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IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2007

MSc and EEE PART IV: MEng and ACGI

Corrected Copy

RADIO FREQUENCY ELECTRONICS

Wednesday, 25 April 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) :	E. Rodriguez-Villegas

Special instructions for invigilators:	This is a Closed Book examination. A Smith Chart is to be distributed.
Information for candidates:	This is a Closed Book examination. A Smith Chart is provided and, if used, you must attach this to your answer book.

The Questions

1.

a) The Michelson interferometer, shown in Figure 1.1, can be analysed as a general two-port network. By inspection of Figure 1.1, write down equations for the effective forward voltage wave transmission coefficient (S_{21}) and input voltage wave reflection coefficient (S_{11}) for this passive and reciprocal network. Clearly define all variables used. Hints, the electrical path lengths can be represented by $(k_o dx)$, where $k_o = 2\pi/\lambda$, λ is the wavelength for a monochromatic input source, x is the designation of a particular path and the beam splitter is both symmetrical and reciprocal.

[6]

b) Given that the optical path difference is given by $\delta = 2(d3 - d4)$, if $d1 = d2 = \lambda$ and both mirrors are made from perfectly conducting metals, simplify the equations obtained in 1(a).

[3]

c) For this interferometer to function properly, an ideal beam splitter must reflect 50% of any incident power and allow the rest of the power to be transmitted through without attenuation.

i) Write down the effective forward voltage wave transmission and forward voltage wave reflection coefficients for an ideal beam splitter, given that they must be in phase quadrature with one another. Hint, there are a number of possible solutions, so only choose one.

[4]

ii) From the solution obtained in 1(c)(i), show that the beam splitter obeys the conservation of energy principle.

[2]

iii) Using the solution obtained in 1(c)(i), simplify the equations obtained in 1(b).

[2]

iv) From the solution obtained in 1(c)(iii), show that this Michelson interferometer obeys the conservation of energy principle for $\delta = n\lambda$ and $(n+1/2)\lambda$, where n is any positive integer.

[3]

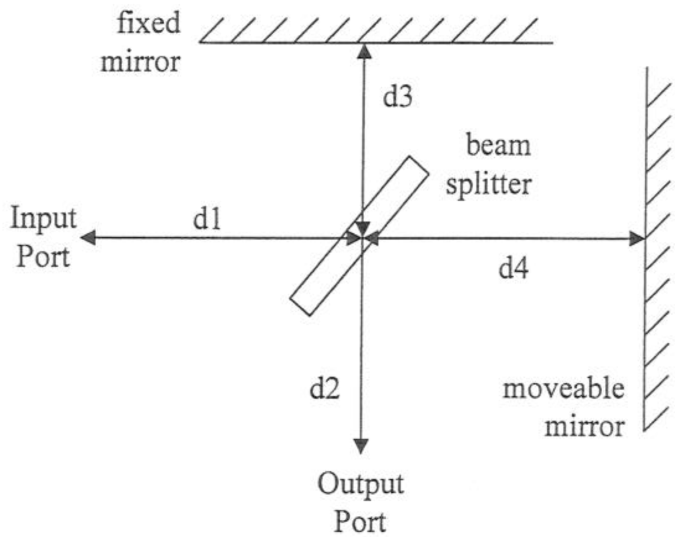


Figure 1.1A Michelson interferometer

2.

a) Draw the circuit diagram of a simple class-A amplifier, having ideal components and describe clearly the function of each component. Describe the performance characteristics of a class-A RF power amplifier and state its applications.

[6]

b) Consider a 4 x 75 μm FET with the following specifications:

$V_{gd|BD} = 12$ V
$V_p = -1.5$ V
$V_k = 0.5$ V
$I_{dss} = 60$ mA
Small-Signal Power Gain = 4 dB

All variables have their usual meaning

Calculate the following for delivering the maximum linear output power:

i) Optimal bias voltages. [2]

ii) Optimal load impedance. [2]

iii) Values of maximum linear output power and peak output power. [2]

iv) DC power and power dissipated per unit gate width. [3]

v) Drain efficiency and power-added efficiency. [2]

c) Explain the Cripps technique for impedance matching of power amplifiers.

[3]

3.

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 3(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:

$$[S] = \begin{bmatrix} 0.5 & 0.5 \\ 10 & 0.5 \end{bmatrix} \qquad (3.1)$$

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 3(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 3(c). What is the maximum gain that can be achieved with a passive load impedance termination?

[5]

4.

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]

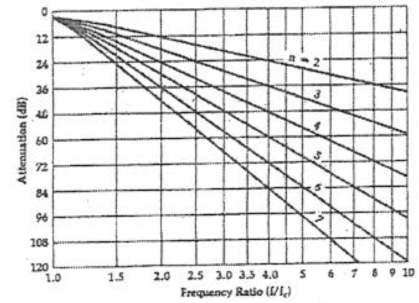
b) Using the worst-case pass band insertion loss level calculated in 3(a), design a lumped-element L-C band stop filter to meet the following specifications:

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, Z_S:	50 Ω
Load impedance, Z_L:	100 Ω

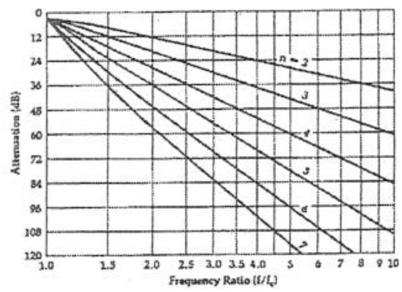
[10]

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

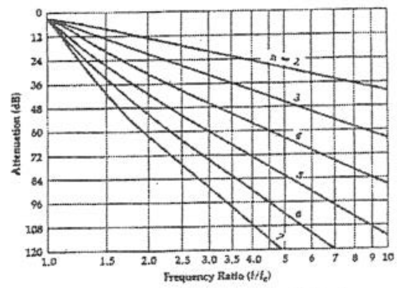
[5]



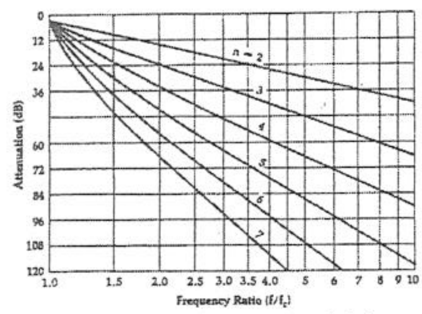
Attenuation characteristics for Butterworth filters.



