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Lookup Tables for Ring Resonators

by Christopher S Kenyon

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REPORT DOCUMENTATION PAGE

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14. ABSTRACT This report is intended as a guide for creation of data that ring resonators require for soil permittivity measurement. It starts with computational electromagnetic modeling of the resonators with the aim of graphically capturing the power transferred from an input port to the output port of the ring resonator, namely the S21 parameter of the resonator circuit as the input frequency is monotonically varied searching for humps or resonances in the S21 graph. The modeling is done over a collection of possible permittivities to span those that test samples might possess. Each permittivity from this collection causes resonances at unique frequencies and resonance quality factors (Q's). These data, after some manipulation, can then be put in a form or "lookup table" that the MATLAB software then uses for permittivity calculation. As the simulations can take considerable time to create and execute, this report describes a method that may speed up the lookup table creation process.					
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1. Introduction

Knowledge of soil permittivity is vital for estimating radar returns of targets and clutter. Ring resonators are important as a means for estimating soil permittivity. We have used ring resonators for measuring the permittivity of soil placed in contact with the circuit plane on the top of the resonators. The resonator software to effect these measurements requires tabular data relating resonance characteristics with soil electrical permittivities. Computer simulation of a resonator with a collection dielectrics spanning the range of permittivities and frequencies of interest is our means of creating that data. The simulations create the data from which MATLAB “lookup tables” can be created to work with MATLAB resonator software so that the ring resonators can measure soil permittivity over these frequencies. Specifically, lookup tables are used by the resonator software to interpolate soil sample permittivities from measured resonance characteristics.

The generation of lookup tables starts with modeling the ring resonators using FEKO¹ electromagnetic modeling software. Template models have been created in the Cadfeko portion of FEKO software that are used as a starting point for new variants or simulations of the ring resonators. These include a 1200-MHz ring resonator, which at its core does have a ring in the classic sense as shown in Fig. 1, and a 250-MHz model, distinguished by its meandered line, as shown in Fig. 2. Both were originally created by Greg Mazzaro.² A 28-MHz resonator that has many more meanders was created by Christopher Kenyon.³

