

SIMULATION OF INTERDIGITATED STRUCTURES USING TWO-COUPLED LINE MODELS

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Acknowledgements:

This work was supported by contract P96093259 of INDRA DTD and Project
TIC-99-1172-C02-01 of the National Board of Scientific and Technology Research
(CIYCIT).

ABSTRACT

Some commercial microwave CAD programs do not incorporate models for more than three coupled lines. This fact is especially critical in the design and analysis of multiple-line planar structures, such as interdigital, combline and hairpin filters, meander lines, spiral inductors and couplers. In this paper, a new and very simple technique to simulate circuits with multiple coupled lines in commercial simulators without the suitable models is presented. The proposed method, called NTL (Negative Transmission Line) method, uses pairs of two-coupled lines, single transmission lines, current controlled current sources (CCCS) and voltage controlled voltage sources (VCVS), which are available in any commercial microwave CAD program. One of the greatest advantages of the proposed technique is that the analysis and optimization parameters are the physical dimensions of the coupled structure (line widths and spacings between them). Therefore, optimization and tuning of the structure are easy and fast.

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I. INTRODUCTION

Accurate models for the analysis of multiconductor structures are not available in some commercial microwave CAD programs, like LIBRA Series IV from HP-Eesof. In fact, this simulator only includes models for two and three asymmetric and symmetric coupled lines. Therefore, the analysis and simulation of multiple-line planar structures, such as interdigital, combline and hairpin filters, meander lines, spiral inductors and couplers, using these types of simulators, require new methods.

To overcome this limitation, two alternative approaches have been proposed. One of them consists of using an equivalent circuit composed of ideal non-coupled transmission lines and short-circuited stubs [1-4]. These techniques do not include effects such as losses in substrate and conductors, discontinuities and dispersive effects of the transmission lines, which are very important in the case of microstrip lines.

The other approach consists of modeling the multiple-line structure decomposing it into pairs of coupled lines [5-7]. These methods are based on the identities developed by Grayzel [8], who divides every line into several parts in order to form pairs of coupled lines. From this, every coupling can be simulated with the model of two coupled lines, which is available in any microwave CAD tool. In most cases, dispersive effects, substrate and conductor losses are not considered [6,7]. However, Denig's approach [5] takes them into account. Its main disadvantages are that it is only valid for

coupled lines of equal width and the optimization and tuning process is very tedious because the structure parameters are even- and odd-mode impedances which need to be calculated every time a geometrical modification in the coupled structure is carried out. Additionally, it can be obtained a coupled structure whose even and odd-mode impedances do not have a physical realization.

The proposed technique belongs to the last kind of methods and solves the aforementioned Denig's method problems. Physical dimensions of the coupled structure are used as parameters, so the optimization process is easier and faster and the physical perspective of the design is not lost. By this technique, n coupled lines, which can be of different widths, are transformed into $(n-1)$ pairs of coupled lines and $(n-2)$ single transmission lines loaded by an element referred to as "negator". This element can be implemented by current controlled current sources (CCCS) and voltage controlled voltage sources (VCVS). As in Denig's approach, the proposed technique does not take into account coupling between non-adjacent lines.

II. FUNDAMENTALS

The method presented in this paper is based on the non-coupled equivalent circuit for coupled lines proposed by Sato and Cristal [1], where the multiple-coupled transmission line structure is transformed into a set of non-coupled transmission lines. Figure 1 shows the physical parameters for three coupled lines, where W_1 , W_2 and W_3 are the widths of the lines and S_{12} and S_{23} are the spacings between lines 1-2 and 2-3, respectively. The structure length is l . The equivalent circuit of [1] for the three-coupled line case is shown in figure 2. The coils represent short-circuited stubs. The length of all

these lines is the same as the multiple-line structure and the characteristic admittances Y_{ii} and Y_{ij} are elements of its characteristic admittance matrix. Lines of characteristic admittances $-Y_{12}$ and $-Y_{23}$ are Negative Transmission Lines (NTLs).

Figure 1: Geometric parameters of a planar structure of three coupled lines.

Figure 2: The non-coupled equivalent circuit for three coupled lines.

If we introduce a line of characteristic admittance $-Y_{22}$ of the same length, as can be observed in figure 3, and another one of characteristic admittance Y_{22} in parallel, we get an equivalent network. But in this network, we can separate the coupling between lines 1 and 2 from the coupling between lines 2 and 3. In this way, the coupled structure has been decomposed into 2 independent couplings plus a NTL. The problem of simulating a NTL using geometrical parameters is treated in the next section.

Figure 3: Coupling separation in a three-coupled line structure.

II.1. Simulation of a NTL

In this subsection we will show how to simulate a NTL using physical dimensions and catalog elements of any microwave CAD program. The ABCD-matrix of a lossless NTL of characteristic impedance $-Z_0$ ($Z_0 > 0$) is shown in (1):

$$[ABCD] = \begin{pmatrix} \cos(\theta) & -jZ_0 \tan(\theta) \\ -j \tan(\theta) / Z_0 & \operatorname{ch}(\theta) \end{pmatrix} \quad (1)$$

where θ is the electrical length.

The matrix of the previous equation can be obtained by multiplying both sides of the ABCD-matrix of the transmission line Z_0 as follows:

$$\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(\theta) & jZ_0 \tan(\theta) \\ j \tan(\theta) / Z_0 & \cos(\theta) \end{pmatrix} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -jZ_0 \tan(\theta) \\ -j \tan(\theta) / Z_0 & \cos(\theta) \end{pmatrix} \quad (2)$$

Then, equation (2) can be seen as the resultant ABCD-matrix of three quadripoles connected in cascade, where the central matrix corresponds to a transmission line of impedance Z_0 . The first and last matrices correspond to the elements called negators. An equivalent circuit for a possible implementation of the negator is depicted in figure 4. This component can be implemented by a CCCS and a VCVS.

Figure 4: Negator circuit implementation.

Therefore, a NTL can be replaced by an identical line with positive characteristic impedance and two negators.

II.2. Use of physical dimensions. Generalization of the technique

Using the negators, the three-coupled line network of figure 3 ends up as shown in figure 5. A line of characteristic admittance Y_{22} and two negators appear instead of

the previous NTL. It can be proved that the geometrical parameters of the independent couplings are the same as the physical parameters of the original structure doing the following approximations:

1. The width of the line i , W_i , depends only on the characteristic admittance of this line, Y_{ii} .
2. The spacing between lines i and $i+1$, $S_{i,i+1}$, depends only on the characteristic admittances of these lines, Y_{ii} and $Y_{i+1,i+1}$, and the mutual characteristic admittance $Y_{i,i+1}$.