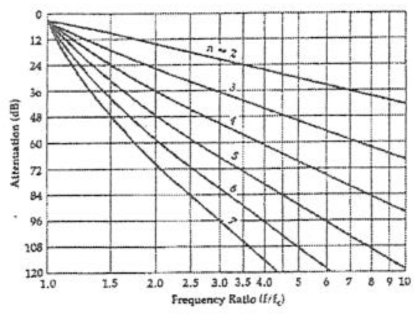
Attenuation characteristics for a Chebyshev filter with 0.01-dB ripple.



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

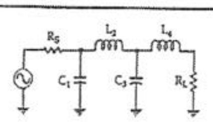


Attenuation characteristics for a Chebyshev filter with 0.5-dB ripple.

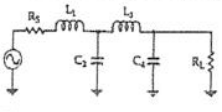


Attenuation characteristics for a Chebyshev filter with 1-dB ripple.

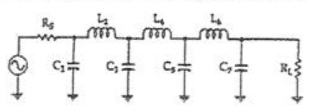
Chebyshev Low-Pass Prototype Element Values for 1.0-dB Ripple



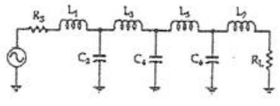
R_S/R_L	C_1	L_2	C_3	L_4
3.000	0.572	3.132		
4.000	0.365	4.600		
8.000	0.157	9.658		
∞	1.213	1.109		
1.000	2.216	1.088	2.216	
0.500	4.431	0.817	2.216	
0.333	6.647	0.726	2.216	
0.250	8.862	0.680	2.216	
0.125	17.725	0.612	2.216	
∞	1.652	1.460	1.108	
3.000	0.653	4.411	0.814	2.535
4.000	0.452	7.083	0.612	2.848
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



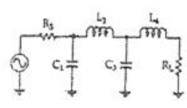
Chebyshev Low-Pass Prototype Element Values for 1.0-dB Ripple



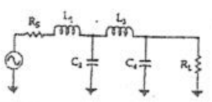
n	R_S/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	1.000	2.207	1.128	3.103	1.128	2.207		
	0.500	4.414	0.565	4.653	1.128	2.207		
	0.333	6.622	0.376	6.205	1.128	2.207		
	0.250	8.829	0.282	7.756	1.128	2.207		
	0.125	17.657	0.141	13.961	1.128	2.207		
	∞	1.721	1.645	2.061	1.493	1.103		
6	3.000	0.679	3.873	0.771	4.711	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



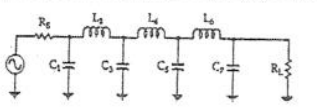
Butterworth Low-Pass Prototype Element Values



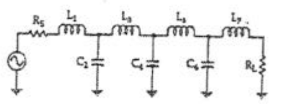
n	R_S/R_L	C_1	L_2	C_3	L_4
2	1.111	1.035	1.835		
	1.250	0.849	2.121		
	1.429	0.697	2.439		
	1.667	0.566	2.828		
	2.000	0.448	3.346		
	2.500	0.342	4.095		
	3.333	0.245	5.313		
	5.000	0.156	7.707		
	10.000	0.074	14.814		
	∞	1.414	0.707		
3	0.900	0.808	1.633	1.599	
	0.800	0.844	1.384	1.926	
	0.700	0.915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



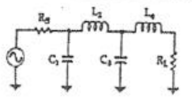
Butterworth Low-Pass Prototype Element Values



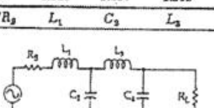
n	R_S/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	0.900	0.442	1.027	1.910	1.756	1.389		
	0.800	0.470	0.866	2.061	1.544	1.738		
	0.700	0.517	0.731	2.285	1.333	2.108		
	0.600	0.586	0.609	2.600	1.126	2.552		
	0.500	0.686	0.496	3.051	0.924	3.133		
	0.400	0.838	0.388	3.736	0.727	3.965		
	0.300	1.094	0.285	4.884	0.537	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	2.490	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



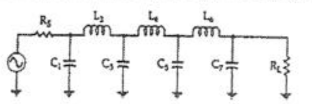
Chebyshev Low-Pass Element Values for 0.01-dB Ripple



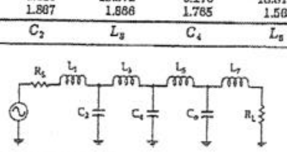
n	R_S/R_L	C_1	L_2	C_3	L_4
2	1.101	1.347	1.483		
	1.111	1.247	1.595		
	1.250	0.943	1.997		
	1.429	0.759	2.344		
	1.667	0.609	2.750		
	2.000	0.479	3.277		
	2.500	0.363	4.033		
	3.333	0.259	5.255		
	5.000	0.164	7.650		
	10.000	0.078	14.749		
	∞	1.412	0.742		
3	1.000	1.181	1.821	1.181	
	0.900	1.092	1.660	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	1.694	1.312	0.523
n	R_L/R_S	L_1	C_2	L_3	C_4



