EE4-18
EE9-AO6

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014

MSc and EEE PART IV: MEng and ACGI

Corrected Copy

RADIO FREQUENCY ELECTRONICS

Tuesday, 13 May 10:00 am

Time allowed: 3:00 hours

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks

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

Examiners responsible First Marker(s) : S. Lucyszyn
Second Marker(s) : A.S. Holmes

Special instructions for invigilators

This is a closed book examination.

Special instructions for students

All variables and abbreviations have their usual meaning.

Boltzmann's constant, $k = 1.3805 \times 10^{-23}\ [W.s/K]$

Absolute temperature, $T[K] \approx 273 + T\ [^\circ C]$

The Questions

1. The Active Denial System is a non-lethal electromagnetic weapon for crowd control. It generates enough incident radiation to penetrate human skin (i.e. 400 μm), just beyond the epidermis layer. One system has the following specifications (all variables have their usual meaning):

- $fo = 95$ GHz
- $P_T = 100$ kW
- $R_{MAX} = 750$ m
- Circular parabolic reflector antenna diameter, $D = 2.2$ m, with 75% efficiency.

At 95 GHz, dry human epidermis has the following approximate parameter values:

- Mass density, $\rho_m = 1330$ kg/m^3
- Specific heat capacity, $c_p = 3590$ J/kg.K
- Conductivity, $\sigma = 39$ S/m
- Dielectric constant, $\varepsilon_r' = 5.79$
- Voltage-wave reflection coefficient at the air-skin boundary, $|\rho| = 0.56$

a) Calculate the following antenna parameters:

i) Effective area. [1]

ii) Directivity. [2]

iii) Far-field distance. [2]

iv) Gain (state any assumptions). [2]

b) Calculate the following link budget parameters:

i) EIRP and define this parameter. [1]

ii) Incident and absorbed power densities at the maximum target range. [2]

iii) Electric field density at the maximum target range. [2]

c) Define and at the maximum target range calculate the following:

i) SAR. [3]

ii) ΔT for an exposure time of $\Delta t = 4$ seconds. [3]

iii) From the results given in 1(b)(ii) and 1(c)(ii), do you think this would be a serious hazard to humans? Explain your answer. [2]

2. The ultra-high speed 60 GHz wireless LAN defined, by the IEEE 802.11ad standard, has a 57 to 66 GHz operating frequency range within the European Union and a maximum permitted transmit power of +10 dBm. You are required to design the LO for a direct-conversion transmitter architecture. QuinStar Technology Inc. offers the following range of active frequency multiplier modules.

Output Frequency, Band, GHz	Multiplier Factor	Input Frequency, GHz	Output Power Range Offered, dBm[1]	Input Power Required dBm
8-20	2	4-10	13-27	3-6
18-26.5	2	9-13.25	13-27	5-10
26.5-40	2	13.25-20	10-20	5-10
26.5-40	3	8.83-13.33	10-20	4-6
26.5-40	4	6.62-10	10-20	3-6
33-50	2	16.5-25	10-17	0-5
33-50	3	11-16.67	10-17	5-10
33-50	4	8.25-12.5	10-15	5-10
40-60	2	20-30	10-13	5-10
40-60	3	13.3-20	10-13	5-10
40-60	4	10-15	10-13	5-10
50-75	2	25-37.5	7-16	5-8
50-75	3	16.7-25	7-16	7-10
50-75	4	12.5-18.75	7-16	5-8
50-75	6	8.33-12.5	7-16	4-6
50-75	8	6.25-9.38	7-16	4-6
60-90	2	30-45	0-5	5-8
60-90	3	20-30	0-5	5-8
60-90	4	15-22.5	0-5	5-8
60-90	6	10-15	0-5	5-8
60-90	8	7.5-11.25	0-5	5-8

Table 2.1 Commercially available frequency multiplier modules (QuinStar Technology Inc.)

