One Circuit, Three Uses – The RLB (Return Loss Bridge)

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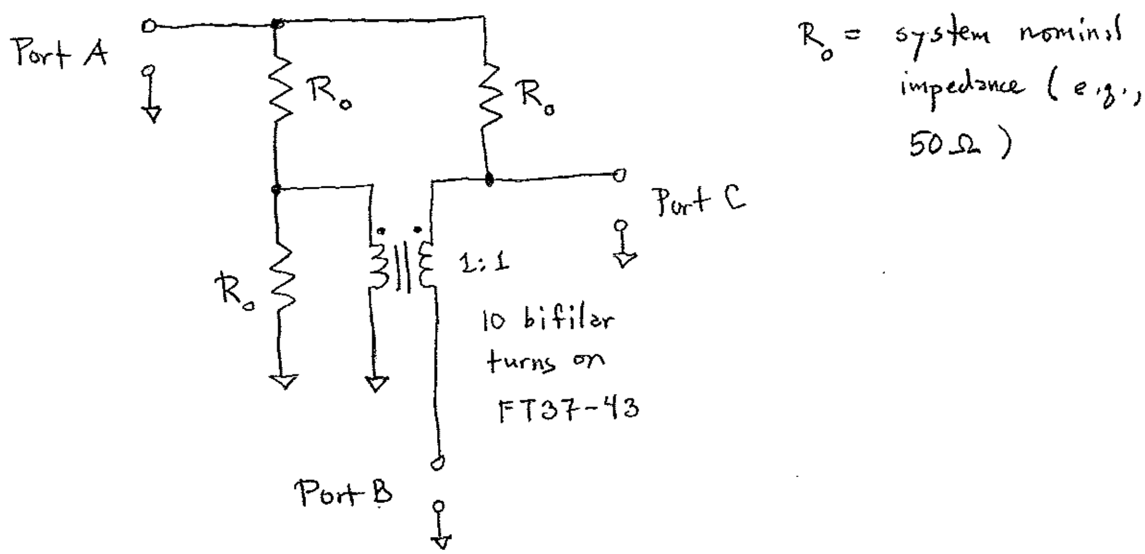
I ran across this circuit in a college textbook on analog radio circuits, then found it in Experimental Methods in RF Design (EMRFD), Ch. 7. (The two circuits differ slightly but perform identically except as a splitter.)



Here are the three uses. (We only use signal sources and terminations with impedence R_o.)

Combiner (Linear mixer)

Port A : Signal source 1, power P_1 input

Port B : Signal source 2, power P_2 input

Port C : Sum of input signals with power $\frac{P_1 + P_2}{4}$ output (6 dB attenuation)

Theoretically, no power from Port A will enter Port B and vice versa, so they have perfect isolation from each other.

Splitter

Port C: Signal source, power P input

Port A: Same as source, power P/4 (6 dB attenuation) output

Port B: Same as Port A

With the circuit shown (EMRFD version) the two outputs are in phase. If the lower connections on the transformer are switched (textbook version), the two outputs are 180° out of phase.

Return Loss Bridge

Port A: Signal source

Port B: Detector (voltmeter, power meter, or oscilloscope)

Port C: Device under test (DUT) with unknown impedance Z

The detector measures the power (or voltage) reflected by the impedance. The basic procedure is as follows:

1. Leave Port C open (disconnected) and measure the power P_{oc} or voltage V_{oc} at Port B.
2. Connect the DUT to Port C and measure the power P_{DUT} or voltage V_{DUT} at Port B.
3. Calculate

$$\rho = \left| \text{reflection coefficient } \Gamma \right| = \left| \frac{Z - R_0}{Z + R_0} \right|$$

$$= \frac{V_{DUT}}{V_{OC}} = \sqrt{\frac{P_{DUT}}{P_{OC}}}$$

$$\text{Return Loss RL} = -20 \log_{10} \rho$$

~~Because an open (or short) reflects all power, V_{OC} is the (forward) power going to the DUT when it is connected to Port C. Thus~~

$\rho = V_{DUT} / V_{OC}$ is the ratio (of the magnitudes) of the reflected to forward voltages.