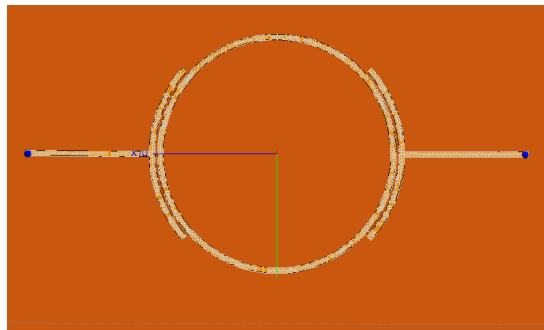


Fig. 1 Top view Cadfeko Image of 1200-MHz ring resonator

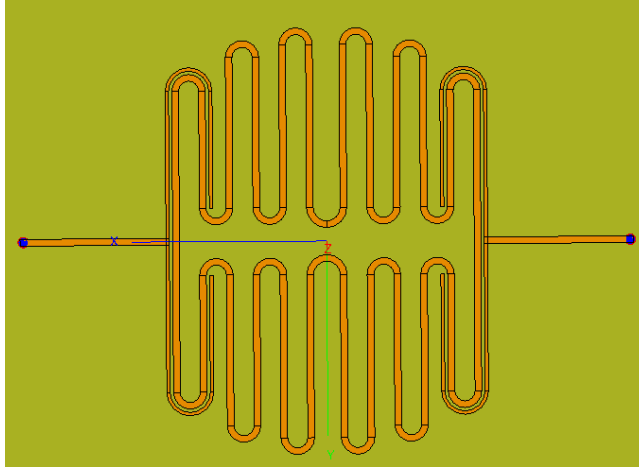


Fig. 2 Top view Postfeko image of 250-MHz resonator

2. Description of Computer Model

Each resonator has an input stub and an output stub on opposite sides of the resonators shown in Figs. 1 and 2 as well as a central loop which, itself, is separated by a gap from the input and output lines. These circuits lie over a substrate such as the Rogers 4350B dielectric,⁴ which in turn is backed by a conductive sheet. During operation, a voltage is applied over a range of frequencies covering those of interest to the input port (one side to the “top” and the other to the conductive back plane). Plots of S21 parameter versus frequency for this two-port circuit result in the resonance peaks across the frequency band of interest. In the computer simulations, these graphs appear through Postfeko plots. In the physical ring resonator permittivity measurement system, graphs appear on a network analyzer connected to the physical circuit.

In the FEKO modeling, we use a planar multilayer substrate to characterize the resonator device, including its ground plane, substrate, circuit plane position, and the dielectric to be measured as shown by a screen shot of Cadfeko in Fig. 3. The bottom of layer 1 has a perfect electric conductor ground plane and layer 1, otherwise, has the substrate. The top of the substrate and the circuit plane is at the top of layer 1 and at $Z = 0$. The dielectric of interest here starts at $Z = 0$ and is in layer 0, which, technically for the computation, is of infinite depth, although in practice the sensing drops off rapidly after only the first couple millimeters or so.

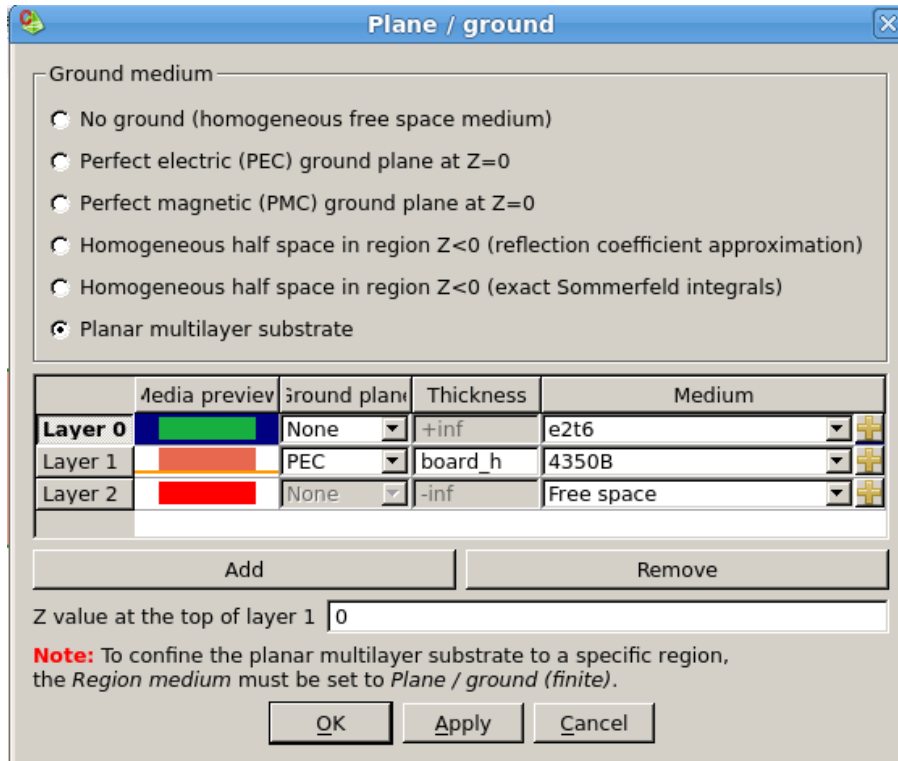


Fig. 3 Sample CadfeKO settings for resonator device layers and soil sample

During the simulations, S21 graphs of the resonances are created for each permittivity pair (real and loss tangent) of interest. The collection of permittivities covers the desired range of permittivities. The shifts in the resonance frequencies along with changes in quality factors are compared between air- and dielectric-loaded simulations. The changes are stored in a lookup table, which is later used to estimate the permittivity of measured samples.