a) Draw a simple circuit topology that can be used as an even-order harmonic frequency multiplier and sketch typical plots of the input and out voltage waveforms and output frequency spectrum. [6]

b) With a VCO and selecting the most appropriate module(s) available in Table 2.1, draw the block diagram of the LO that will have the least number of subsystem blocks to meet the IEEE 802.11ad specifications. Clearly identify each block and the frequency range of the VCO. [2]

c) For the design in 2(b), and assuming a linear decrease with increasing frequency of the power gain specified in dB, calculate the values of VCO output powers to meet the IEEE 802.11ad specifications. [6]

d) With reference to an equivalent circuit model, briefly describe the difference between *small-signal* and *large-signal* operation. Which of these describe the operation of the active devices listed in Table 2.1. [3]

e) With a VCO and using the modules available in Table 2.1, draw the block diagram of the LO that will have the most number of subsystem blocks to meet the IEEE 802.11ad frequency specifications only. Clearly identify each block and all associated frequency ranges. Using data from Table 2.1, briefly explain why this solution would not work in practice. [3]

3. To meet maximum permitted transmit power of +10 dBm and output frequency specifications for the IEEE 802.11ad wireless LAN standard, a chain of three frequency multiplier stages are used. The respective power gain, noise figure and second-order intercept point values are as follows:

	G [dB]	F [dB]	IP_2 [dBm]
Stage 1:	14.0	2.6	20.0
Stage 2:	8.0	3.1	15
Stage 3:	5.0	4.7	10

Assuming linear operation for each stage, calculate the following where appropriate:

i) Carrier power levels and overall power gain. [2]

ii) Second-order intermodulation component power levels. [3]

iii) Suppression of second-order intermodulation components. [3]

iv) Noise figure. [3]

v) Noise temperature, given a room temperature of 20 °C. [2]

vi) Input noise power. [2]

vii) Input signal-to-noise ratio. [1]

viii) Output noise power. [2]

ix) Output signal-to-noise ratio. [1]

x) Show that the value from 3(iv) can be calculated using the values from 3(vii) and 3(ix). [1]

4. Your laboratory has the following:

- One matched load having a 1 to 10 GHz bandwidth.
- Four identical power attenuators having a 1 to 10 GHz bandwidth and tuneable over a 0 to 20 dB dynamic range.
- Four identical carrier oscillators having a fixed output power of 0 dBm and tuneable over a 1 to 10 GHz frequency range.
- One amplifier having a 1 to 10 GHz bandwidth and tuneable power gain from 0 to 20 dB.
- Four ideal circulators having a 1 to 10 GHz bandwidth.

a) Using some of the above, design a system that will best synthesize the waveform defined by the following general mathematical expression (clearly identify all values of power attenuation, power gain and any assumptions about appropriate operating frequencies and impedance matching conditions):

$$f(x) = \frac{4}{\pi} \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi x}{L}\right) \tag{4.1}$$

[10]

b) What waveform does the series in (4.1) represent? Also, sketch the output voltage waveform from the approximating implementation design given in 4(a).

[2]

c) If the original circulators now have a 0.1 dB insertion loss, re-tune the design given in 4(a) to restore operation.

[2]

d) If the original circulators now have ideal transmission line interconnects that introduce a combined insertion phase delay of 45 degrees at the first harmonic frequency, calculated the differential-phase group delay as a fraction of the period of the first harmonic. Similarly, for each harmonic, calculate the overall differential-phase group delay at the output of the waveform generator. Briefly explain the effect of the interconnect delays on the output waveform generated.

[4]

e) If there is an impedance mismatch at the input of the original circulators, attenuators or amplifier, what could be the effects on the performance of the waveform generator?

[2]

5. A MESFET has input and output impedances of $2 - j\,5\ \Omega$ and $40 - j\,10\ \Omega$, respectively. You are required to design the inter-stage impedance matching network for a two-stage 1 GHz amplifier. Assume that the MESFET input and output impedances are fixed and ignore DC biasing networks.

a) Draw the *RC* lumped-element models for the output of the first-stage transistor and the input for the second-stage transistor. Identify the dominant intrinsic parasitic resistive and capacitive elements of the MESFET. [2]

b) From the *RC* lumped-element models drawn in 5(a), calculate:

i) Parasitic values for both resistances and both capacitances. [4]

ii) Using the values in 5(b)(i), calculate the loaded quality factors for the input and output of the MESFET. State if it is the input or output that limits the bandwidth of operation. [4]

c) Using discrete lumped-element matching, calculate the:

i) lumped-element component values and state their orientation needed to resonate out the intrinsic parasitic capacitances of the MESFET at the output of the first MESFET and input of the second MESFET. [2]

ii) loaded quality factor of the inter-stage impedance matching network and its bandwidth. State if it is the input of the first MESFET, inter-stage impedance matching network or output of the second MESFET that limits the bandwidth of operation. [2]

iii) lumped-element component values needed to implement a one-stage resistive L-matching network. Draw the complete impedance matching network having the minimal number of lumped-element components. [4]

d) With a two-stage resistive L-matching network calculate the new loaded quality factor. State if it is the input of the first MESFET, new inter-stage impedance matching network or output of the second MESFET that limits the bandwidth of operation. [2]