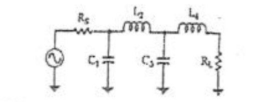
Chebyshev Low-Pass Element Values for 0.01-dB Ripple



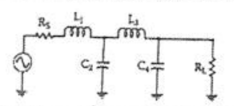
n	R_S/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	1.000	0.977	1.685	2.037	1.685	0.977		
	0.900	0.880	1.456	2.174	1.641	1.274		
	0.800	0.877	1.235	2.379	1.499	1.607		
	0.700	0.926	1.040	2.658	1.323	1.977		
	0.600	1.019	0.863	3.041	1.135	2.424		
	0.500	1.166	0.699	3.584	0.942	3.009		
	0.400	1.398	0.544	4.403	0.749	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	0.756	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



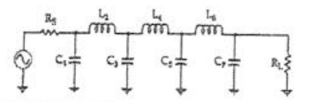
Chebyshev Low-Pass Prototype Element Values for 0.1-dB Ripple



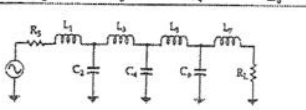
n	R_S/R_L	C_1	L_2	C_3	L_4
2	1.355	1.209	1.638		
	1.429	0.977	1.982		
	1.667	0.733	2.489		
	2.000	0.580	3.054		
	2.500	0.417	3.827		
	3.333	0.293	5.050		
	5.000	0.184	7.426		
	10.000	0.087	14.433		
	∞	1.391	0.819		
3	1.000	1.433	1.594	1.433	
	0.900	1.426	1.494	1.622	
	0.800	1.451	1.356	1.871	
	0.700	1.521	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



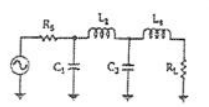
Chebyshev Low-Pass Prototype Element Values for 0.1-dB Ripple



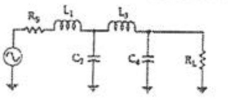
n	R_S/R_L	C_1	L_2	C_3	L_4	C_5	L_6	C_7
5	1.000	1.301	1.556	2.241	1.556	1.301		
	0.900	1.285	1.433	2.380	1.488	1.488		
	0.800	1.300	1.282	2.582	1.382	1.738		
	0.700	1.358	1.117	2.868	1.244	2.062		
	0.600	1.470	0.947	3.269	1.085	2.484		
	0.500	1.654	0.778	3.845	0.913	3.055		
	0.400	1.954	0.612	4.720	0.733	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	1.263	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



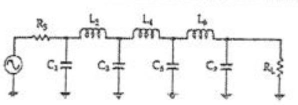
Chebyshev Low-Pass Prototype Element Values for 0.5-dB Ripple



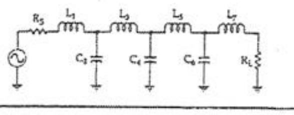
n	R_S/R_L	C_1	L_2	C_3	L_4
2	1.984	0.983	1.950		
	2.000	0.909	2.103		
	2.500	0.564	3.165		
	3.333	0.375	4.411		
	5.000	0.228	6.700		
	10.000	0.105	13.322		
	∞	1.307	0.975		
3	1.000	1.864	1.280	1.834	
	0.900	1.918	1.209	2.028	
	0.800	1.997	1.120	2.237	
	0.700	2.114	1.015	2.517	
	0.500	2.557	0.759	3.436	
	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	14.202
	∞	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	3.384	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



5.

a) Draw the topology of a double-balanced amplifier. 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 500 MHz small-signal amplifier has an output impedance of $20 - j\,15\ \Omega$. Using the Smith charts provided, design suitable impedance matching networks to transform this impedance to $50\ \Omega$.

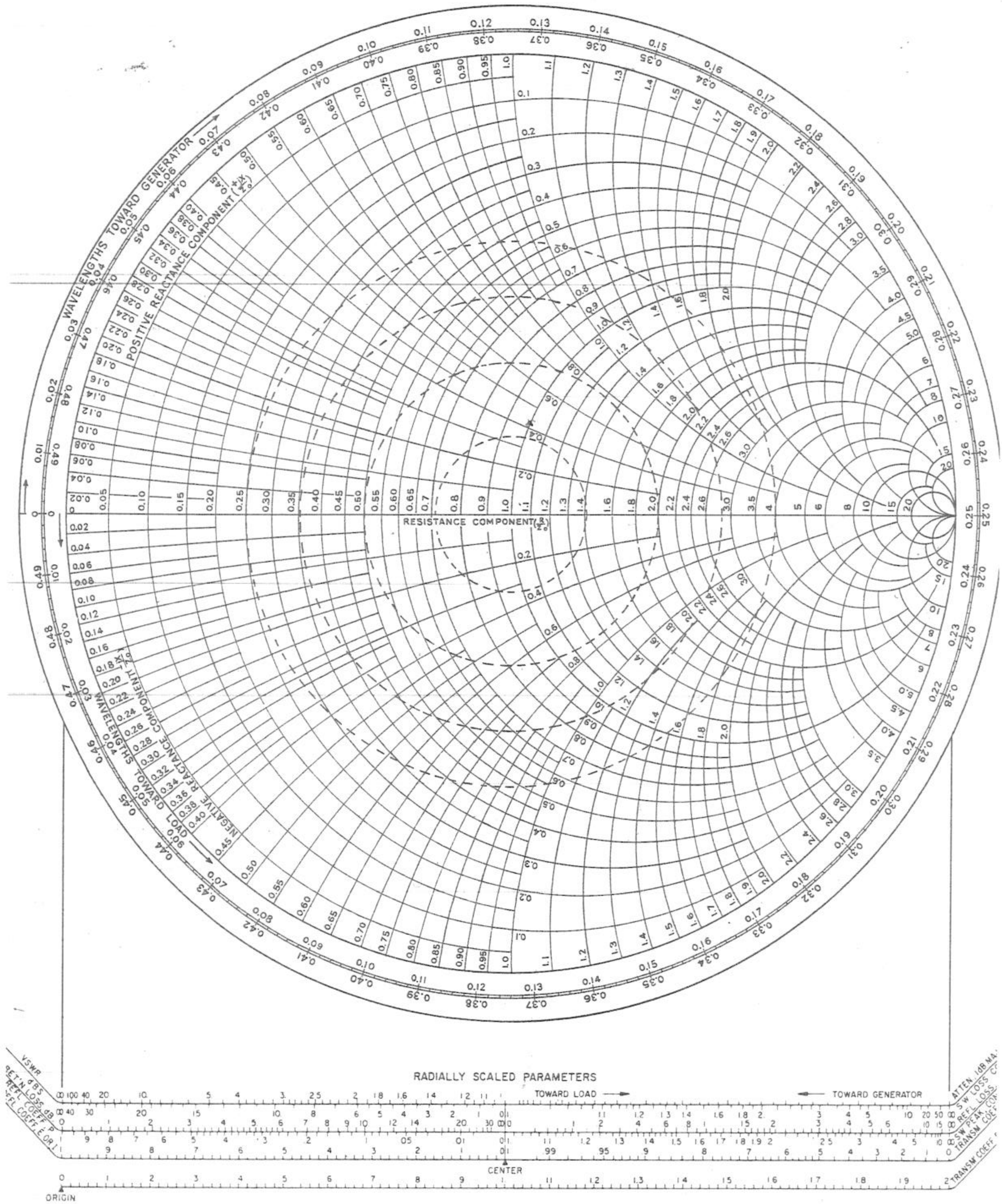
a) using a quarter-wavelength transformer [3]