Each resonator is also likely to produce resonances at integer multiples of its primary resonance frequency. This necessitates creation of additional lookup tables for each harmonic, allowing a single ring resonator to yield permittivity estimates across a band of frequencies.

3. Guidance

FEKO models surfaces with triangular facets. To obtain a good model for a given dielectric, one should model the geometry well enough by proper sizing of the facets both to properly express curves and be of sizes much smaller than a wavelength associated with the highest simulation frequency. Final models for a given resonance using these models may take on the order of 15 CPU-hours, so an

emphasis was placed on developing guidelines to efficiently create the lookup tables. These guidelines are summarized as follows.

Resonances with the same real epsilon, $\text{Re}\{\epsilon\}$, largely have the same peak frequency and are sharpest when the loss tangent, $\tan \delta$, is the smallest. This is a guide for where the other resonances with the same real epsilon lie. A minimum criterion for a resonance is that it must be strong enough so that its width can be measured at approximately -3.01 dB from the peak. A Postfeko resonance width measurement tool conveniently makes that measurement available. The resonances are successively broader as the loss tangent gets larger so that resonance frequency “boundaries” set by width measurement can serve as guides for coarse frequency searches for resonances of successive loss tangent values. Figure 4 is sample of S21 resonance curves for a 250-MHz meandered-line resonator at the fourth harmonic with $\text{Re}\{\epsilon\} = 4$.