The VSWR can be easily calculated from ρ by the equation

$$VSWR = \frac{1+\rho}{1-\rho}$$

ρ	0	0.0100	0.1000	0.3311	0.5623	0.7943	0.8913	1
RL	$+\infty$	40	20	9.6	5	2	1	0
VSWR	1	1.02	1.22	1.99	3.57	8.72	17.39	$+\infty$

This table gives an idea of the relationships among these three ways of quantifying impedance mismatches between Z and R_0.

Quality of a RLB

How well an RLB measures reflected power is expressed by two quantities:

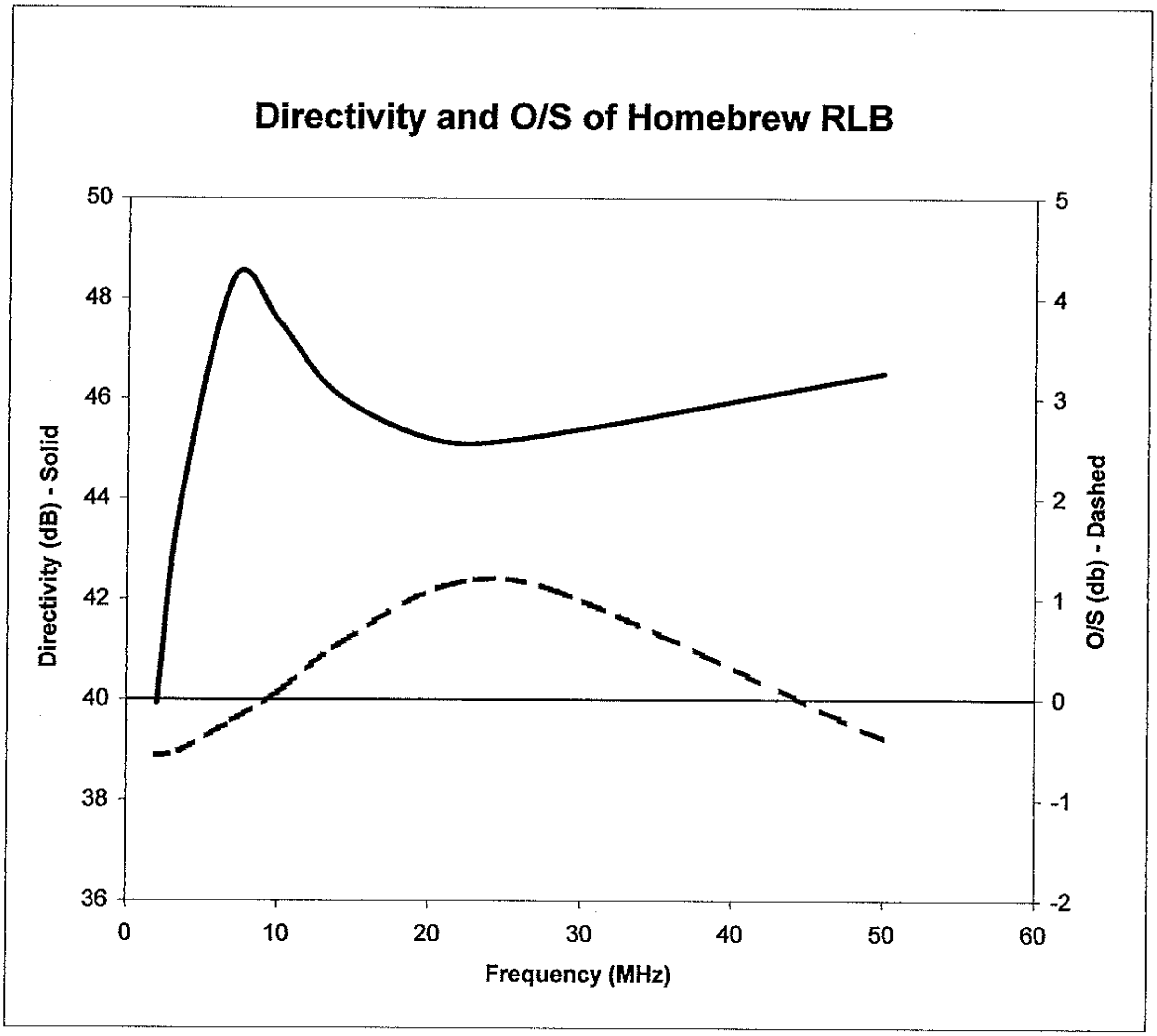
Directivity = RL measured when a precision matched termination R_0 is put at Port C as the DUT.
The higher the better for directivity. Bridges with at least 40 dB are considered acceptable.

