A NEW COMPUTER AID FOR MICROWAVE FILTER DESIGN

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Summary

A recent development for the synthesis, as well as the analysis, of microwave filters, multiplexers, and impedance matching circuits is described in this paper. The new program offers interactive design of filter networks constructed by commensurate transmission line stubs and unit elements. Lowpass, highpass, bandpass, linear-phase lowpass and band-reject filters can be specified with maximally flat or equal-ripple passband, having monotonic, equal-minimum or arbitrary stopband specifications. If finite transmission zero locations are not known, the program can compute them by an optimization procedure. Circuit topology may also be specified by the user, or the program can generate it internally. At the command level, all the known network manipulations (Norton Transformations, Kuroda Identities including Levy's Extension, etc.) are readily available; additional unit elements may be inserted at the source or the load side to increase the complexity of an existing network. Filter size may be specified by its degree or by the appropriate stopband specifications.

To demonstrate a typical design procedure, consider a bandpass filter centered around the quarter-wave frequency of 4 GHz with the bandwidth of ±2 GHz and a passband ripple of .05 dB. The network should have four unit elements and a single transmission zero at DC; input and output terminations are 50 ohms. The computer generated structure will be requested. The filter will be realized in microstrip form; therefore, the line impedances should be kept in the 20-100 ohm range.

Since the quarter-wave frequency is at the center of the passband, the filter is described as a highpass structure as follows (underlined portions indicate user inputs):

```
PLACER(P), FILSYN(F), LADDER(L), DIGITAL(D) OR END(E) ? F
ENTER TITLE
? MICROWAVE BANDPASS (LOWPASS)
FILTER TYPE - LOWPASS: 1, HIGHPASS: 2, LIN.-PHASE LOWPASS: 3, BANDPASS: 4 ? 2
LUMPED: 0, BILINEAR DIGITAL: 1 OR MICROWAVE: 2 ? 2
ENTER QUARTER WAVE FREQUENCY IN HZ ? 4E9
LOWER EDGE OF THE PASSBAND IN HZ ? 2E9
PASSBAND KIND - MAX.-FLAT: 0, EQUAL-RIPPLE: 1 ? 1
WHAT IS THE BAND EDGE LOSS IN DB ? .05
ENTER ZS (-1,0 OR 1). FOR DEFAULT ENTER 0 ? 0
MONOTONIC(0) OR SPECIFIED(2) STOPBAND ? 2
ENTER NUMBER OF UNIT ELEMENTS
IF IMPEDANCE MATCHING, ENTER -1 ? 4
ENTER MULTIPLICITY OF TRANSMISSION ZERO AT ZERO ? 1
ENTER NUMBER OF FINITE TRANSMISSION ZEROS ? 0
ENTER INPUT TERMINATION IN OHMS ? 50.
ENTER OUTPUT TERMINATION (0. INDICATES OPEN OR SHORT) ? 50.
IS ANALYSIS REQUIRED (Y/N) ? N
```

The resultant circuit as generated by the program is shown next:

```
**** ALL VALUES ARE IMPEDANCES ****

 1   ....R....     5.0000000E+01
     .       .
     *       *
 2   *  U E  *     3.2981446E+01
     *       *

     .       .
     *       *
 4   *  U E  *     1.4448549E+01
     *       *
     .       .
 5   ....L....     6.8390097E+00
     .       .
     *       *
 8   *  U E  *     1.4448549E+01
     *       *
     .       .
     *       *
12   *  U E  *     3.2981446E+01
     *       *
     .       .
15   ....R....     5.0000000E+01
     .       .
```

Circuit Element Summary

Abbreviation	Lumped	Distributed
UE		Cascade Line
L	Inductor	Shorted Stub
C	Capacitor	Open Stub
R	Termination	Termination