From that, the separated coupling between lines 1 and 2 can be characterized by the width of the lines 1 and 2 of the original structure and by the physical spacing between them. The same can be said of the separated coupling between lines 2 and 3. The width of the single transmission line Y_{22} will be the width of line 2.

Figure 5: Three-coupled line structure using negators.

The generalization to the n -coupled line case is shown in figure 6, where the negators have been included. The striped area corresponds to the couplings between adjacent lines. Every single line, together with its two negators, comprises a NTL. As stated before, the parameters of this network are the physical parameters of the coupled structure. The pairs of coupled lines and the single transmission lines can be simulated with the corresponding models of the simulator. As these models include losses, the NTL method is capable of estimating them.

Figure 6: Generalization for n coupled lines.

III. SIMULATIONS AND MEASUREMENTS.

In order to test the utility and validity of the proposed technique an example of microstrip tapped-line interdigital filter is presented. It is a fifth order Chebyshev filter, with 0.01 dB of ripple and a passband from 4.5 to 5.5 GHz. The plastic substrate chosen was epsilom-10 with 0.025'' thick and a dielectric constant of 9.9. This filter has been designed using the method proposed in [9]. Table I summarizes the calculated filter parameters. The layout and schematic of the filter are shown in figures 7 and 8 respectively. Although it has been removed from these figures for clarity, the ground connection of the resonators has been modeled by an inductance of 0.05 nH.

TABLE I: Calculated filter parameters (See figure 8).

Strip	Z_{oe} (Ω)	Z_{oo} (Ω)	W (mm)	S (mm)
1 and 2	35.36	26.00	1.400	0.425
2 and 3	34.25	27.62	1.400	0.675
3 and 4	34.25	27.62	1.400	0.675
4 and 5	35.36	26.00	1.400	0.425
Tap point (l_2)	2.125 mm			
l_1+l_2	4.825 mm			
l_a	0.140 mm			

Figure 7: Layout of the filter.

Figure 8: Implementation of the filter with the developed technique.

If we simulate the filter using the negator of figure 6, convergence problems arise which can be overcome with a small resistor placed as shown in figure 9. A value of $10^{-3} \Omega$ has been used in the simulation so that its presence does not affect the simulation results.

Figure 9: The practical implementation of the negator in LIBRA Series IV.

The simulations have been performed with LIBRA Series IV. These results are compared with SERENADE 7.5 from Ansoft, which is a CAD tool providing a full-wave model for multiple-coupled lines. The NTL method has been also tested in SERENADE to show the NTL-method dependence on the two-coupled line model used. Additionally, a comparison with the measurements is carried out.

In figures 10a-b, the transmission behavior of the filter predicted by the NTL method in LIBRA, with 'x', can be compared with the response of the full-wave model of SERENADE, depicted with continuous line. The measurements are plotted with 'o'. In the filter passband, the agreement between SERENADE and the measurements is excellent because its full-wave model is very accurate. Since the NTL model is an approximate model, it gives a good estimation of the bandwidth and passband losses with a small frequency shift (about 100 MHz upwards) of the passband. However, the disagreement with the measurements grows around the filter edges. The main reason is that the NTL method does not consider coupling between non-adjacent lines. Even

though the SERENADE model has not this limitation, it cannot adjust very well the filter edges either.

With regard to the reflection behavior, shown in figure 11, the deviations of the NTL model are larger, up to 10 dB more optimistic. It is not due to the NTL model itself but due to the two-coupled line model used by LIBRA, as can be shown as follows.

Figure 10: Comparison of the transmission behavior among measurements ('o'), the full-wave model of SERENADE ('-') and the NTL method in LIBRA ('x'). Figure 10b plots in detail the same as figure 10a.

Figure 11: Comparison of the reflection behavior among measurements ('o'), the full-wave model of SERENADE ('-') and the NTL method in LIBRA ('x').

If the NTL method is implemented in SERENADE, the response in the passband is closer to the full-wave model as can be seen in figures 12 and 13. This shows the dependence of the NTL method on the two-coupled line model used. Around the filter edges, the behavior of the NTL method in SERENADE is very close to that in LIBRA because the NTL method does not consider the coupling between non-adjacent lines.

Figure 12: Comparison of the transmission behavior among the full-wave model of SERENADE ('-'), the NTL method in SERENADE ('o') and the NTL method in LIBRA ('x').

Figure 13: Comparison of the reflection behavior among the full-wave model of SERENADE ('-'), the NTL method in SERENADE ('o') and the NTL method in LIBRA ('x').

IV. CONCLUSIONS.

A new technique that allows simulating multiple-coupled transmission line structures with commercial microwave CAD simulators without the suitable models has been proposed. It decomposes the coupled structure into a cascade of sections of two coupled lines and single transmission lines loaded by negators. Every negator can be implemented using a current controlled current source and a voltage controlled voltage source. This method uses physical dimensions as analysis and optimization parameters. For that reason, the physical aspect of the structure is always present. Optimization and tuning are easier and faster than using previous techniques. The new method gives a good estimate of the behavior of the coupled structure that is very useful in the design stage.

APPENDIX A.

The ckt file used to simulate the filter described in this paper with LIBRA is shown in figure A.1. This is suitable for LIBRA 3.5 and TOUCHSTONE. The filter schematic with LIBRA Series IV has not been included for clarity. However, it can be deduced from this ckt file and from figure 8. The results with LIBRA 3.5 and LIBRA Series IV are similar because the models are the same. The ckt file follows the

schematic of figure 8 considering the inductances as connection to ground of the resonators.

Figure A.1: LIBRA simulation file of the interdigital filter of figure 7.

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LIST OF FIGURE CAPTIONS.

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Figure 2: The non-coupled equivalent circuit for three coupled lines.

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Figure 4: Negator circuit implementation.

Figure 5: Three-coupled line structure using negators.

Figure 6: Generalization for n-coupled lines.

Figure 7: Layout of the filter.

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Figure 9: The practical implementation of the negator in LIBRA Series IV.

Figure 10: Comparison of the transmission behavior among measurements ('o'), the full-wave model of SERENADE ('-') and the NTL method in LIBRA ('x'). Figure 10b plots in detail the same as figure 10a.

Figure 11: Comparison of the reflection behavior among measurements ('o'), the full-wave model of SERENADE ('-') and the NTL method in LIBRA ('x').

Figure 12: Comparison of the transmission behavior among the full-wave model of SERENADE ('-'), the NTL method in SERENADE ('o') and the NTL method in LIBRA ('x').

Figure 13: Comparison of the reflection behavior among the full-wave model of SERENADE ('-'), NTL method in SERENADE ('o') and NTL method in LIBRA ('x').