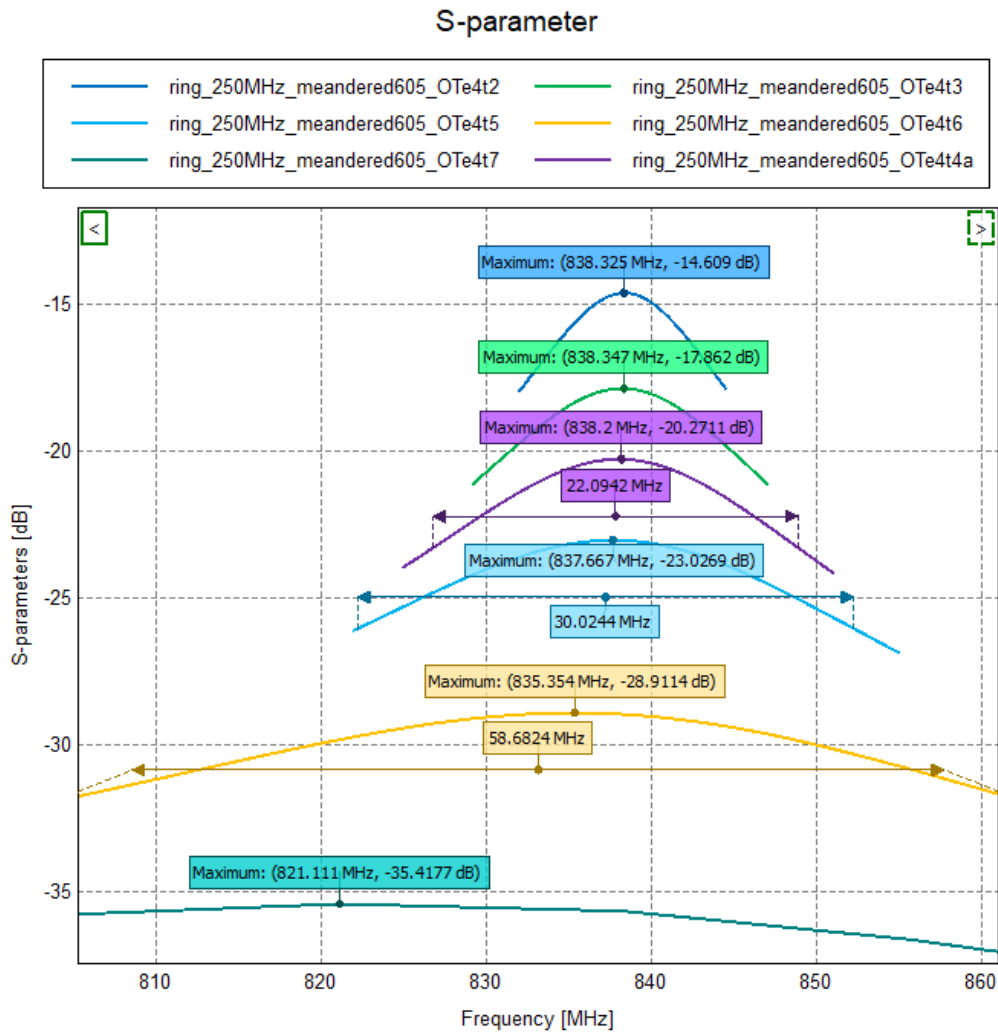


Fig. 4 S21 resonance curves for the fourth harmonic of a 250-MHz resonator

At sufficiently high values of $\text{Re}\{\mathcal{E}\}$, $\tan \delta$, or especially in combination with higher harmonics, the resonances will fail to meet the criterion for measuring width. For these cases, one cannot create entries for the lookup tables from the FEKO computations that are valid or reliable.

Once one has measurable coarsely sampled graphs of the resonances, the run models can be rerun with fine sampling for accuracy and more limited frequency boundaries to reduce the number of unnecessary computations. These runs are time-consuming but can be submitted as chains in batch files (e.g., XXX.bat in Windows) from the “Feko terminal” using the `runfeko` command for each model.

When the data for the resonance peaks and widths are available, they can be converted into a form that the MATLAB resonator software can use. A spreadsheet as exemplified in Fig. 5 for the fourth harmonic of a 250-MHz resonator can be a convenient means to do this. The figure shows four large blocks of data. Counterclockwise from the upper right is a table of resonance widths, then a table of frequencies of the resonance peaks, or resonance frequencies. Next is the ratio (C13–I18) of the resonance frequencies (C4–I9) to the unloaded resonator (from B3), and finally, the fourth block (L13–R18) is the ratio of the resonance Q’s (from L4–R9) to the Q (from K3) of the unloaded resonator.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1		0	0.03	0.05	0.07	0.1	0.2	0.4	0.6		0	0.03	0.05	0.07	0.1	0.2	0.4	0.6
2		1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8
3		1	963.4								4.622							
4		2	913.6	913.7	913.7	913.5	913.2	910.6	906		4.425	9.807	13.41	17.04	22.5	41.3	83.8	150.2
5		3	872.9	872.8	872.7	872.6	872.4	871.1	864.8	850	4.223	10.955	15.475	20.032	26.94	51.15	118.5	155
6		4	838.5	838.3	838.3	838.2	837.7	835.4	821	800	4.04	11.72	16.88	22.09	30.02	58.7	120	160
7		5	808.8	808.6	808.4	808.4	807.5	803.8	787	765	3.834	12.21	17.608	23.57	32.35	65.9	123	170
8		6	782.8	782.6	782.3	781.8	781.1	776	758	733	3.674	12.57	18.57	24.69	34.21	74.6	127	180
9		7	759.7	759.5	759	758.7	757.6	751	731	706	3.502	12.78	19.07	25.54	35.73	85	135	200
10																		
11																		
12		1	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.00000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
13		2	0.948	0.948	0.948	0.948	0.948	0.948	0.945	0.940	0.99053	0.44698	0.32689	0.25725	0.19478	0.10608	0.05213	0.02894
14		3	0.906	0.906	0.906	0.906	0.906	0.904	0.898	0.882	0.99167	0.38223	0.27056	0.20898	0.15536	0.08170	0.03501	0.02631
15		4	0.870	0.870	0.870	0.870	0.870	0.867	0.852	0.830	0.99574	0.34316	0.23826	0.18204	0.13388	0.06828	0.03282	0.02399
16		5	0.840	0.839	0.839	0.839	0.838	0.834	0.817	0.794	1.01207	0.31772	0.22026	0.16455	0.11975	0.05852	0.03070	0.02159
17		6	0.813	0.812	0.812	0.812	0.811	0.805	0.787	0.761	1.02220	0.29869	0.20211	0.15191	0.10954	0.04991	0.02863	0.01954
18		7	0.789	0.788	0.788	0.788	0.786	0.780	0.759	0.733	1.04076	0.28512	0.19095	0.14252	0.10173	0.04239	0.02598	0.01694
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Fig. 5 Spreadsheet for fourth harmonic of a 250-MHz resonator data