b) using a short-circuit stub [8]

c) using a discrete inductor and capacitor [6]

d) make general comments about the loaded-Q factor of the matching networks in 6(a), (b) and (c) and how this relates to the resulting bandwidth of the networks. [3]

Chartwell Graph Data Ref. 7513 Impedance Chart 2



The Solutions for E4.18 (2007)

A0 6

Model answer to Q 1(a): New Application of Theory

The effective input voltage wave transmission coefficient is given by:

$$S_{21} = \exp(-jk_o d1)\rho_s \exp(-jk_o d3)\rho_m \exp(-jk_o d3)\tau_s \exp(-jk_o d2)$$
$$+\exp(-jk_o d1)\tau_s \exp(-jk_o d4)\rho_m \exp(-jk_o d4)\rho_s \exp(-jk_o d2)$$

ρ_s = **voltage wave reflection coefficient of the beam splitter**

τ_s = **voltage wave transmission coefficient of the beam splitter**

ρ_m = **voltage wave reflection coefficient of a mirror**

$$S_{11} = \exp(-jk_o d1)\rho_s \exp(-jk_o d3)\rho_m \exp(-jk_o d3)\rho_s$$
$$+\exp(-jk_o d1)\tau_s \exp(-jk_o d4)\rho_m \exp(-jk_o d4)\tau_s$$

[6]

Model answer to Q 1(b): New Application of Theory

Given:

$d1 = d2 = \lambda \quad \therefore \exp(-jk_o d1) = \exp(-jk_o d2) = \exp(-j2\pi) = 1$

And the mirrors are made from perfectly conducting metal, $\therefore \rho_m = -1$

$$S_{21} = -\rho_s \tau_s [\exp(-j2k_o d3) + \exp(-j2k_o d4)]$$

$$S_{11} = -\rho_s^{\,2} \exp(-j2k_o d3) - \tau_s^{\,2} \exp(-j2k_o d4)$$

[3]

Model answer to Q 1(c): New Application of Theory

(i) Since 50% of the power is reflected and 50% is transmitted through the ideal beam splitter then it must have the following solutions for its forward voltage wave transmission coefficient and input voltage wave reflection coefficient:

$$\tau_s = \rho_s \exp(\pm j\pi/2) = \frac{\exp[j(\angle\rho_s \pm \pi/2)]}{\sqrt{2}} \quad e.g.\ \tau_s = \pm\frac{j}{\sqrt{2}}$$

$$\rho_s = \tau_s \exp(\pm j\pi/2) = \frac{\exp[j(\angle\tau_s \pm \pi/2)]}{\sqrt{2}} \quad e.g.\ \rho_s = \pm\frac{1}{\sqrt{2}}$$

[4]

(ii) For a lossless 2-port network, the beam splitter must satisfy the following in order to obey the conservation of energy principle:

$|\tau_s|^2 + |\rho_s|^2 = 1$ and this is confirmed!

[2]

(iii)

$$S_{21} = \pm\frac{j}{2}\exp(-j2k_o d3)[1+\exp(+jk_o\delta)]$$

$$S_{11} = \pm\frac{1}{2}\exp(-j2k_o d3)[1-\exp(+jk_o\delta)]$$

[2]

(iv) For a lossless 2-port network, the interferometer must satisfy the following in order to obey the conservation of energy principle:

$|S_{21}|^2 + |S_{11}|^2 = 1$ and this is confirmed, since:

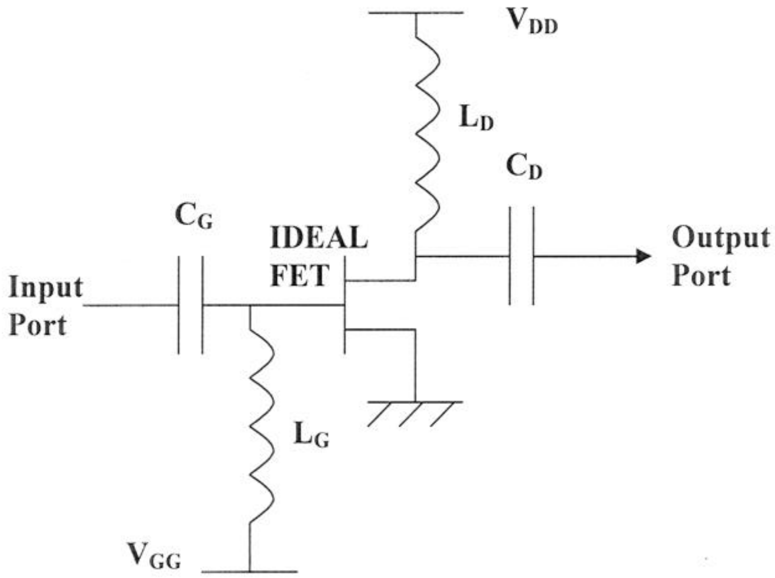
$|S_{21}| = 1$ and $|S_{11}| = 0$ when $\delta = n\lambda$

$|S_{21}| = 0$ and $|S_{11}| = 1$ when $\delta = (n+1/2)\lambda$

[3]

Model answer to Q 2(a): Bookwork

The topology for a class-A amplifier is given below:



L_D and L_G are Radio Frequency Chokes (RFCs), ideally having infinite inductance. C_D and C_G are DC blocking capacitors, ideally having infinite capacitance. Since the field-effect transistor is also ideal, there is no need for any impedance matching networks.
In practice, all these inductors and capacitors will be finite in value and lossy. They may also be absorbed into any impedance matching networks.

The class-A amplifiers have the following characteristics, when compared to other classes:

- Output current flows for the full period of the input voltage cycle.
- No high order harmonics are generated and, therefore, minimum output signal distortion (in the time-domain) is found.
- This gives the best Pout to Pin linearity.
- Maximum dynamic range.
- Ideal for non-CW applications (e.g. AM, multi-carrier and band-filtered CW modulated signals).
- Continuously dissipates power (as heat), even when there is no input signal.
- Low theoretical efficiency (<50%) and, therefore, it can get hot without cooling.

[6]

Model answer to Q 2(b): Computed Example

(i)

$$Vds|_{\max} = Vgd|_{BD} - |Vp| = 10.5V$$

$$\therefore Vdd = \frac{Vds|_{\max} - Vk}{2} = 5.5V$$

[2]

(ii)

$$R_L = \frac{Vds|_{\max} - Vk}{Idss} = 167\Omega$$

[2]

(iii)

$$P_{OUT|MAXLIN} = \frac{\left(\frac{Vds|_{\max} - Vk}{2\sqrt{2}}\right)^2}{R_L} = 75mW = +19dBm$$

$$P_{OUT|PEAK} = 2P_{OUT|MAXLIN} = 150mW = +22dBm$$

[2]

(iv)

$$P_{DC} = Ids|_Q \, Vds|_Q = \frac{Idss}{2} Vdd = 165mW$$

$$Pin = \frac{Pout}{G} = \frac{75mW}{2.51} = 30mW = +14.75dBm$$

$$\therefore P_{DISS} = (Pin + P_{DC}) - Pout = 120mW$$

$$but, Wg = 4 \times 75\mu m = 300\mu m$$

$$\therefore \frac{P_{DISS}}{Wg} = 0.4W / mm$$

[3]

(v)

$$\eta_{DRAIN} = \frac{Pout}{P_{DC}} = 45\%$$

$$\eta_{ADD} = \frac{Pout}{P_{DC}}\left(1 - \frac{1}{G}\right) = 27\%$$

[2]

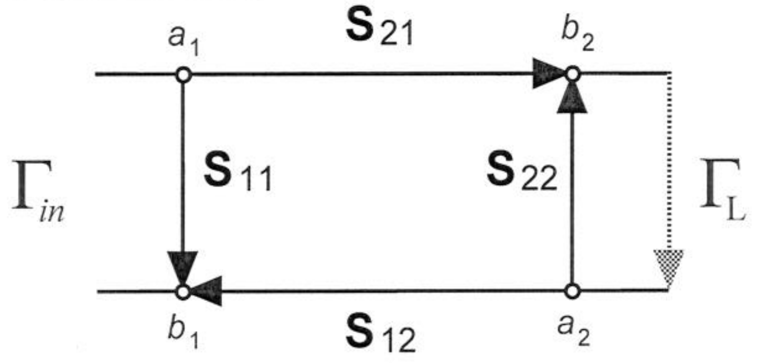
Model answer to Q 2(c): Bookwork

Cripps Technique assumes that the optimal load resistance is identical to that calculated using the I-V characteristics of the transistor and that the optimal load reactance is the conjugate of the FET's small- or large-signal output reactance (since Cds is not a strong function of the input power level).

The input stage is then matched to the complex conjugate of the resulting input impedance of the FET (having the optimal load impedance at its output), using the resulting linear S-parameters at the $P_{OUT|MAXLIN}$ point.

[3]

Model answer to Q 3(a): Bookwork



Flow graph representation of a device with output load termination

Using Mason's non-touching loop rule it can easily be shown that:

$$\Gamma_{in} = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1 - S_{22}\Gamma_L}$$

$$where, \Gamma_L = \frac{Z_L - Zo}{Z_L + Zo}$$

[5]

Model answer to Q 3(b): Bookwork

Conditional stability occurs when the magnitude of the input voltage wave reflection coefficient is equal to or greater than unity. Therefore, the stability circle for the terminating impedance can be determined by equating the expression in 3(a) to unity. When the circle encompasses the matched impedance, zo, point then when the terminating impedance's voltage wave reflection coefficient is inside the circle this corresponds to conditional stability and instability outside the circle. Conversely, the opposite is true when the stability circle does not encompass the zo point.