Figure A.1: LIBRA simulation file of the interdigital filter of figure 7.

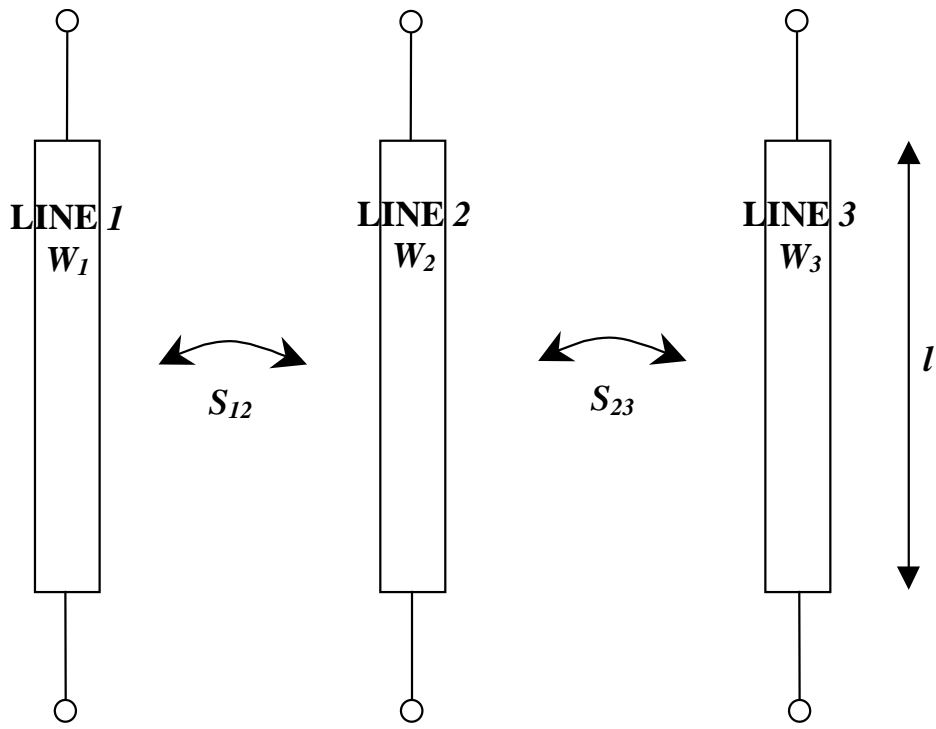


FIGURE 1

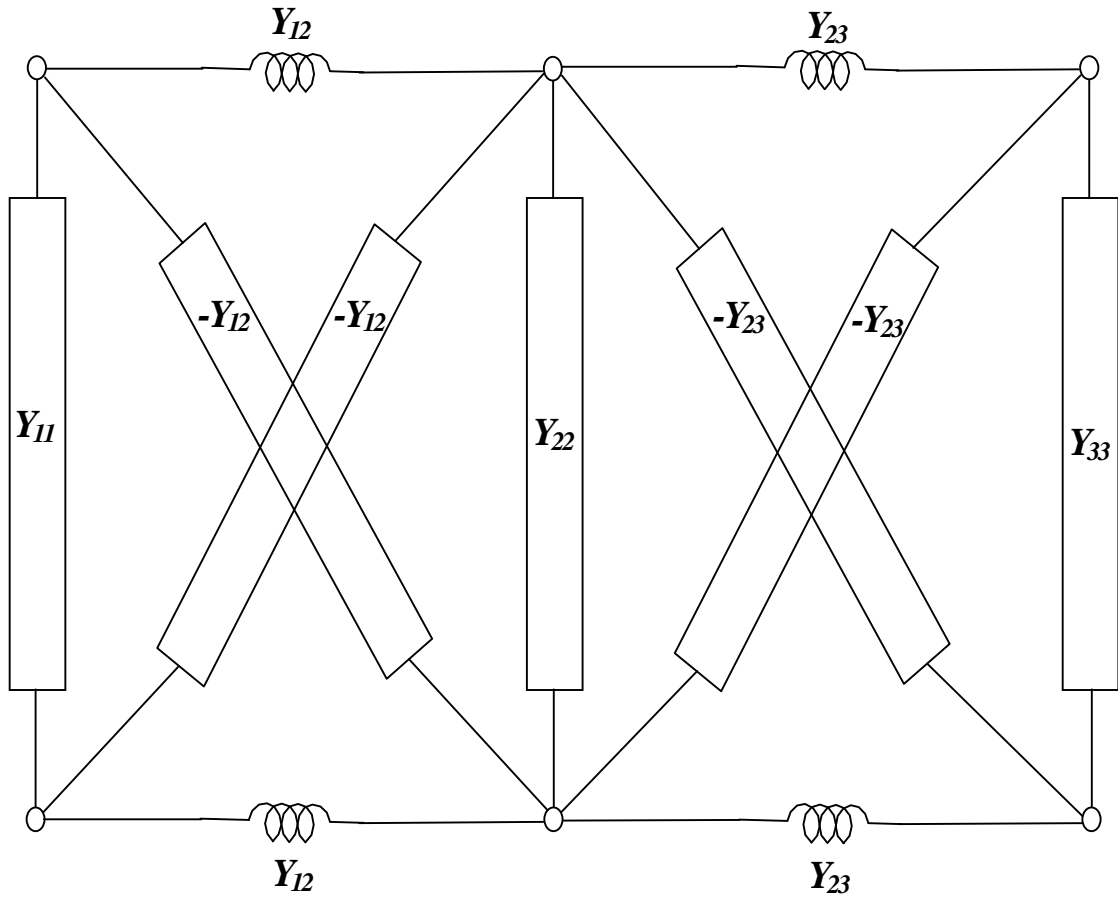