O/S Ratio = $20 \log V_{OC}/V_{SC}$ where V_{OC} = voltage at Port B for an open circuit DUT, V_{SC} = same for short circuit.
Ideally this value is zero, since a short and open should reflect all power.

Nominal voltage values

Gen V	6	V
V in	3	V
V_{OPEN}	750	mV

Freq f MHz	V_{OPEN} mV_{pp}	V_{SHORT} mV_{pp}	O/S dB	Har Avg mV_{pp}	$V_{Matched}$ mV_{pp}	ρ	Dir dB	VSWR
2	720	768	-0.56	743.6	7.5	0.010086	39.9	1.020
3.5	718	762	-0.52	739.7	4.75	0.006422	43.8	1.013
7	728	746	-0.21	736.9	2.8	0.003799	48.4	1.008
10	740	734	0.07	737.0	3.1	0.004206	47.5	1.008
14	756	710	0.55	732.6	3.65	0.004982	46.1	1.010
21	780	685	1.13	731.0	4.05	0.005541	45.1	1.011
28	774	682	1.10	726.5	3.95	0.005437	45.3	1.011
50	704	736	-0.39	719.8	3.4	0.004723	46.5	1.009



The previous page shows the directivity and O/S ratio for the bridge I made. Its values are reasonable over HF to 6m frequencies.

The directivity values come from some signal forward power sneeking into the detector port. Some tedious math gives us limits on the measurement error due to finite directivity. They are shown on the next page for an RLB with 40 dB directivity.

The plot shows that measurements are practical for return losses of 35 dB and lower (greater mismatch). This is plenty for a decent match (VSWR 1.04 : 1)!

Measuring Impedance Z with a RLB

This can be done using two known impedances (e.g. a resistor and a capacitor). Measure ρ or RL for:

1. The DUT alone
2. The DUT in series with Known 1
3. The DUT in series with Known 2

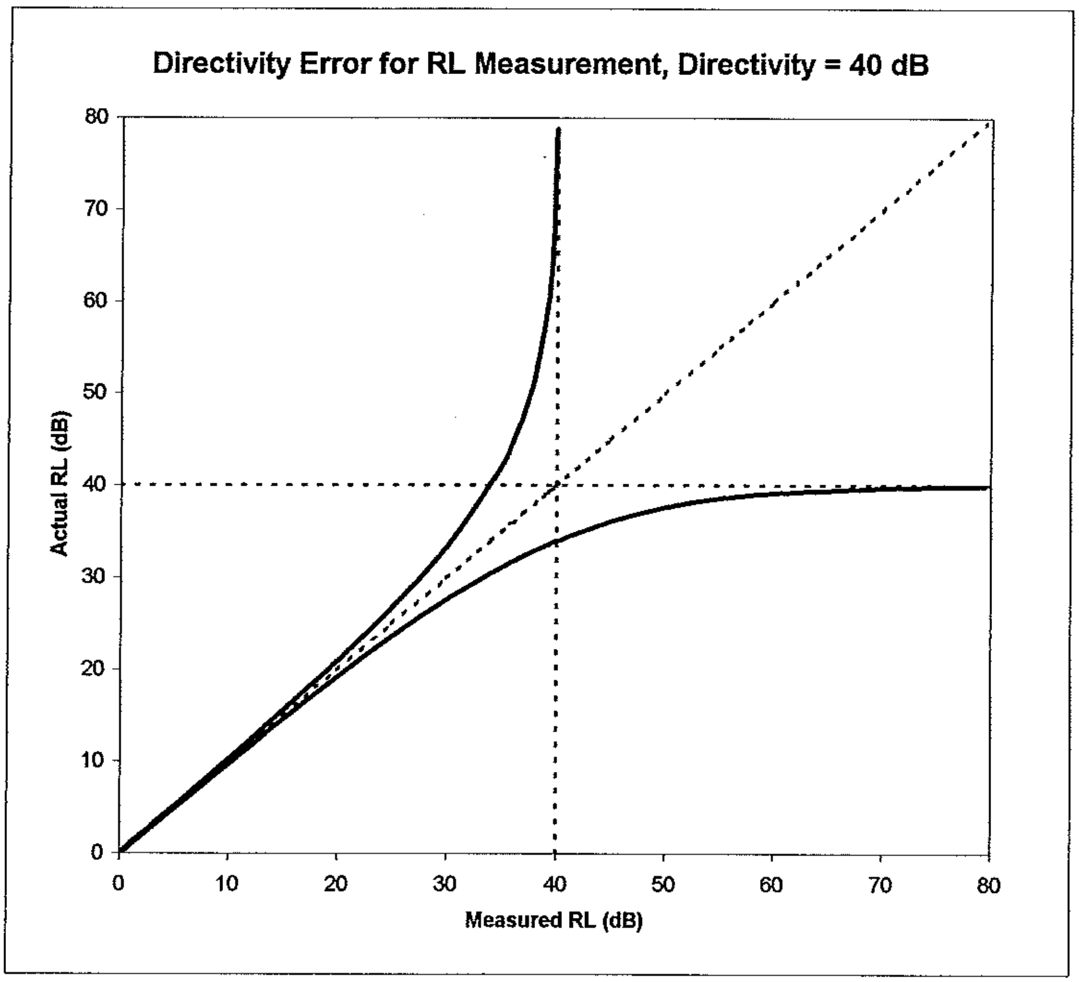
For each of these we get a circle in the impedance plane. Where the three circles intersect each other gives the unknown impedance Z. The math details are a bit messy.

The last two pages show how well this worked using my RLB and two unknowns, a 98.4 Ω resistor (100 Ω nominal) and that same resistor in series with a 100 pF capacitor.

The measurements were done at 7 MHz where my bridge had the best directivity and O/S ratio.