6. Using the standard filter curves and tables provided, you are required to design a BPF that meets the following specifications:

- Pass band attenuation ripple = 0.5 dB
- Centre frequency, fo = 1.0 GHz
- -3 dB bandwidth = 70 MHz
- Attenuation ±250 MHz from centre frequency = 36 dB
- Source impedance, $Z_S = 0.504\ \Omega$
- Load impedance, $Z_L = 1.000\ \Omega$

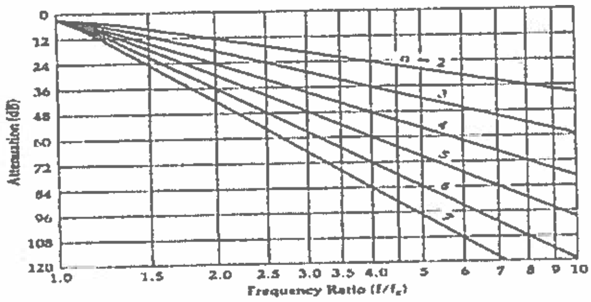
a) Identify the minimum theoretical order of the filter and draw the LPF prototype circuit, quoting the coefficients for each element. [5]

b) Calculate all the component values for the BPF and draw the complete circuit. [5]

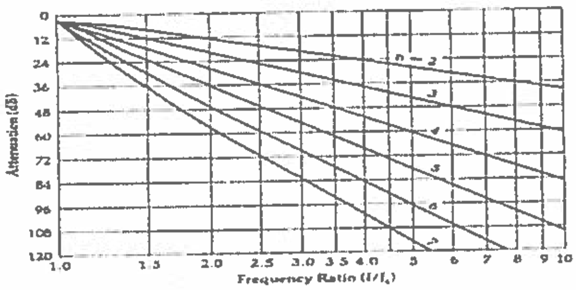
c) Given a series $R_S L_S C_S$ circuit, with the aid of a diagram, show how an admittance inverter employing lumped-element capacitors can be used to *synthesise* the $R_S L_S C_S$ circuit using a shunt $R_P L_P C_P$ circuit. Derive expressions for all the $R_P L_P C_P$ components. [5]

d) Use the technique in 6(c) to impedance match the source impedance of the circuit in 6(b) to Z_L. Calculate all the new component values for the BPF and draw the complete circuit. [5]

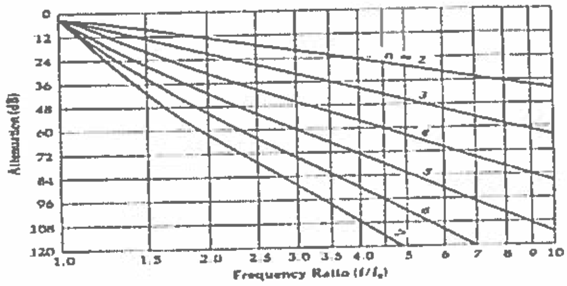
Standard Filter Curves and Tables



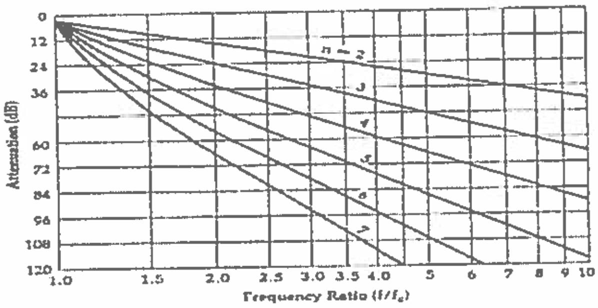
Attenuation characteristics for Butterworth filters.