FIGURE 2

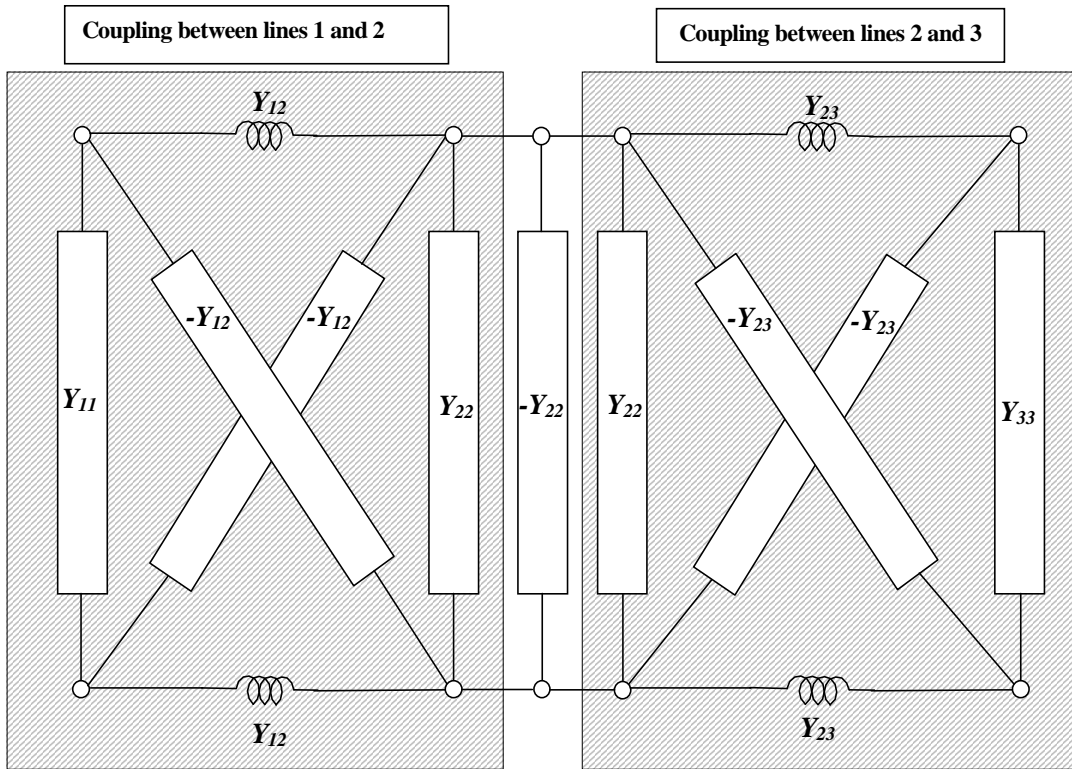


FIGURE 3

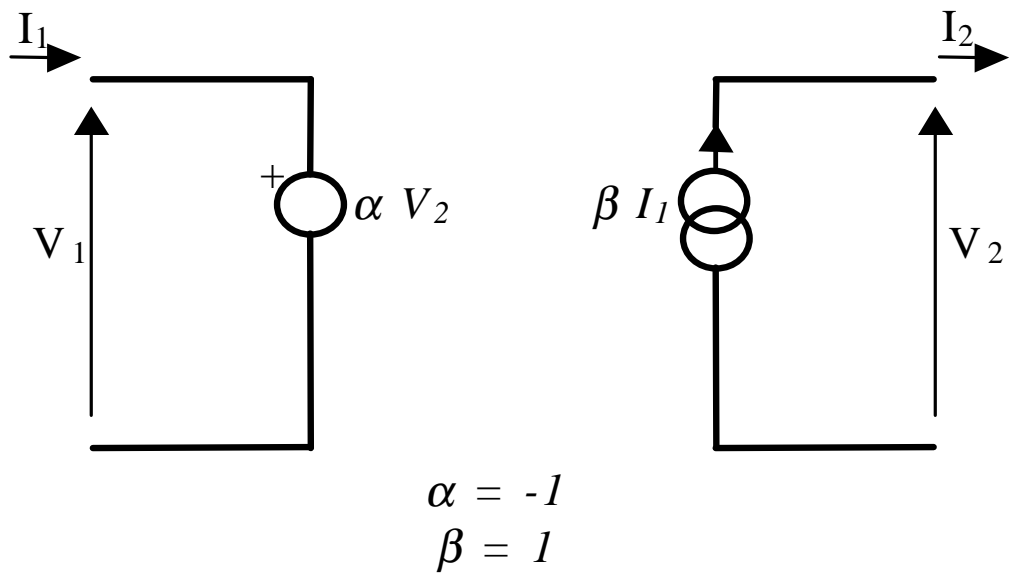


FIGURE 4

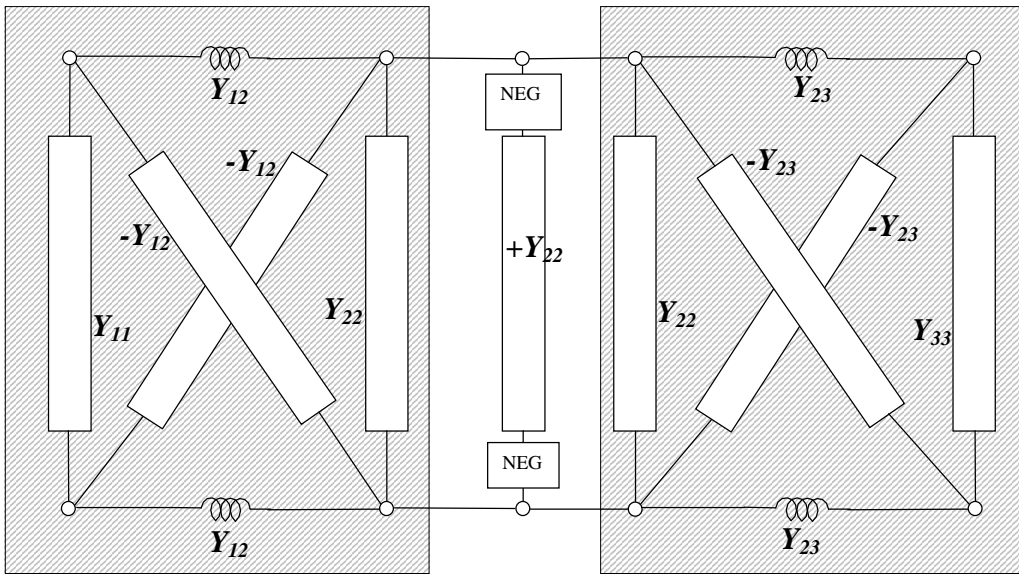