[5]

Model answer to Q 3(c): Computed Example

Γ_L = -1.222 and therefore Γ_{IN} = -3.3

[5]

Model answer to Q 3(d): Computed Example

A Rollett's stability factor of K = 2.3 is greater than unity and, therefore, it would normally represent an unconditionally stable circuit. However, since the magnitude of the reflection coefficient of the load is greater than unity then the circuit is now unstable.

When K is greater than unity (and the magnitudes of S_{11} and S_{22} are both less than unity), the device is unconditionally stable and the maximum gain that can be achieved is called the maximum available gain (MAG), given by:

$$\text{MAG} = \left|\frac{S_{21}}{S_{12}}\right|\left(K - \sqrt{K^2 - 1}\right) = 4.575 = 6.6 \text{ dB}$$

[5]

Model answer to Q 4(a): Lecture Discussions

From the conservation of energy, for a lossless tow-port network: $|S21|^2 = 1 - |S11|^2$

At the –3 dB cut-off frequency, $|S21|^2 = 0.5$ and, therefore, $|S11|^2 = 0.5$
In other words both the insertion loss and return loss levels are -3 dB.

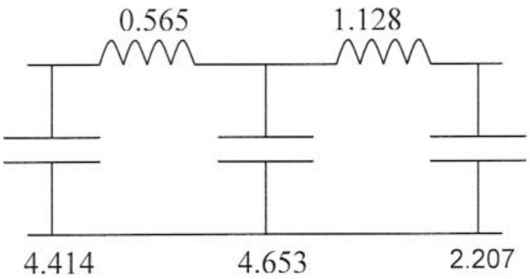
For a maximum return loss level or –6.868 dB, the worst-case insertion loss level is 1 dB.

[5]

Model answer to Q 4(b): New Application of Theory

-3 dB cut-off frequencies are at f_{P1} = 540 MHz and f_{P2} = 660 MHz
centre frequency, fo = $\sqrt{(f_{P1}\, f_{P2})}$
pass band bandwidth, Bp = f_{P1}- f_{P2} = 120 MHz
stop band bandwidth, Bs = 60 MHz
f/fc = Bp/Bs = 2

From the attenuation curves, the 5th order 1 dB ripple Chebyshev filter with $Rs/R_L = 0.5$ meets the specification with a stop band attenuation margin of 3 dB. The normalised values for the low-pass prototype is given below:

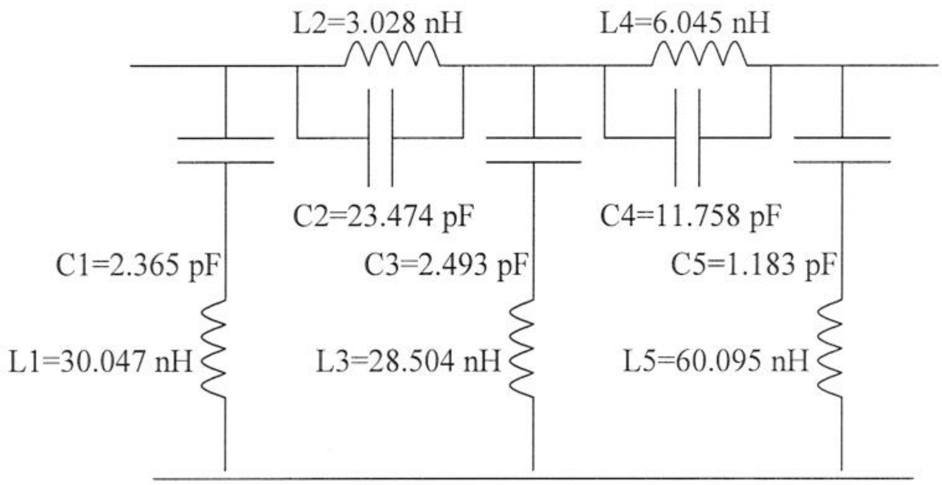


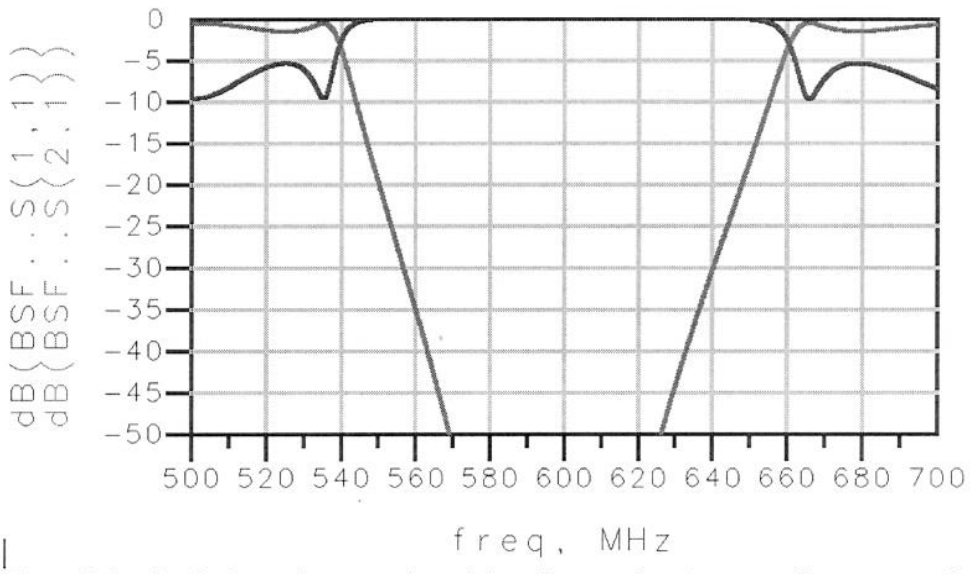
For a band stop filter, the capacitors are replaced by a series L-C resonators and the inductors are replaced by parallel L-C resonators. The un-normalized shunt connected series tuned circuit element values are:

$$Cs = \frac{BpCn}{2\pi f_o^2 R_L} \quad and \quad Ls = \frac{R_L}{2\pi BpL_n}$$

The un-normalized series connected parallel tuned circuit element values are:

$$Cp = \frac{1}{2\pi BpCnR_L} \quad and \quad Lp = \frac{BpLnR_L}{2\pi f_o^2}$$





The slight deviations in pass band levels are due to rounding errors in the component values (3 decimal places).