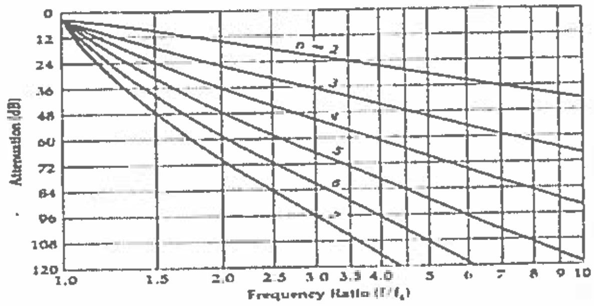
Attenuation characteristics for a Chebyshev filter with 0.01-dB ripple.



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

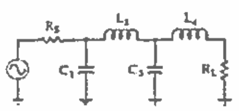


Attenuation characteristics for a Chebyshev filter with 0.5-dB ripple.

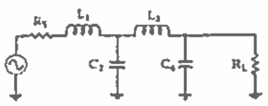


Attenuation characteristics for a Chebyshev filter with 1-dB ripple.

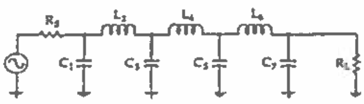
Chebyshev Low-Pass Prototype Element Values for 1.0-dB Ripple



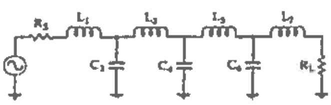
R_s/R_L	C_1	L_2	C_3	L_4
3.000	0.572	3.132		
4.000	0.365	4.600		
8.000	0.157	9.658		
∞	1.213	1.109		
1.000	2.216	1.088	2.216	
0.500	4.431	0.817	2.216	
0.333	6.647	0.726	2.216	
0.250	8.862	0.680	2.216	
0.125	17.725	0.612	2.216	
∞	1.652	1.460	1.108	
3.000	0.653	4.411	0.814	2.535
4.000	0.452	7.083	0.612	2.648
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



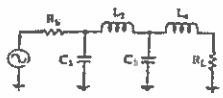
Chebyshev Low-Pass Prototype Element Values for 1.0-dB Ripple



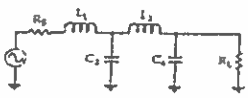
n	R_s/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	1.000	2.207	1.128	3.103	1.128	2.207		
	0.500	4.414	0.565	4.653	1.128	2.207		
	0.333	6.622	0.376	6.205	1.128	2.207		
	0.250	8.829	0.282	7.756	1.128	2.207		
	0.125	17.657	0.141	13.961	1.128	2.207		
	∞	1.721	1.645	2.061	1.403	1.103		
6	3.000	0.679	3.873	0.771	4.711	0.969	2.406	
	4.000	0.481	5.844	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



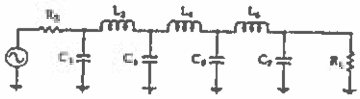
Butterworth Low-Pass Prototype Element Values



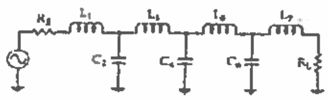
n	R_s/R_L	C_1	L_2	C_3	L_4
2	1.111	1.035	1.835		
	1.250	0.849	2.121		
	1.429	0.697	2.439		
	1.667	0.566	2.828		
	2.000	0.448	3.346		
	2.500	0.342	4.095		
	3.333	0.245	5.313		
	5.000	0.156	7.707		
	10.000	0.074	14.814		
	∞	1.414	0.707		
3	0.900	0.808	1.633	1.599	
	0.800	0.844	1.384	1.926	
	0.700	0.915	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	5.167	0.138	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



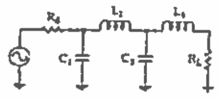
Butterworth Low-Pass Prototype Element Values



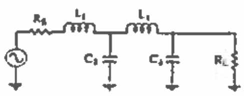
n	R_s/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	0.900	0.442	1.027	1.910	1.756	1.389		
	0.800	0.470	0.866	2.061	1.544	1.738		
	0.700	0.517	0.731	2.285	1.333	2.108		
	0.600	0.586	0.609	2.600	1.126	2.552		
	0.500	0.686	0.496	3.051	0.924	3.133		
	0.400	0.838	0.388	3.736	0.727	3.965		
	0.300	1.094	0.285	4.884	0.537	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	3.084
	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