FIGURE 5

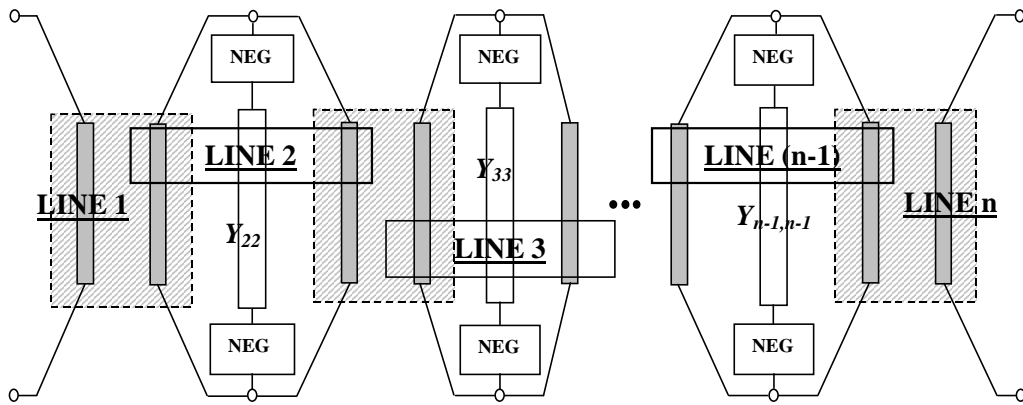


FIGURE 6

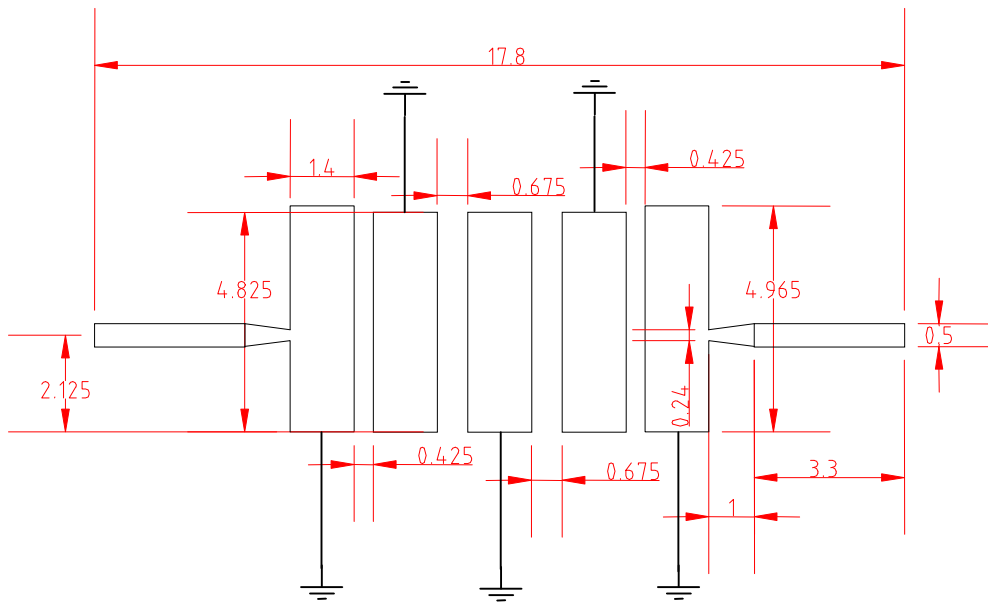


FIGURE 7

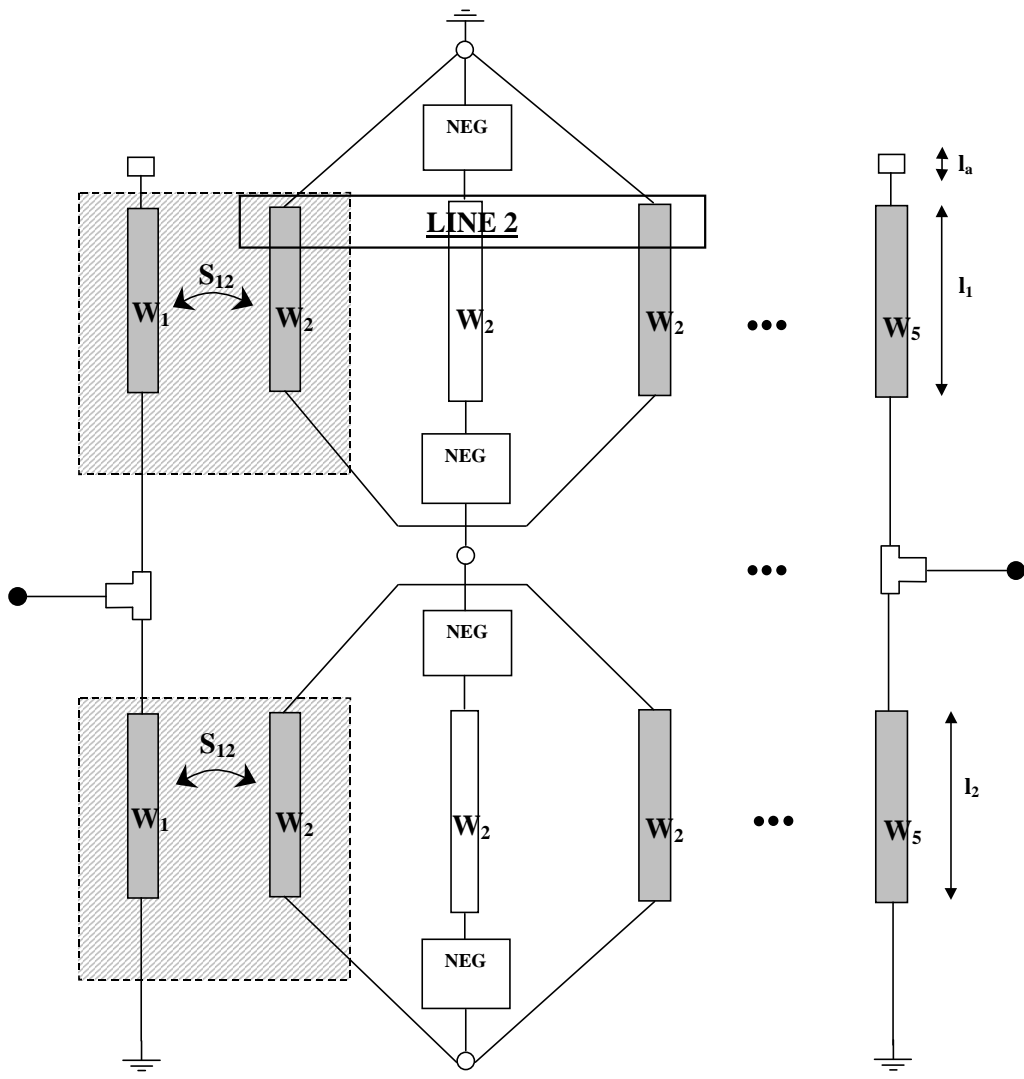