4. Results

The lookup table is a MATLAB “mat” file containing two vectors and two matrices. In this example, a column vector, “eps_real”, contains the values of the $\text{Re}\{\mathcal{E}\}$, [2;3;4;5;6;7], and a row vector, “loss_tan”, contains the $\tan \delta$ values, [0,0.0300, 0.0500, 0.0700, 0.1000, 0.2000, 0.4000, 0.6000]. The MATLAB 6×8 array “f_shift” is extracted from the third block (C13 – I18), and the MATLAB 6×8 array “Q_reduce” is extracted from the fourth block (L13 – R18). In Fig. 5, a number of entries are colored red because the resonances were too weak for these

combinations of $\text{Re}\{\mathcal{E}\}$ and $\tan \delta$. Those values should be regarded as unreliable dummy values. They are beyond the measuring capability of that resonator.

5. Conclusions

Using these techniques, with successive lookup table projects honing it to the currently described one, we have created tables for the first four harmonics of the 250-MHz meandered-line resonator as well as the first two for the 1200-MHz ring resonator. In an earlier project, a table was created for first harmonic of the 28-MHz meandered-line resonator.³ The data in the “mat” files are given in the Appendix.

Using 10–16 frequencies worked well for the coarse run to determine “boundaries” resonances adequately, especially once the “0” or lowest $\tan \delta$ resonance is discerned. For the “fine” runs, roughly 10 times more frequencies yielded good accuracy. With the availability of 12 cores, well-crafted batch jobs of fine runs run overnight can cut the lookup table creation time in half.

As the data in red shown in the spreadsheet of Section 3 (Fig. 5) and in the Appendix are not valid, the resonator graphical user interface software could be altered to flag it. However, an actual measurement attempt for such a case would fail to give a fully measureable Q by our standard in so far as it is a good model of the device.

6. References

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**Appendix. MATLAB “mat” File Contents for Four Harmonics of
the 250-MHz and Two Harmonics of the 1200-MHz Ring
Resonator**

250 MHz harmonic 1

eps_real = [1;2;3;4;5;6;7;8;9;10;12;15]

loss_tan = [0,0.03,0.05,0.07,0.10,0.20,0.40]

f_shift =

1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.9473	0.9473	0.9473	0.9473	0.9475	0.9486	0.9465
0.9049	0.9053	0.9053	0.9053	0.9053	0.9053	0.9053
0.8695	0.8695	0.8700	0.8700	0.8700	0.8704	0.8704
0.8399	0.8399	0.8403	0.8403	0.8405	0.8395	0.8395
0.8140	0.8140	0.8140	0.8148	0.8148	0.8148	0.8128
0.7914	0.7918	0.7918	0.7922	0.7922	0.7922	0.7901
0.7712	0.7716	0.7720	0.7716	0.7716	0.7716	0.7695
0.7535	0.7539	0.7539	0.7541	0.7541	0.7551	0.7506
0.7374	0.7374	0.7377	0.7373	0.7379	0.7387	0.7346
0.7091	0.7091	0.7095	0.7099	0.7099	0.7099	0.7053
0.6745	0.6749	0.6749	0.6749	0.6749	0.6745	0.6704