[10]

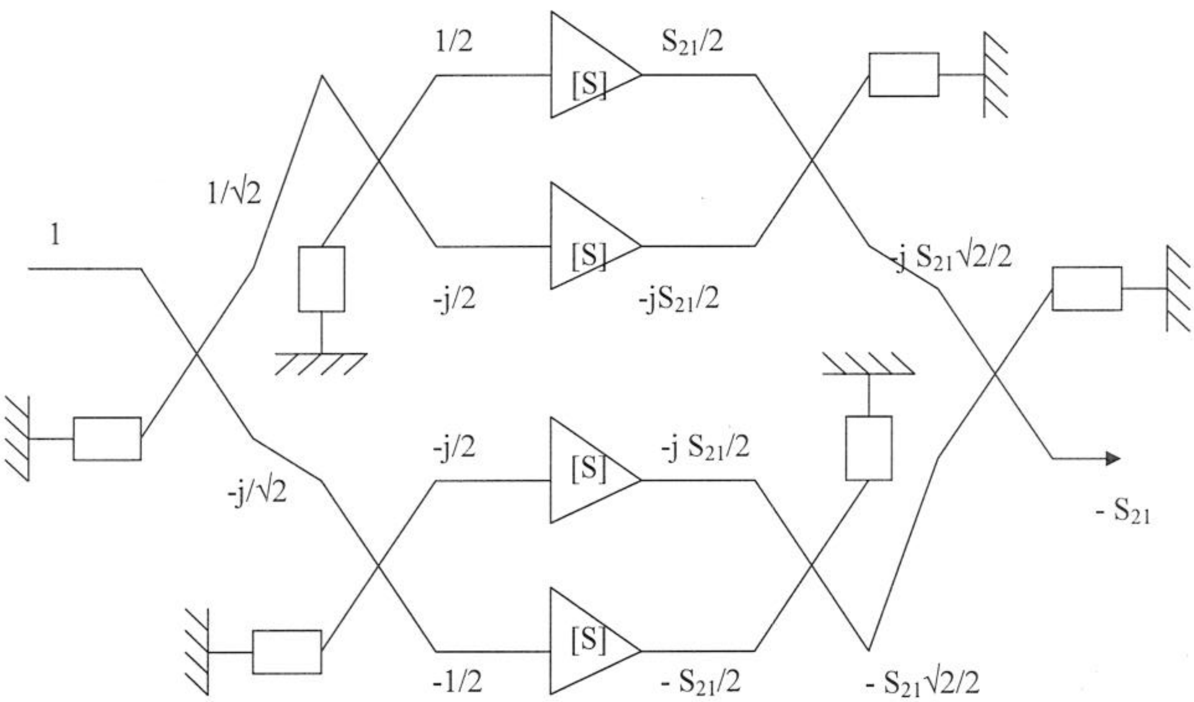
Model answer to Q 4(c): Lecture Discussions

Group delay is defined as $\tau = -\partial \angle S21 / \partial \omega$

With sharp cut-off frequencies, high order filters are needed. This means that there are large numbers of passive filter components, where electromagnetic energy is exchanged between them. As a result the signal stays within the filter longer than for filters with a less sharp insertion loss cut off and, thus, the group delay is higher. Also, more energy is dissipated in the components and, therefore, insertion loss is higher unless larger components are employed.

[5]

Model answer to Q 5(a): New Application of Theory



$$S_{21}\,|_{overall} = \left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)S_{21}\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)+\left(\frac{1}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)S_{21}\left(\frac{-1}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)+$$
$$\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)S_{21}\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)+\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)S_{21}\left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)=S_{21}$$

$$Insertion\ Loss = 10\log\left\{|S_{21}|^2\right\}$$
$$S_{11}\,|_{overall} = \left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)S_{11}\left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)+\left(\frac{1}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)S_{11}\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)+$$
$$\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2}}\right)S_{11}\left(\frac{1}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)+\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)S_{11}\left(\frac{-j}{\sqrt{2}}\right)\left(\frac{-j}{\sqrt{2}}\right)=0$$

$$\mathrm{Re}turn\ Loss = 10\log\left\{|0|^2\right\}\rightarrow -\infty$$

[5]

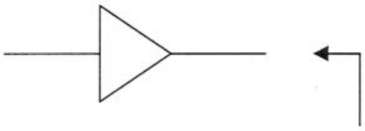
Model answer to Q 5(b): Lecture Discussion

The main application of this amplifier is power combining, since the output power is ideally a factor of 4 greater than that of the single-ended amplifier. If one of the single-ended amplifiers fails then $S_{21}|_{overall} = 3S_{21}/4$ and Insertion loss is $10\log\{(3|S_{21}|/4)^2\} = 17.5$ dB, i.e. a drop of 2.5 dB from a fully working amplifier. The input return loss should not change if the impedance of the failed amplifier doesn't change and is, therefore, still minus infinity. Therefore, this type of power combining amplifier is useful because it provides redundancy in the case of failure and also ideal port impedance matching. The disadvantages of this topology is that it requires 4 identical single-ended amplifiers. Also, practical losses in the couplers result in a direct loss in power gain and output efficiency will be significantly reduced.

