 1.102 |
| $n$ | $R_L/R_S$ | $L_1$ | $C_2$ | $L_3$ | $C_4$ | $L_5$ | $C_6$ | $L_7$ |



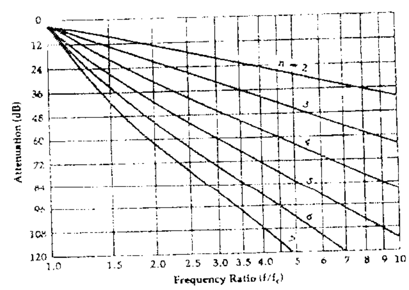

Filter tables



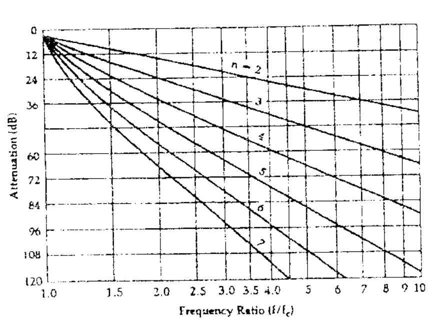

Attenuation characteristics for Butterworth filters.



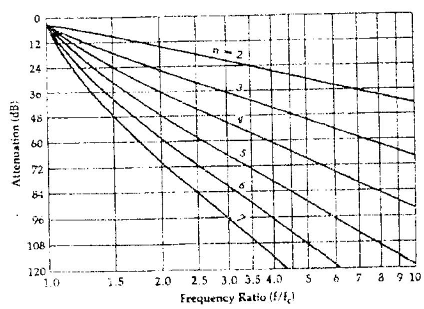

Attenuation characteristics for a Chebyshev filter with 0.01-dB ripple.




Attenuation characteristics for a Chebyshev filter with 0.1-dB ripple.




Attenuation characteristics for a Chebyshev filter with 0.5-dB ripple.




Attenuation characteristics for a Chebyshev filter with 1-dB ripple.