Q_reduce =

1.0000	0.5115	0.3862	0.3102	0.2392	0.1357	0.0724
0.7674	0.3469	0.2505	0.1980	0.1507	0.0837	0.0440
0.5427	0.2577	0.1912	0.1519	0.1161	0.0649	0.0342
0.4114	0.2072	0.1559	0.1249	0.0963	0.0547	0.0293
0.3218	0.1746	0.1334	0.1082	0.0841	0.0484	0.0263
0.2654	0.1511	0.1172	0.0960	0.0755	0.0442	0.0241
0.2242	0.1336	0.1052	0.0869	0.0689	0.0409	0.0226
0.1937	0.1202	0.0960	0.0797	0.0637	0.0383	0.0214
0.1696	0.1093	0.0883	0.0741	0.0597	0.0364	0.0204
0.1512	0.1001	0.0817	0.0692	0.0563	0.0347	0.0197
0.1250	0.0869	0.0722	0.0618	0.0507	0.0320	0.0184
0.1004	0.0734	0.0622	0.0539	0.0450	0.0290	0.0171

250 MHz harmonic 2

eps_real = [1;2;3;4;5;6;7;8;9;10;12;15]

loss_tan = [0,0.03,0.05,0.07,0.10,0.20,0.40]

f_shift =

1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.9479	0.9479	0.9481	0.9479	0.9477	0.9473	0.9463
0.9062	0.9060	0.9062	0.9060	0.9060	0.9060	0.9039
0.8715	0.8715	0.8715	0.8715	0.8715	0.8709	0.8667
0.8419	0.8419	0.8419	0.8419	0.8415	0.8409	0.8362
0.8163	0.8163	0.8165	0.8161	0.8161	0.8147	0.8099
0.7934	0.7938	0.7940	0.7934	0.7934	0.7915	0.7847
0.7733	0.7736	0.7733	0.7733	0.7729	0.7717	0.7643
0.7541	0.7539	0.7541	0.7552	0.7548	0.7529	0.7455
0.7378	0.7380	0.7376	0.7376	0.7390	0.7366	0.7283
0.7091	0.7093	0.7091	0.7087	0.7087	0.7074	0.6971
0.6736	0.6733	0.6731	0.6731	0.6725	0.6707	0.6589

Q_reduce =

1.0000	0.5827	0.4551	0.3731	0.2941	0.1720	0.0932
0.7881	0.4081	0.3076	0.2456	0.1895	0.1074	0.0570
0.6393	0.3217	0.2417	0.1933	0.1487	0.0838	0.0441
0.5335	0.2715	0.2045	0.1640	0.1264	0.0713	0.0374
0.4576	0.2390	0.1808	0.1454	0.1123	0.0636	0.0332
0.4103	0.2169	0.1648	0.1328	0.1027	0.0582	0.0303
0.3689	0.1990	0.1525	0.1232	0.0956	0.0542	0.0281
0.3384	0.1856	0.1424	0.1157	0.0900	0.0512	0.0264
0.3149	0.1754	0.1355	0.1095	0.0855	0.0488	0.0250
0.2939	0.1665	0.1289	0.1052	0.0819	0.0468	0.0238
0.2643	0.1527	0.1190	0.0973	0.0764	0.0436	0.0218
0.2348	0.1386	0.1086	0.0892	0.0701	0.0401	0.0193