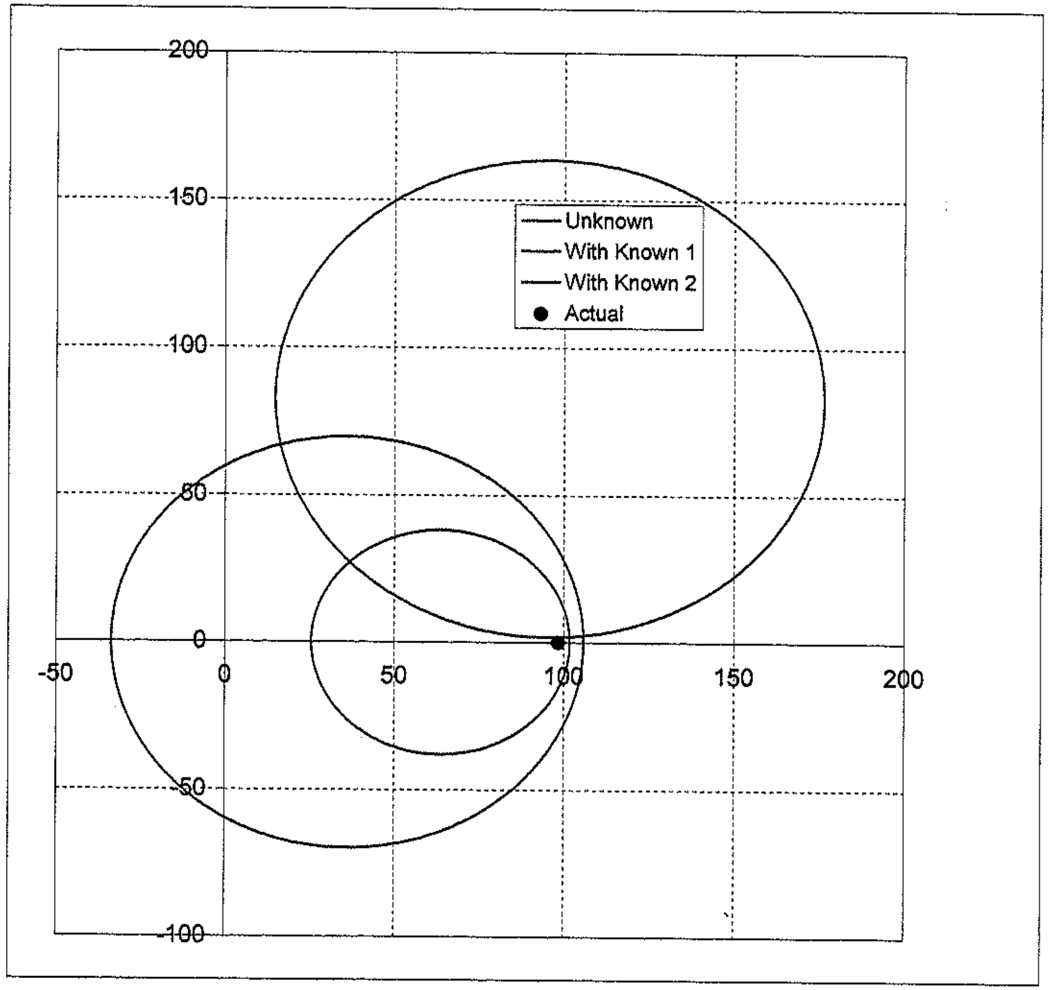
Directivity 40

RL Measured	ρ	VSWR	RL Lower Bound	RL Upper Bound	
0.1	0.9886	173.72	0.0	0.2	
1	0.8913	17.39	0.9	1.1	
2	0.7943	8.72	1.9	2.1	
5	0.5623	3.57	4.8	5.2	
9.6	0.3311	1.99	9.3	9.9	
15	0.1778	1.43	14.5	15.5	
20	0.1000	1.22	19.2	20.9	
25	0.0562	1.12	23.6	26.7	
30	0.0316	1.07	27.6	33.3	
35	0.0178	1.04	31.1	42.2	Practical range limit
36	0.0158	1.03	31.8	44.7	
37	0.0141	1.03	32.4	47.7	
38	0.0126	1.03	32.9	51.7	
39	0.0112	1.02	33.5	58.3	
39.3	0.0108	1.02	33.6	61.5	
39.6	0.0105	1.02	33.8	66.5	
39.9	0.0101	1.02	33.9	78.7	
40	0.0100	1.02	34.0		
45	0.0056	1.01	36.1		
50	0.0032	1.01	37.6		
55	0.0018	1.00	38.6		
60	0.0010	1.00	39.2		
70	0.0003	1.00	39.7		
79.5	0.0001	1.00	39.9		



Freq.	7		Resistor		275 pF cap	
			Known 1		Known 2	
R_0	51	R	50.3		0	
X_0	0	X	0		-82.68	
Z_0	51	Z	50.3		-82.68j	
	Unknown		Unknown		Unknown	
	Alone		In Series		In Series	
ρ	0.332414		0.507587		0.551725	
λ	1.248452		1.694126		1.875216	
r	38.11828		69.74263		80.90271	
Center x	63.67105		36.10043		95.63602	
Center y	0		0		82.68	