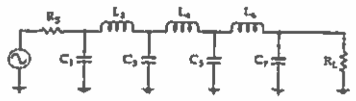
Chebyshev Low-Pass Element Values for 0.01-dB Ripple



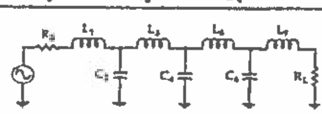
n	R_s/R_L	C_1	L_2	C_3	L_4
2	1.101	1.347	1.483		
	1.111	1.247	1.595		
	1.250	0.943	1.997		
	1.429	0.759	2.344		
	1.667	0.609	2.750		
	2.000	0.479	3.277		
	2.500	0.363	4.033		
	3.333	0.259	5.255		
	5.000	0.164	7.650		
	10.000	0.078	14.749		
	∞	1.412	0.742		
3	1.000	1.181	1.821	1.181	
	0.900	1.092	1.660	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	0.920	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



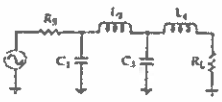
Chebyshev Low-Pass Element Values for 0.01-dB Ripple



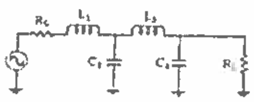
n	R_s/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	1.000	0.977	1.685	2.037	1.685	0.977		
	0.900	0.880	1.456	2.174	1.641	1.274		
	0.800	0.877	1.235	2.379	1.499	1.607		
	0.700	0.926	1.040	2.658	1.323	1.977		
	0.600	1.019	0.863	3.041	1.135	2.424		
	0.500	1.166	0.699	3.584	0.942	3.009		
	0.400	1.398	0.544	4.403	0.749	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



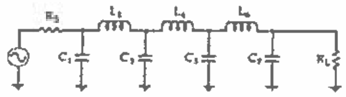
Chebyshev Low-Pass Prototype Element Values for 0.1-dB Ripple



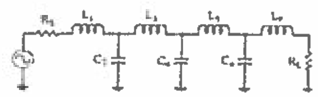
n	R_S/R_L	C_1	L_2	C_3	L_4
2	1.355	1.209	1.638		
	1.429	0.977	1.982		
	1.667	0.733	2.480		
	2.000	0.560	3.054		
	2.500	0.417	3.927		
	3.333	0.293	5.050		
	5.000	0.184	7.420		
	10.000	0.087	14.433		
	∞	1.391	0.819		
3	1.000	1.433	1.594	1.433	
	0.900	1.426	1.494	1.622	
	0.800	1.451	1.356	1.871	
	0.700	1.521	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



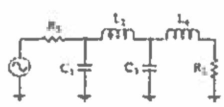
Chebyshev Low-Pass Prototype Element Values for 0.1-dB Ripple



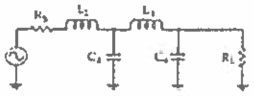
n	R_S/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	1.000	1.301	1.556	2.241	1.556	1.301		
	0.900	1.285	1.433	2.380	1.488	1.488		
	0.800	1.300	1.282	2.582	1.382	1.738		
	0.700	1.358	1.117	2.868	1.244	2.062		
	0.600	1.470	0.947	3.289	1.085	2.484		
	0.500	1.654	0.778	3.845	0.913	3.065		
	0.400	1.954	0.612	4.720	0.733	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	1.183	2.174	
	2.000	0.414	3.068	0.958	3.712	0.970	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	1.061	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



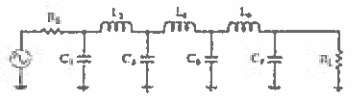
Chebyshev Low-Pass Prototype Element Values for 0.5-dB Ripple



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	4.342	
	0.300	3.729	0.463	5.570	
	0.200	5.231	0.309	8.225	
	0.100	9.860	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	5.150	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	1.850	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	8.387		
	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	0.633	5.699	0.635	4.481	
	5.000	0.206	7.615	0.406	8.732	0.412	7.031	
	10.000	0.098	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	2.860	1.308	2.663	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	2.453
	0.600	2.174	0.882	3.772	0.979	3.852	0.944	2.848
	0.500	2.428	0.747	4.370	0.835	2.280	0.814	3.405
	0.400	2.835	0.604	5.295	0.685	5.470	0.609	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	19.619	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