[5]

Model answer to Q 6(a): Computed Example

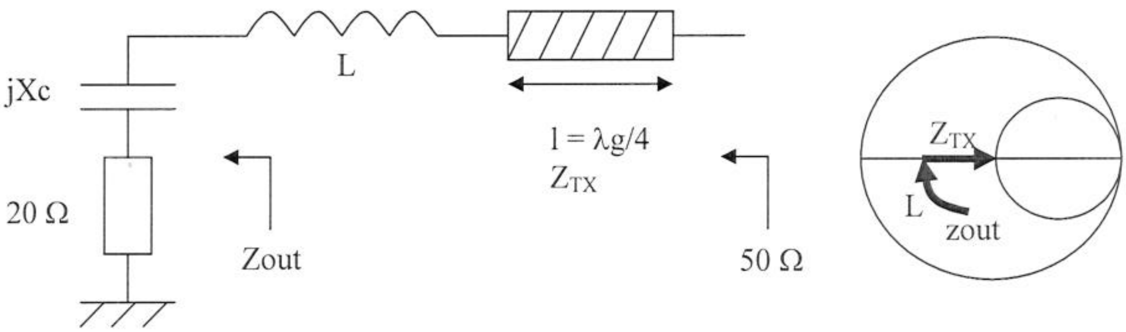
There are a number of possible solutions.



$$Zout = 20 - j15\Omega$$

$$Zo = 50\Omega$$

$$\therefore z_{out} = \frac{Zout}{Zo} = 0.4 - j0.3$$



$$Xc = -15\Omega$$

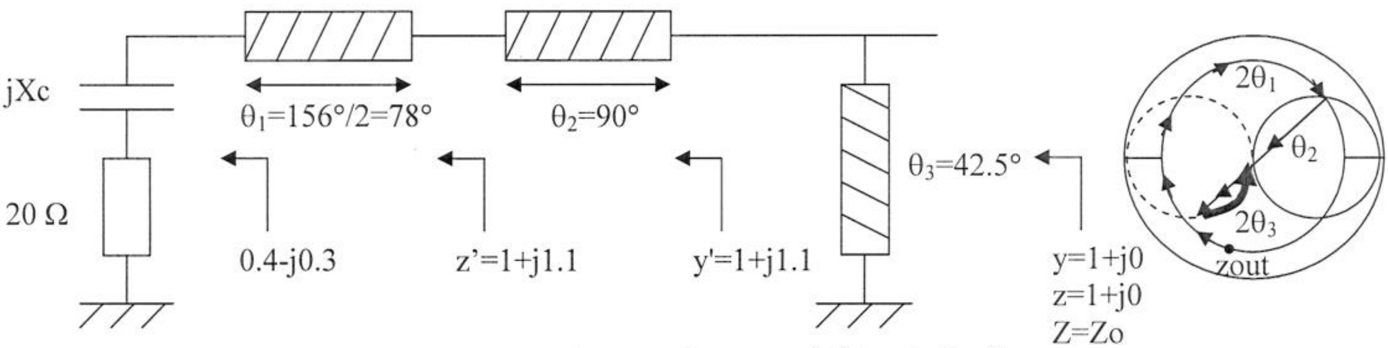
$$\therefore X_L = +15\Omega \quad \therefore L = \frac{15}{\omega} = 4.78nH$$

$$Z_{TX} = \sqrt{50Rout} = 31.6\Omega$$

[3]

Model answer to Q 6(b): Computed Example

There are a number of possible solutions.

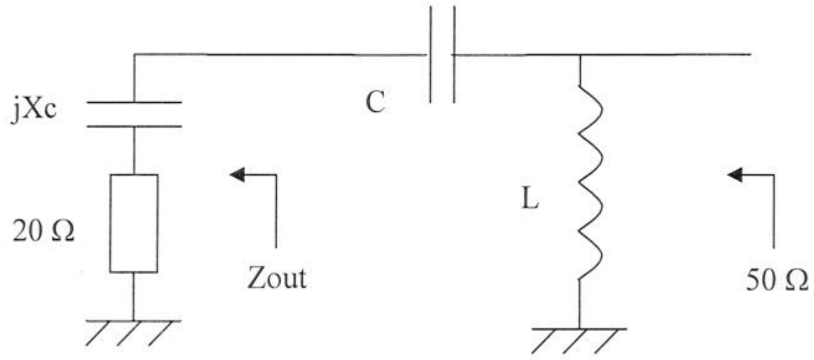


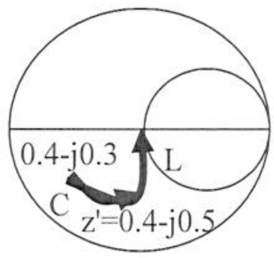
b_{STUB} = -1.1 i.e. inductive

[8]

Model answer to Q 6(c): Computed Example

There are a number of possible solutions.





$$x_c = -0.2 \quad \therefore X_c = -Zox_c = -10\Omega$$

$$X_c = -\frac{1}{\omega C} \quad \therefore C = 31.8pF$$

$$z' = 0.4 - j0.5$$

$$\therefore y' = \frac{1}{z'} \approx 1 + j1.22$$

$$B_L = \frac{b_L}{Zo} = -\frac{1}{\omega L} = -0.0244 \quad \therefore L = 13nH$$

[6]

Model answer to Q 6(d): Textbook

On the Smith chart, loaded Q-factor is zero at the centre and infinite on the unit circle. This means that the L-C network has a point closer to the unit circle, when compared with that using the quarter-wave transformer or single stub solutions. Also, the bandwidth will be less, since loaded Q-factor is inversely proportional to bandwidth. Since the stub solution has more length of transmission line, it will operate over a narrower bandwidth, when compared to the quarter-wave transformer solution.

[3]