FIGURE 8

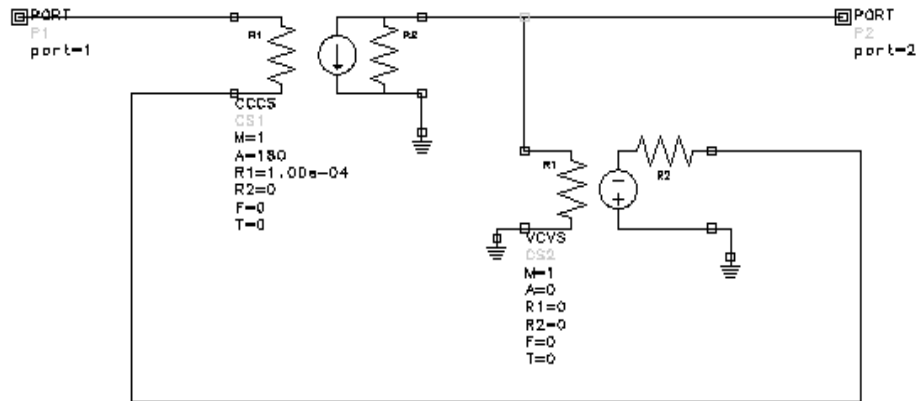


FIGURE 9

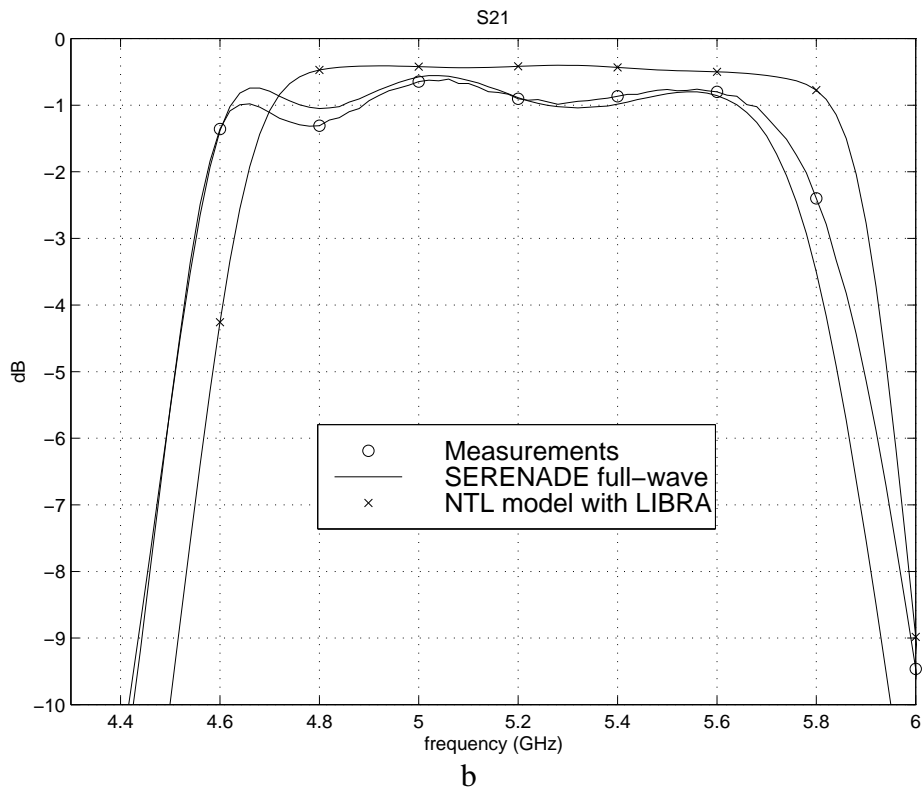
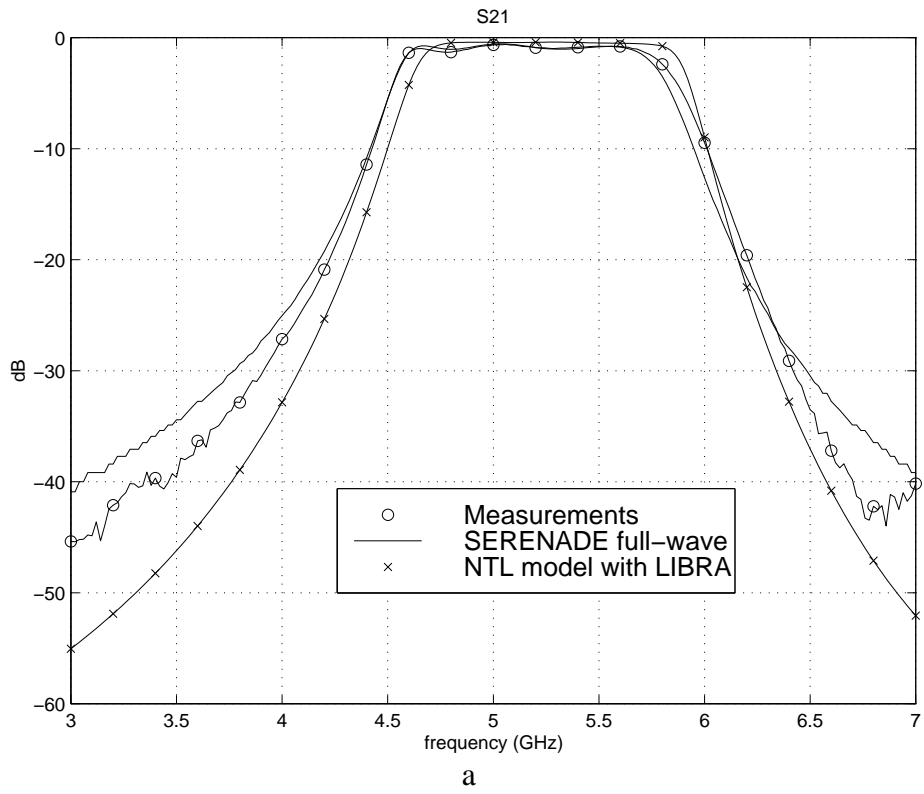