The requested 50 ohm terminations have been achieved but the three elements at the center of the filter have very low impedances that cannot be conveniently realized. At this point, the impedances may be manipulated by two consecutive highpass Kuroda transformations after which the line impedances remain between 20 and 50 ohms. The available network transformation commands and the resultant final filter circuit are shown on the following page.

```
COMMAND (OR HELP): ? HELP

TP   : TEE-TO-PI OR PI-TO-TEE CONVERSION
IB   : INTERCHANGE BRANCHES
RS   : IMPEDANCE SCALING
FS   : FREQUENCY SCALING
INS  : INSERT A BRANCH
DEL  : DELETE A BRANCH
PRI  : PRINT COMPLETE NETWORK
TR   : NORTON (IMPEDANCE) TRANSFORMATION
COM  : COMBINE TWO BRANCHES
DUAL : GET DUAL CIRCUIT
BE   : TRANSFORM LOWPASS TO BAND-ELIMINATION
FILE : WRITE RESULTS ON FILE
FREQ : FREQUENCY DOMAIN ANALYSIS
LAT  : CONVERSION OF LADDER SEGMENT TO LATTICE
INCL : INCLUSION OF FLANKING CAPACITORS INTO LATTICE
HELP : PRINT LIST OF COMMANDS
END  : LEAVE LADDER SEGMENT
```

```
**** ALL VALUES ARE IMPEDANCES ****

 1    ....R....       5.0000000E+01
      .       .
      *       *
 2    *  U E  *       3.2981446E+01
      *       *
      .       .
 5    ....L....       4.9330433E+01
      .       .
      *       *
 8    *  U E  *       2.0433334E+01
      *       *
      .       .
11    ....L....       2.2501327E+01
      .       .
      *       *
16    *  U E  *       2.0433334E+01
      *       *
      .       .
17    ....L....       4.9330433E+01
      .       .
      *       *
20    *  U E  *       3.2981446E+01
      *       *
      .       .
23    ....R....       5.0000000E+01
```

Although the number of circuit elements are increased from five to seven, the degree of the circuit has not changed and frequency response is identical to that of the previous network.

A second example illustrates a more complicated design, involving a combline filter. A bandpass ripple of .1 dB is required between 1.2 and 1.8 GHz minimum. Stopband attenuations of 20 dB at .5 GHz and 30 dB at 2.4 GHz are also specified. An additional requirement states that all parallel open stubs must have the same impedances. The user inputs of the design are shown below. Again, the computer generated topology is requested; however, this time the dual of the synthesized circuit yields the proper initial filter configuration.

```
PLACER(P), FILSYN(F), LADDER(L), DIGITAL(D) OR END(E) ? F
ENTER TITLE
? COMBLINE FILTER
FILTER TYPE - LOWPASS: 1, HIGHPASS: 2, LIN.-PHASE LOWPASS: 3, BANDPASS: 4 ? 4
LUMPED: 0, BILINEAR DIGITAL: 1 OR MICROWAVE: 2 ? 2
ENTER QUARTER WAVE FREQUENCY IN HZ ? 4.909E9
LOWER EDGE OF THE PASSBAND IN HZ ? 1.2E9
UPPER EDGE OF THE PASSBAND IN HZ ? 1.8E9
PASSBAND KIND - MAX.-FLAT: 0, EQUAL-RIPPLE: 1 ? 1
WHAT IS THE BAND EDGE LOSS IN DB ? .1
CONVENTIONAL(1), PARAMETRIC(2) OR MATCHING(3) BANDPASS ? 1
MONOTONIC(0) OR SPECIFIED(2) STOPBAND ? 0
ENTER NUMBER OF UNIT ELEMENTS ? 0
ENTER FREQUENCY-LOSS PAIR IN LOWER STOPBAND ? 5E8 20
ENTER FREQUENCY-LOSS PAIR IN UPPER STOPBAND ? 2.4E9,30.
ENTER INPUT TERMINATION IN OHMS ? 50
ENTER OUTPUT TERMINATION (0. INDICATES OPEN OR SHORT) ? 50.
IS ANALYSIS REQUIRED (Y/N) ? N
```

```
**** ALL VALUES ARE IMPEDANCES ****

 1    ....R....       5.0000000E+01
      .       .
 2    .       L       2.1036727E+02
      .       .
 3    ....C....       6.3456599E+01
      .       .
 4    .       L       1.3549856E+03
      .       .
 6    .       C       3.0076762E+02
      .       .
 7    ....C....       6.3456599E+01
      .       .
 8    .       L       2.1036727E+02
      .       .
 9    ....R....       5.0000000E+01
      .       .
COMMAND (OR HELP): ? DUAL
```

```
**** ALL VALUES ARE IMPEDANCES ****

 1    ....R....       5.0000000E+01
      .       .
 3    ....C....       1.1883978E+01
      .       .
 4    .       L       3.9397006E+01
      .       .
 5    ....C....       1.8450380E+00
      .       .
 7    ....L....       8.3120649E+00
      .       .
 8    .       L       3.9397006E+01
      .       .
 9    ....C....       1.1883978E+01
      .       .
11    ....R....       5.0000000E+01
      .       .
```