250 MHz harmonic 3

eps_real = [1;2;3;4;5;6;7;8;9;10;12;15]

loss_tan = [0,0.03,0.05,0.07,0.10,0.20,0.40]

f_shift =

1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9967
0.9479	0.9479	0.9479	0.9479	0.9479	0.9472	0.9452
0.9058	0.9058	0.9056	0.9056	0.9052	0.9045	0.8990
0.8705	0.8705	0.8705	0.8703	0.8701	0.8687	0.8613
0.8406	0.8403	0.8403	0.8400	0.8398	0.8377	0.8281
0.8143	0.8143	0.8140	0.8139	0.8136	0.8108	0.7977
0.7900	0.7900	0.7899	0.7903	0.7902	0.7870	0.7853
0.7702	0.7694	0.7691	0.7688	0.7684	0.7662	0.7661
0.7516	0.7523	0.7520	0.7516	0.7494	0.7462	0.7440
0.7352	0.7351	0.7349	0.7346	0.7339	0.7291	0.7275
0.7050	0.7049	0.7046	0.7041	0.7035	0.6984	0.6958
0.6645	0.6644	0.6640	0.6634	0.6622	0.6557	0.6531

Q_reduce =

1.0000	0.5324	0.4495	0.3682	0.2896	0.1690	0.0906
0.8782	0.4225	0.3138	0.2495	0.1908	0.1065	0.0547
0.7829	0.3480	0.2543	0.2002	0.1514	0.0829	0.0412
0.7072	0.3048	0.2209	0.1728	0.1302	0.0704	0.0335
0.6487	0.2761	0.1993	0.1554	0.1166	0.0626	0.0275
0.6094	0.2555	0.1842	0.1436	0.1076	0.0570	0.0223
0.5898	0.2439	0.1750	0.1352	0.1006	0.0528	0.0211
0.5577	0.2310	0.1656	0.1288	0.0961	0.0495	0.0199
0.5343	0.2190	0.1568	0.1217	0.0915	0.0468	0.0186
0.5152	0.2103	0.1508	0.1173	0.0871	0.0442	0.0174
0.4791	0.1973	0.1415	0.1093	0.0813	0.0402	0.0155
0.4570	0.1850	0.1317	0.1017	0.0750	0.0348	0.0134

250 MHz harmonic 4

eps_real = [2;3;4;5;6;7]

loss_tan = [0,0.03,0.05,0.07,0.10,0.20,0.40,0.60]

f_shift =

0.9480	0.9480	0.9480	0.9480	0.9480	0.9480	0.9450	0.9400
0.9060	0.9060	0.9060	0.9060	0.9060	0.9040	0.8980	0.8820
0.8700	0.8700	0.8700	0.8700	0.8700	0.8670	0.8520	0.8300
0.8400	0.8390	0.8390	0.8390	0.8380	0.8340	0.8170	0.7940
0.8130	0.8120	0.8120	0.8120	0.8110	0.8050	0.7870	0.7610
0.7890	0.7880	0.7880	0.7880	0.7860	0.7800	0.7590	0.7330

Q_reduce =

0.9905	0.4470	0.3269	0.2572	0.1948	0.1061	0.0521	0.0289
0.9917	0.3822	0.2706	0.2090	0.1554	0.0817	0.0350	0.0263
0.9957	0.3432	0.2383	0.1820	0.1339	0.0683	0.0328	0.0240
1.0121	0.3177	0.2203	0.1646	0.1197	0.0585	0.0307	0.0216
1.0222	0.2987	0.2021	0.1519	0.1095	0.0499	0.0286	0.0195
1.0408	0.2851	0.1910	0.1425	0.1017	0.0424	0.0260	0.0169

1200 MHz harmonic 1

eps_real = [1;2;3;4;5;6;7;8;9;10;12;15]

loss_tan = [0,0.03,0.05,0.07,0.10,0.20,0.40]

f_shift =

1.0000	0.9995	0.9998	0.9995	0.9998	0.9994	0.9990
0.9569	0.9569	0.9560	0.9561	0.9559	0.9552	0.9538
0.9261	0.9254	0.9254	0.9255	0.9251	0.9244	0.9224
0.9038	0.9030	0.9023	0.9024	0.9024	0.9014	0.8987
0.8846	0.8844	0.8843	0.8845	0.8841	0.8834	0.8803
0.8702	0.8689	0.8691	0.8690	0.8689	0.8677	0.8646
0.8570	0.8570	0.8567	0.8568	0.8565	0.8554	0.8522
0.8478	0.8464	0.8455	0.8453	0.8453	0.8448	0.8409
0.8366	0.8366	0.8365	0.8365	0.8362	0.8357	0.8323
0.8284	0.8284	0.8286	0.8282	0.8282	0.8272	0.8238
0.8150	0.8131	0.8130	0.8131	0.8128	0.8126	0.8093
0.7970	0.7960	0.7964	0.7962	0.7959	0.7953	0.7935