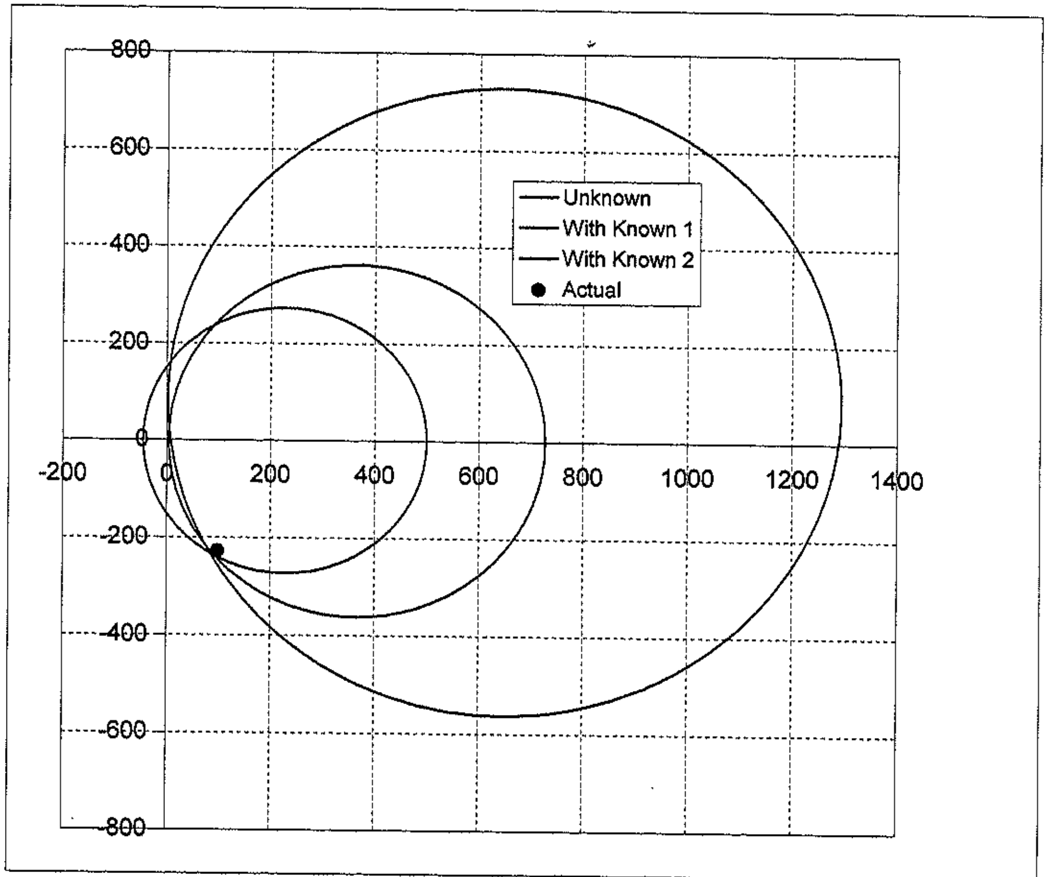
Angle	x	y	x	y	x	y
0	101.7893	0	105.8431	0	176.5387	82.68
0.017453	101.7835	0.665256	105.8324	1.217177	176.5264	84.09195
0.034907	101.7661	1.330309	105.8006	2.433983	176.4894	85.50346
0.05236	101.7371	1.994956	105.7475	3.650047	176.4279	86.91412
0.069813	101.6965	2.658997	105.6732	4.865	176.3417	88.32349
0.087266	101.6443	3.322227	105.5777	6.078471	176.2309	89.73114
0.10472	101.5805	3.984445	105.461	7.29009	176.0955	91.13664
0.122173	101.5052	4.645449	105.3232	8.499488	175.9357	92.53956
0.139626	101.4184	5.305039	105.1643	9.706298	175.7514	93.93948
0.15708	101.32	5.963012	104.9844	10.91015	175.5427	95.33597
0.174533	101.2102	6.619169	104.7835	12.11068	175.3096	96.72861
0.191986	101.089	7.27331	104.5617	13.30752	175.0523	98.11696
0.20944	100.9564	7.925235	104.319	14.50031	174.7708	99.50062
0.226893	100.8124	8.574746	104.0556	15.68868	174.4652	100.8791
0.244346	100.6571	9.221646	103.7714	16.87227	174.1356	102.2521
0.261799	100.4905	9.865736	103.4666	18.05072	173.782	103.6192
0.279253	100.3127	10.50682	103.1413	19.22367	173.4047	104.9798
0.296706	100.1237	11.14471	102.7956	20.39077	173.0037	106.3337
0.314159	99.92369	11.7792	102.4296	21.55166	172.5791	107.6803
0.331613	99.71259	12.4101	102.0434	22.70598	172.131	109.0193
0.349066	99.49052	13.03722	101.6371	23.85338	171.6597	110.3504
0.366519	99.25753	13.66037	101.2108	24.99352	171.1652	111.6729
0.383972	99.0137	14.27936	100.7647	26.12605	170.6477	112.9867
0.401426	98.75911	14.894	100.2989	27.25062	170.1074	114.2912
0.418879	98.49383	15.5041	99.81349	28.36688	169.5443	115.5861
0.436332	98.21794	16.10948	99.30872	29.47451	168.9588	116.871
0.453786	97.93153	16.70995	98.78469	30.57316	168.3509	118.1454
0.471239	97.63469	17.30534	98.24157	31.66249	167.7209	119.4091
0.488692	97.32749	17.89545	97.67952	32.74218	167.0689	120.6615
0.506145	97.01005	18.48011	97.09871	33.8119	166.3951	121.9024
0.523599	96.68245	19.05914	96.49932	34.87131	165.6998	123.1314