Although the circuit is symmetrical, the capacitive stubs are not all the same. However, the impedances can be equalized by two consecutive Norton transformations between element pairs of 7-8 and 4-7. The first transformation lowers the 50 ohm load resistance by a factor of Z_5/Z_9 to 7.76 ohm, and the second one brings it up to 50 ohms. Now, all the parallel open stubs have the same impedances (11.88 ohm). If desired, the method can also be applied to obtain equal parallel inductances (shorted stubs) instead of the parallel capacitors.

```
COMMAND (OR HELP): ? TR,7.762712115,7,8
LARGEST TRANSFORMATION RATIO:    3.0354000E-02
TRANSFORMATION RATIO USED:       1.5525424E-01
  7     ....L....         1.2304583E+01
        .       .
  8     .       L         1.5523332E+01
        .       .
  9     ....L....         1.0093706E+01
        .       .
 11     ....C....         1.8450380E+00
        .       .
 13     ....R....         7.7627121E+00
        .       .
```

Analysis can be performed to obtain the frequency response and group delay of circuits at two different levels. The first one is from the transfer function during the approximation phase and the second is directly from the circuit. The effect of finite Q can also be included and the synthesis may be predistored.

```
**** ALL VALUES ARE IMPEDANCES ****

  1     ....R....         5.0000000E+01
        .       .
  3     ....C....         1.1883978E+01
        .       .
  5     ....L....         6.5014044E+01
        .       .
  6     .       L         9.9986526E+01
        .       .
  7     ....L....         1.5250855E+02
        .       .
  9     ....C....         1.1883978E+01
        .       .
 10     .       L         9.9986526E+01
        .       .
 11     ....L....         6.5014044E+01
        .       .
 13     ....C....         1.1883978E+01
        .       .
 15     ....R....         5.0000000E+01
        .       .
```

Analyzing the second filter structure shows that both the passband and stopband specifications have been satisfied.