Q_reduce =

1.0000	0.6294	0.4920	0.4080	0.3239	0.1921	0.1044
0.8741	0.5031	0.3867	0.3169	0.2471	0.1442	0.0779
0.7684	0.4364	0.3395	0.2777	0.2179	0.1250	0.0692
0.7006	0.4051	0.3141	0.2582	0.2031	0.1172	0.0651
0.6478	0.3831	0.3008	0.2479	0.1962	0.1155	0.0637
0.6211	0.3700	0.2923	0.2410	0.1912	0.1112	0.0626
0.5979	0.3630	0.2871	0.2375	0.1886	0.1105	0.0625
0.5832	0.3577	0.2821	0.2337	0.1864	0.1091	0.0620
0.5748	0.3531	0.2806	0.2328	0.1858	0.1094	0.0611
0.5683	0.3527	0.2810	0.2344	0.1868	0.1106	0.0631
0.5631	0.3484	0.2780	0.2314	0.1818	0.1098	0.0632
0.5184	0.3364	0.2714	0.2237	0.1797	0.1106	0.0631

1200 MHz harmonic 2

eps_real = [1;2;3;4;5;6;7;8;9;10;12;15]

loss_tan = [0,0.03,0.05,0.07,0.10,0.20,0.40]

f_shift =

1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.9490	0.9490	0.9490	0.9490	0.9490	0.9490	0.9470
0.9070	0.9060	0.9060	0.9070	0.9070	0.9060	0.9020
0.8710	0.8710	0.8710	0.8710	0.8700	0.8690	0.8620
0.8400	0.8400	0.8400	0.8400	0.8400	0.8370	0.8270
0.8130	0.8130	0.8130	0.8130	0.8120	0.8090	0.7930
0.7890	0.7890	0.7890	0.7890	0.7870	0.7840	0.7650
0.7680	0.7670	0.7670	0.7660	0.7650	0.7590	0.7550
0.7480	0.7470	0.7470	0.7460	0.7450	0.7380	0.7340
0.7300	0.7290	0.7290	0.7280	0.7270	0.7180	0.7130
0.7120	0.7120	0.7120	0.7110	0.7090	0.7000	0.6920
0.6970	0.6960	0.6960	0.6950	0.6930	0.6820	0.6710

Q_reduce =

1.0000	0.6320	0.5079	0.4244	0.3405	0.2042	0.1130
0.8349	0.4576	0.0352	0.2860	0.0194	0.1284	0.0689
0.7193	0.3734	0.2828	0.2276	0.1759	0.1000	0.0531
0.6396	0.3235	0.2432	0.1947	0.1499	0.0845	0.0439
0.5745	0.2881	0.2161	0.1728	0.1328	0.0743	0.0372
0.5179	0.2607	0.1958	0.1565	0.1203	0.0668	0.0309
0.4669	0.2383	0.1794	0.1437	0.1103	0.0606	0.0226
0.4218	0.2192	0.0166	0.1328	0.1019	0.0550	0.0205
0.3787	0.2015	0.1531	0.1230	0.0944	0.0497	0.0185
0.3386	0.1853	0.1417	0.1141	0.0873	0.0445	0.0160
0.3035	0.1705	0.1311	0.1057	0.0806	0.0389	0.0140
0.2725	0.1571	0.1212	0.0978	0.0743	0.0321	0.0119

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