Actual 98.4 0 — nominal 100 Ω resistor

Freq.	7		Resistor		275 pF cap	
			Known 1		Known 2	
R_0	51	R	50.3		0	
X_0	0	X	0		-82.68	
Z_0	51	Z	50.3		-82.68j	
	Unknown		Unknown		Unknown	
	Alone		In Series		In Series	
ρ	0.868966		0.830346		0.924139	
λ	7.166682		5.440681		12.70168	
r	361.9252		272.7476		645.7752	
Center x	365.5008		227.1747		647.7859	
Center y	0		0		82.68	

Angle	x	y	x	y	x	y
0	727.426	0	499.9223	0	1293.561	82.68
0.017453	727.3708	6.316465	499.8808	4.760101	1293.463	93.95033
0.034907	727.2055	12.63101	499.7562	9.518753	1293.168	105.2172
0.05236	726.93	18.9417	499.5485	14.2745	1292.676	116.4773
0.069813	726.5443	25.24662	499.2579	19.02591	1291.988	127.727
0.087266	726.0487	31.54386	498.8844	23.77152	1291.104	138.963
0.10472	725.4433	37.83148	498.4282	28.50988	1290.023	150.1819
0.122173	724.7282	44.10758	497.8893	33.23957	1288.748	161.3802
0.139626	723.9037	50.37025	497.268	37.95912	1287.276	172.5545
0.15708	722.9701	56.61757	496.5643	42.66712	1285.61	183.7015
0.174533	721.9275	62.84765	495.7787	47.36212	1283.75	194.8177
0.191986	720.7764	69.05858	494.9112	52.04269	1281.696	205.8997
0.20944	719.517	75.24847	493.9621	56.70741	1279.449	216.9442
0.226893	718.1498	81.41545	492.9318	61.35485	1277.01	227.9478
0.244346	716.6752	87.55762	491.8205	65.98361	1274.379	238.9071
0.261799	715.0937	93.67313	490.6287	70.59226	1271.557	249.8189
0.279253	713.4056	99.7601	489.3565	75.17942	1268.545	260.6798
0.296706	711.6116	105.8167	488.0045	79.74367	1265.344	271.4864
0.314159	709.7121	111.841	486.5731	84.28363	1261.955	282.2355
0.331613	707.7078	117.8313	485.0626	88.79792	1258.378	292.9238
0.349066	705.5992	123.7857	483.4736	93.28516	1254.616	303.5481
0.366519	703.387	129.7024	481.8065	97.74399	1250.669	314.1051
0.383972	701.072	135.5796	480.0619	102.173	1246.538	324.5916
0.401426	698.6547	141.4154	478.2402	106.571	1242.225	335.0045
0.418879	696.1359	147.2082	476.342	110.9364	1237.731	345.3404
0.436332	693.5164	152.9562	474.368	115.2681	1233.057	355.5964
0.453786	690.797	158.6576	472.3186	119.5647	1228.205	365.7692
0.471239	687.9785	164.3106	470.1946	123.8248	1223.176	375.8558
0.488692	685.0618	169.9136	467.9966	128.0472	1217.971	385.8531
0.506145	682.0477	175.4648	465.7251	132.2306	1212.594	395.758
0.523599	678.9372	180.9626	463.3811	136.3738	1207.044	405.5676



Actual 98.4 -227.4 — nominal 100 Ω resistor in series with 100 pF capacitor at 7 MHz