FIGURE 10

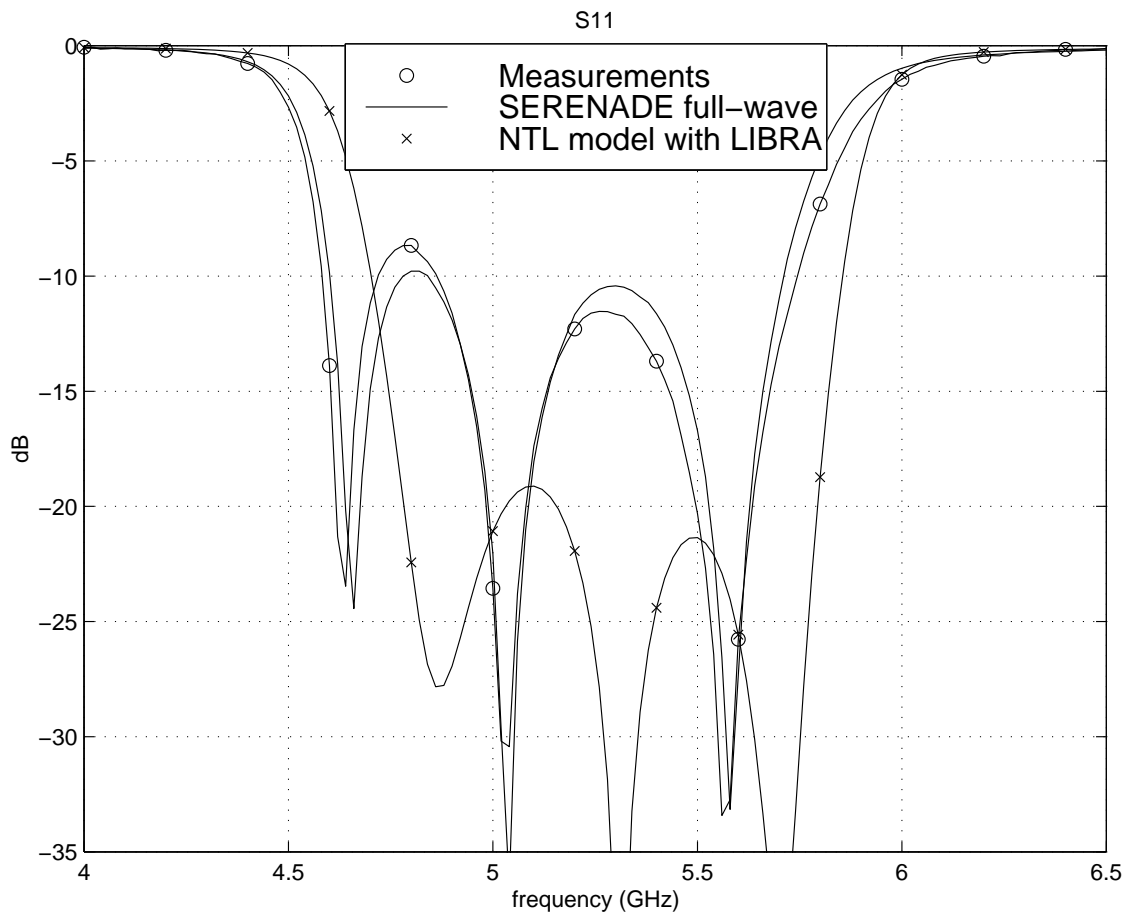


FIGURE 11

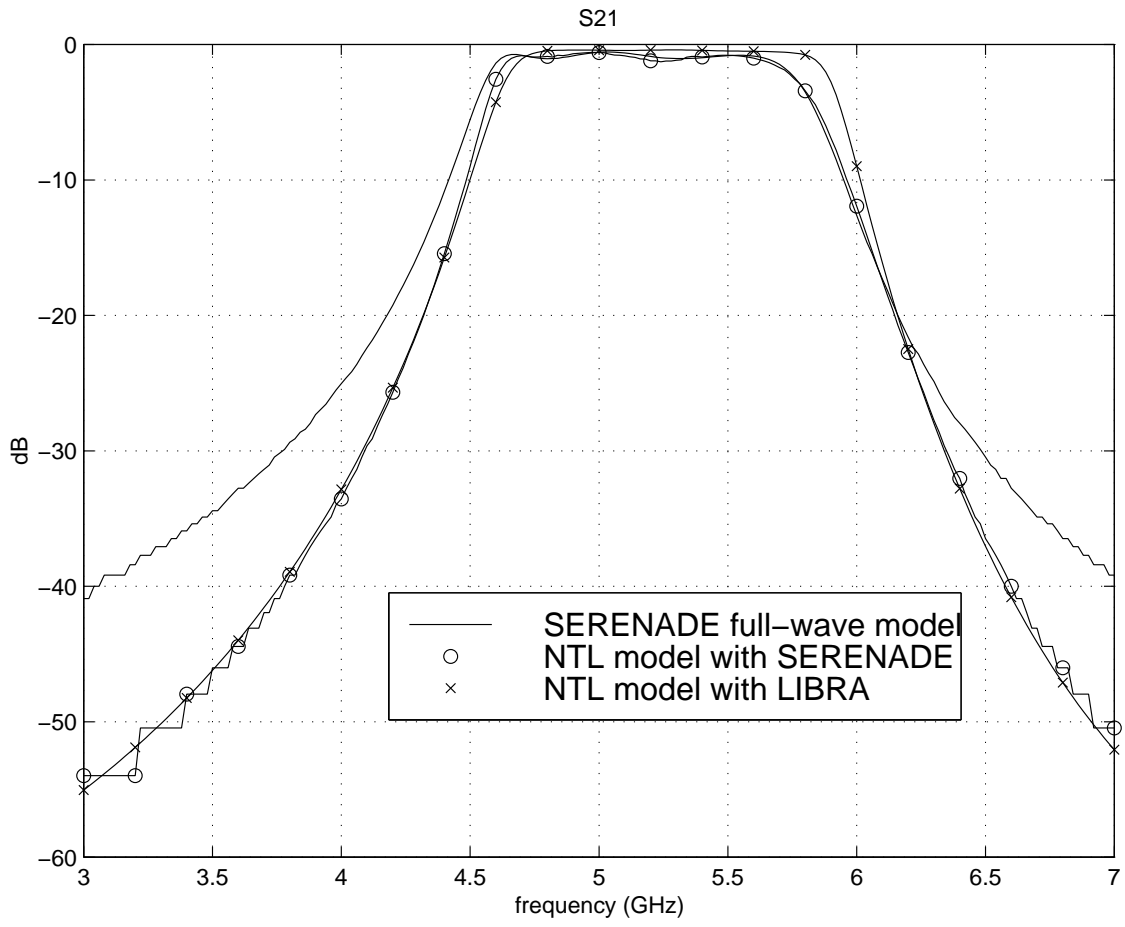


FIGURE 12

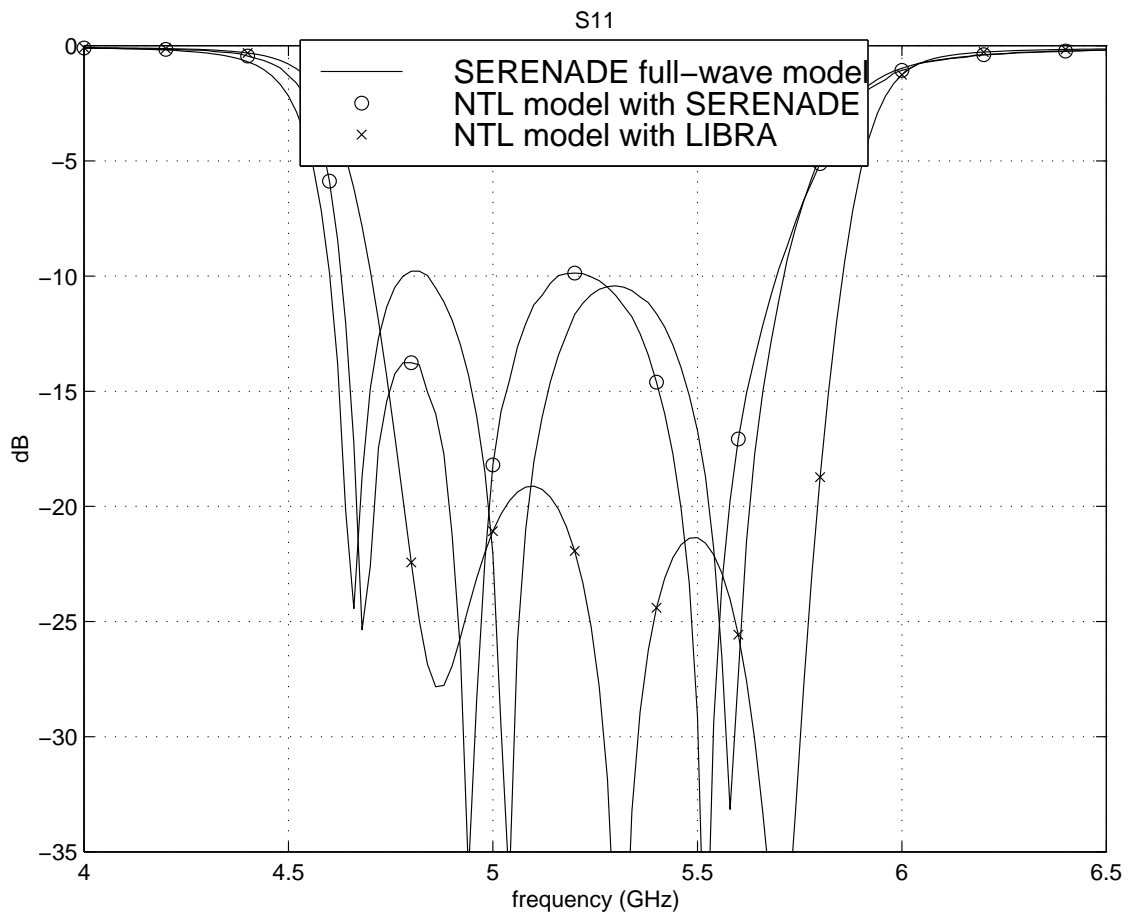


FIGURE 13

```

! FILE ntl_ts.CKT
! NTL model for TOUCHSTONE and LIBRA.
! Parasitic effects and discontinuities are included.

DIM
FREQ MHZ !HZ KHZ MHZ
RES OH !KOH MOH
IND NH !PH MH H
CAP PF !MF FF NF F
LNG UM !MIL CM M
TIME PS !NS SEC
COND /OH !KOH /MOH
ANG DEG !RAD

! VARIABLES.

VAR
! Width of the resonators
WR=1400
! Tapper Connection Width
Wt=240
! Separation between lines 1-2 and 4-5
SUNO=425
! Separation between lines 2-3 and 3-4
SDOS=675
! Tap point
LT=2125
! (Resonator length) - (Tap point)
L1=2700
! Additional length of resonator 1 and 5
Lstub=140
! Parasitic inductance modeling the connection to
!ground
Lpar=0.05

CKT
MSUB ER=9.9 H=635 T=25 RHO=0.77 RGH=0
TAND TAND=9e-4

! Implementation of the negator
VCVS 3 2 0 0 M=1 A=0 R1=0 R2=0 F=0 T=0
CCCS 1 3 2 0 M=1 A=180 R1=1e-3 R2=0 F=0 T=0
DEF2P 1 3 NEGATOR

! Coupling between lines 1 and 2
MCLIN 1 2 4 3 W^WR S^SUNO L^L1
MCLIN 5 2 7 6 W^WR S^SUNO L^LT

! Negator+ line 2 +Negator
NEGATOR 2 8
MLIN 8 9 W^WR L^L1
NEGATOR 9 4

NEGATOR 2 10
MLIN 10 11 W^WR L^LT
NEGATOR 11 7

! Coupling between lines 2 and 3
MCLIN 2 12 13 4 W^WR S^SDOS L^L1