******* COMPUTED PERFORMANCE *******

FREQUENCY IN HZ	TRANSD. LOSS IN DB	PHASE IN DEGREES	DELAY IN SECONDS	OUTPUT IMPEDANCE REAL	IMAGINARY
1.00000E+08	39.355702	273.516471	9.86711E-11	1.45136E-03	1.53483E+00
2.00000E+08	33.012433	277.141948	1.03304E-10	6.27283E-03	3.12030E+00
3.00000E+08	28.940754	280.998965	1.11673E-10	1.61109E-02	4.81400E+00
4.00000E+08	25.645588	285.240989	1.24953E-10	3.47255E-02	6.68963E+00
5.00000E+08	22.634707	290.079586	1.45290E-10	7.04740E-02	8.85214E+00
6.00000E+08	19.659022	295.832931	1.76664E-10	1.43096E-01	1.14666E+01
7.00000E+08	16.548739	303.021593	2.26808E-10	3.04409E-01	1.48204E+01
8.00000E+08	13.161389	312.573528	3.11725E-10	7.12558E-01	1.94774E+01
9.00000E+08	9.385668	326.278375	4.65403E-10	1.96631E+00	2.67093E+01
1.00000E+09	5.286959	347.602077	7.43970E-10	7.16979E+00	3.96980E+01
1.10000E+09	1.674928	20.812608	1.08198E-09	3.70365E+01	5.76001E+01
1.20000E+09	.100000	60.832106	1.06422E-09	6.43530E+01	9.68435E+00
1.30000E+09	.048427	95.231409	8.60720E-10	4.05020E+01	7.86475E-01
1.40000E+09	.090903	124.755830	8.05766E-10	3.89470E+01	6.52617E+00
1.50000E+09	.007020	154.481751	8.52476E-10	4.81734E+01	3.49995E+00
1.60000E+09	.047753	186.086256	9.01289E-10	4.78683E+01	-1.00650E+01
1.70000E+09	.084483	220.141334	1.02431E-09	4.09245E+01	-8.85519E+00
1.80000E+09	.100000	264.450486	1.50844E-09	6.76354E+01	2.01962E+00
1.90000E+09	3.386354	323.046357	1.48026E-09	3.49096E+01	-8.95389E+01
2.00000E+09	10.290065	2.171736	7.50647E-10	2.36375E+00	-4.80840E+01
2.10000E+09	16.841405	22.275315	4.16006E-10	3.79089E-01	-3.35496E+01
2.20000E+09	22.511116	34.301463	2.69719E-10	8.99369E-02	-2.64169E+01
2.30000E+09	27.523814	42.508470	1.93455E-10	2.64087E-02	-2.19961E+01
2.40000E+09	32.074017	48.592116	1.48032E-10	8.86401E-03	-1.88974E+01
2.50000E+09	36.293937	53.353596	1.18421E-10	3.25658E-03	-1.65584E+01
2.60000E+09	40.275103	57.225828	9.78616E-11	1.27480E-03	-1.47036E+01
2.70000E+09	44.084116	60.466436	8.29171E-11	5.22011E-04	-1.31796E+01
2.80000E+09	47.772051	63.239937	7.16704E-11	2.20603E-04	-1.18933E+01
2.90000E+09	51.380140	65.657142	6.29740E-11	9.52018E-05	-1.07843E+01
3.00000E+09	54.943379	67.795868	5.61027E-11	4.15893E-05	-9.81148E+00

Amonth other features, the program is capable of matching resistive terminations in several different ways. One of the most useful circuits of this type matches resistances by quarter-wave transmission lines. To illustrate the simplicity of the use of the program, let us request the matching of 20 ohms to 75 ohms in the band from 2 GHz to 8 GHz with less than .02 dB loss (better than 1.1454 VSWR). The program then indicates that using the band center (5 GHz) as quarter-wave frequency, we need 5 unit elements which will yield a match better than .0103 dB (1.1023 VSWR) and the resulting structure is shown below:

```
**** ALL VALUES ARE IMPEDANCES ****

  1    ....R....        7.5000000E+01
       .       .
       *       *
  3    *  U E  *        6.5509470E+01
       *       *

       .       .
       *       *
  5    *  U E  *        5.2269758E+01
       *       *

       .       .
       *       *
  7    *  U E  *        3.8729833E+01
       *       *

       .       .
       *       *
  9    *  U E  *        2.8697282E+01
       *       *

       .       .
       *       *
 11    *  U E  *        2.2897453E+01
       *       *
       .       .
 13    ....R....        2.0000000E+01
       .       .
```

The analysis (not shown) of this matching network indicates perfect agreement with the results above.

Additional capabilities include functional input in terms of Richard's transformed variable, parametric bandpass filter type, plotting of frequency response, delay and pole zero pattern.

The program has been used by several organizations and universities during the past two months. Upcoming modifications will include physical realization and layout considerations.

References

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4. R.J. Wenzel, "Synthesis of Combline and Capacitively Loaded Interdigital Bandpass Filters of Arbitrary Bandwidth", IEEE Trans. Microwave Theory & Techniuqes, Vol. MTT-19, August 1971, pp. 678-686.