MCLIN 2 12 14 7 W^WR S^SDOS L^LT

! Negator+ line 3 +Negator
NEGATOR 12 15

MLIN 15 16 W^WR L^L1
NEGATOR 16 13

NEGATOR 12 17
MLIN 17 18 W^WR L^LT
NEGATOR 18 14

! Coupling between lines 3 and 4
MCLIN 12 19 20 13 W^WR S^SDOS L^L1
MCLIN 12 19 21 14 W^WR S^SDOS L^LT

! Negator+ line 4 +Negator
NEGATOR 19 22
MLIN 22 23 W^WR L^L1
NEGATOR 23 20

NEGATOR 19 24
MLIN 24 25 W^WR L^LT
NEGATOR 25 21

! Coupling between lines 4 and 5
MCLIN 19 26 27 20 W^WR S^SUNO L^L1
MCLIN 19 28 29 21 W^WR S^SUNO L^LT

! (Input line) + (taper) + (TEE discontinuity)
MTEE 1 5 40 W1^WR W2^WR W3^Wt
MTAPER 40 41 W1^Wt W2=500 L=1000
MLIN 41 42 W=500 L=3300

! (Output line) + (taper) + (TEE discontinuity)
MTEE 26 28 43 W1^WR W2^WR W3^Wt
MTAPER 43 44 W1^Wt W2=500 L=1000
MLIN 44 45 W=500 L=3300

! Line additionally included in resonators 1 and 5.
! Open at one end
MLEF 3 W^WR L^Lstub
MLEF 27 W^WR L^Lstub

! Discontinuities to simulate open at end
!of resonators 2, 3 and 4
MLEF 7 W^WR L=0
MLEF 13 W^WR L=0
MLEF 21 W^WR L=0

! Simulation of the ground connection of the resonators
IND 6 0 L^Lpar
IND 4 0 L^Lpar
IND 14 0 L^Lpar
IND 20 0 L^Lpar
IND 29 0 L^Lpar

DEF2P 42 45 FILTER

FREQ
SWEEP 3000 7000 20

OUT
FILTER DB[S21] GR1
FILTER DB[S11] GR1A

```

FIGURE A.1